Travels with LCA

the evolution of LCA in the construction sector

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BY
ANNE RØNNING

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AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

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ENGLISH SUMMARY

This thesis analyses how Life Cycle Assessment (LCA) as a ‘global concept’ in environmental work has evolved through a period of approximately 25 years. This is the period of time I have been involved in research and standardisation work in this field of knowledge. The departure point is that LCA is a dynamic, ambiguous and controversial approach. Based upon theories on environmental problems as an example of ‘wicked problems’ and LCA as an ‘institutional global standard’, the main research question is:

What has characterised the evolution of LCA as an analytical tool in the construction sector?

Within the frames of this main question, three research questions are formulated:

1. How has LCA been subject to changes related to new knowledge during the years it has been used in the construction sector?
2. How has LCA as analytical tool been linked to other relevant analytical tools?
3. How have the dynamics between different actors involved in the construction sector developed in the studied period?

The thesis is organised in three parts:

Part 1 presents LCA as an analytical tool, theoretical perspectives and contextual environment for the evolvement of LCA. Here, a broad perspective on LCA from the initial phase when the concept was presented in the 1960ties until its present-day status and role is outlined. The scientific and political context of the evolvement of LCA is discussed, including an example of the controversies regarding how to apply LCA in the so-called ‘wood and concrete’ war in Norway. Also, the evolvement of standardisation work regarding LCA is addressed.

Part 2 presents 6 projects I have been involved in since the beginning of my journey between 1992 and 2017. These projects are selected for the purpose of illuminating how scientific knowledge, links to other environmental tools and different stakeholders/actors are mobilised at different times in the context of the Norwegian construction sector.

Part 3 presents main findings and conclusions regarding the research questions and the status and future developments within LCA as a global concept.

The ‘journey’ I have undertaken through a number of empirical projects and standardisation processes reflect some of the main global and national developments of the LCA approach, of which I will emphasise four in particular:

Firstly, when my work with LCA started in the beginning of the 1990'ties, the initial general ideas regarding how LCA should be applied were adopted in my projects as well. At that time, the main purpose was to assess environmental issues regarding single products. The scope of the first projects I was involved in was to compare environmental and health impacts from products in a life cycle perspective. In these first projects, some issues that has permeated the LCA discourse ever since were represented: LCA should be considered as both an instrument for assessing products and as a communication tool for strategic decisions in companies. To succeed the actors' motivation and composition of LCA project organisations were considered to be vital.

Secondly, from the first projects I took part in, LCA analyses had to become coupled with other analytical instruments in order to facilitate knowledge for real decisions regarding environmentally sound strategies in companies. The projects illustrated that from the initial phases of the LCA evolvement knowledge development must be supplemented by other analytical tools in order to create a holistic strategy for product development. During my journey, the coupling between LCA and other analytical standardized tools have been a recurrent issue.

Thirdly, while LCA had political implications from its introduction in the environmental discourse, it gradually became an explicit political issue. LCA projects initially addressed specific products at business level. However, due to the institutionalization of environmental policies governments integrated LCA-approaches in national policies. This process included the questioning of the legitimacy of LCA's (scientific) knowledge at different times. These controversies were then as now related to environmental policies as well – not least in the construction sector.

Fourthly, the actors involved have changed significantly during the period of time that is studied. In the 1960s and 1970s, just a few environmental political activists and a small number of business people were involved, while today many stakeholders in business, politics and the media are engaged in the design and implementation of environmental policies. In the context of LCA evolvement, scientific communities now play an important role together with economic stakeholders, while political actors seem to have become somewhat marginalized. This, however, supposedly reflects the institutionalisation of LCA in environmental policies.

The overall finding is that the evolvement of LCA as a global concept happens through dynamics between concerns with how to make the analyses scientifically credible on one side, and practical manageable on the other side. Scientific credibility has driven LCA to become more complex, while the quest for manageability drives LCA towards simplifications in its applications. The tension between these concerns seems to be an important feature in LCA presently and in the future. The scope of analysis in LCA tools has expanded from products to buildings, there is a likeliness that in the near future, an even broader perspective on ’context” will come. Here, a ‘systems’ approach – where for instance local community/social issues - will be included. Most likely, this will be the next phase of the LCA approach.

DANSK RESUME

Denne afhandling analyserer, hvordan livscyklusanalyse (LCA) som et globalt koncept inden for miljøarbejde har udviklet sig over en periode på ca. 25 år. Det er den periode, jeg har været involveret i forskning og standardiseringsarbejde på dette kundskapsområde. Udgangspunktet er, at LCA er en dynamisk, flertydig og kontroversiel metode. Baseret på teorier om miljøproblemer som et eksempel på "wicked problems" og LCA som en institutionel global standard er hovedforskningsspørgsmålet:

Hvad har karakteriseret udviklingen af LCA som et analytisk værktøj i byggesektoren?

Indenfor dette avgrænsede hovedspørgsmål er de udformet tre forskningsspørgsmål:

1. Hvordan har LCA blevet påvirket af ændringer, der er forbundet med ny viden inden for byggesektoren?
2. Hvordan er LCA som analytisk værktøj blevet knyttet til andre relevante analytiske værktøjer?
3. Hvordan har dynamikken mellem forskellige involverede aktører i byggesektoren udviklet sig i perioden?

Afhandlingen er organiseret i tre dele:

Del 1 præsenterer LCA som et analytisk værktøj, teoretiske perspektiver og kontekstuelle rammer for udviklingen af LCA. Her er det givet en kortfattet sammenstilling med et bredt perspektiv på LCA fra den indledende fase, da konceptet blev præsenteret i 1960'erne, indtil nutidens status og rolle. Den videnskabelige og politiske kontekst for udviklingen af LCA er diskuteret, herunder et eksempel på hvordan LCA bliver anvendt i den såkaldte ”træ- og cement” krigen i Norge. Også udviklingen af standardiseringsarbejde indenfor LCA er beskrevet.

Del 2 beskriver 6 projekter, som jeg har været involveret i siden starten af min rejse fra 1992 til 2017. Disse projekter er udvalgt med det formål at belyse, hvordan videnskabelig kundskab, sammenhæng med andre miljøværktøjer og forskellige interessenter / aktører mobiliseres på forskellige tidspunkter i den norske byggesektor.

Del 3 viser hovedresultater og konklusioner vedrørende forskningsspørgsmål og status og fremtidig udvikling indenfor LCA som et globalt koncept.

‘Rejsen’ jeg har foretaget gennem en række empiriske projekter og standardiseringsprocesser, afspejler nogle af de vigtigste globale og nationale udviklinger i LCA-tilnærmingen, hvor af jeg særlig vil fremheve fire:

For det første, da mit arbejde med LCA startede i begyndelsen af 1990'erne, blev de første generelle ideer om hvordan LCA skulle anvendes, også inkluderet i mine projekter. På det tidspunkt var hovedformålet med LCA at vurdere miljøspørgsmål for enkeltprodukter. Omfanget af de første projekter, jeg var involveret i, var at sammenligne miljø- og sundhedseffekter fra produkter i et livscyklusperspektiv. Disse projekter har nogle af de problemstillinger, der har gennemsyret LCA-diskusjonen siden: LCA betragtes som både et instrument til vurdering af produkter og som et kommunikationsværktøj for strategiske beslutninger i virksomheder. For at lykkes er aktørernes motivation og organisering af LCA-projekter vurderet til at være af afgørende betydning.

For det andet skulle LCA-analyser fra de første projekter, jeg deltog i, blive koblet sammen med andre analytiske instrumenter for at forenkle reelle beslutninger vedrørende miljøvenlige strategier i virksomheder. Projekterne illustrerede fra de indledende faser af af LCA-udviklingen, at LCA skal suppleres med andre analytiske værktøjer for at skabe en holistisk strategi for produktudvikling. Under min rejse har koblingen mellem LCA og andre analytiske standardiserede værktøjer været en tilbagevendende problemstilling.

For det tredje, LCA blev efterhånden et viktig politisk verktøy. LCA-projekter var i første omgang rettet mod specifikke produkter i virksomheder. På grund af institutionaliseringen af miljøstrategier ble imidlertid LCA-tilnærmingen integreret i den nationale politikk. Denne proces omfattede spørgsmålet om legitimiteten af LCA's videnskabelige kundskabsgrundlag på forskellige tidspunkter. Disse kontroverser blev dengang som nu relateret til miljøpolitikken - ikke mindst i byggesektoren.

For det fjerde har de involverede aktører ændret sig betydeligt i den periode, som beskrives her. I 1960'erne og 1970'erne var der kun få miljøpolitiske aktivister og et lille antal forretningsfolk involveret, mens i dag er det mange interessenter fra erhvervslivet, politikken og medierne som er involveret i udformningen og gennemførelsen af miljøpolitikken. I forbindelse med udviklingen af LCA spiller de videnskabelige samfund en vigtig rolle sammen med økonomiske interessenter, mens politiske aktører tilsyneladende er blevet noget marginaliserede i relation til udviklingen av LCA som sådan. Dette afspejler tilsyneladende institutionaliseringen af LCA i miljøpolitikken.

Den overordnede konklusjonen er, at udviklingen af LCA som et globalt koncept sker gennem dynamikken mellem hensynet til hvordan analyserne kan gøres videnskabeligt troværdige på den ene side og praktisk håndterbare på den anden side. Videnskabelig troværdighed har drevet LCA til at blive mere kompleks, mens når metoden anvendes, vil ønsket om praktisk håndterbarhed medføre forenklinger. Spændingen mellem disse to hensyn synes at være et vigtigt træk i LCA i dag og i fremtiden. Omfanget af analysen i LCA-værktøjer er udvidet fra produkter til bygninger, og det er sandsynlig at der i den nærmeste fremtid kommer et endnu bredere perspektiv. Her vil for eksempel lokalsamfund / sociale spørgsmål blive inkluderet i ”systemtilnærmingen” inden LCA. Dette vil sandsynligvis være den næste fase af LCA-tilnærmingen.

ACKNOWLEDGEMENTS

We find after years of struggle, that we do not take a trip; a trip takes us
(John Steinbeck: Travels with Charley - in search of America (1962/1997:3)

This has been a long journey, and there have been times when I struggled - when I thought I will never make it to the end. Still, the trip took me: I have been so many years on the road with LCA that it has become a part of my life which I would not be without! Also, I can see that the enthusiasm and support from many colleagues, friends and family has helped me making my journey an exciting experience. Sometimes even fun.

There are so many people I would like to thank for making these 'travels with LCA' possible. I have been privileged to meet many people with profound knowledge about LCA and environmental issues – both in Norway and abroad. All of them are dedicated to face environmental challenges; as individuals and globally. These people have different roles, some work in the construction sector, some in academic institutions. To name everyone who have inspired me and supported me is an overwhelming task. Nevertheless, I would like to thank those who helped me to finish this thesis particularly:

A special thanks to my supervisor, Professor Arne Remmen. Through our discussions during the time we have known each other, the thesis has been significantly improved – yes, I would say that without your help this thesis would not ever been done! Your profound knowledge, enthusiasm and – not at least – patience with me, is unique. You have been available all the time, ready to offer critical and constructive comments about my efforts to sort out the essence of too many projects and ideas.

Also, I would like to thank Ass. Prof. Søren Kerndrup and Prof. Per Christensen, for fruitful discussions and valuable input during my visits to the University of Aalborg.

Since I started my carrier in 1992 I have been working at Ostfold Research, a small research institute with a clear focus and devoted colleagues. The workplace has been – and still is – an inspiring scientific and social environment. Some of those working there have been directly involved in the projects I have referred to in this thesis: Ole Jørgen Hanssen, who introduced me to LCA projects when I began my work in 1992, Mie Vold, Cecilia Askham, Andreas Brekke and Kari-Anne Lyng – thank you all!

The close collaboration with all partners in the building and construction sector during 25 years have been a prerequisite for my research. It has been a privilege to be a part of and follow the development when environmental issues have increasingly become integrated into the sector and your businesses. Also, these companies that have been my empirical cases in this thesis.

Thanks to the experts in the standardisation society and a special thanks to all the devoted members of the ISO/TC59/SC17 working group 3 experts.

A special thanks to Prof. Michael Isaacson at University of California, Santa Cruz that arranged for my 6 months stay as visiting scholar in 2016. The time at your wonderful campus in the Redwoods gave time for reflection and fresh ideas. Also, I appreciated the opportunity to give lectures to your competent students. And thanks Rachel Cordero for all you support and inspiring conversation where you introduced me to the Californian way of living and explaining the contrasts in American society!

Helge, your wisdom - what can I say. You are always bringing me the balance in life by your knowledge, engagement, humour, unlimited support and love. Thanks for encouraging me to take this travel. You are my best traveling companion!

Last, but not least - Maria and Rakel, I love you to the moon and back! Thank you for your patience. I dedicate this work to you as an inspiration for your own travels.

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1 THEMES AND RESEARCH ISSUES

1.1 MY JOURNEY WITH LCA

Life cycle assessments (LCA) have been performed since around 1970 using different methods in several countries in North America and Europe before the name was coined (Boustead, 1996, Finkbeiner et al., 1998, Köppfer, 2006). Society of Environmental Toxicology and Chemistry (SETAC) has promoted LCA (Köppfler, 2006). SETAC initiated a standardization process, which culminated in the LCA-guidelines ('A code of practice') in 1993 (Consoli et al, 1993). The 'Code of Practice, laid the foundation for further development to the practice of environmental Life Cycle Assessments (LCA). In 1993, ISO took over the leadership in standardization and the ISO 14040 series were first published in 1997 (Klöppfer, 2006).

'My travels with LCA' is referring to my general experience over 25 years with environmental assessments of buildings and construction materials. These 'travels' cover many destinations (research projects), and interactions with different communities and actors at these destinations, as well as the journey in itself as a process of learning and interacting in order to explore the blank spots on the map. In this chapter, I will first give a brief background information about my 'travels' in general, before I present my main theme, LCA as an instrument for assessing environmental impacts in the building sector.

I began as a researcher in 1992 at Ostfold Research Foundation, and my first project was an LCA of two interior paint products commissioned by Jotun AS, (Rønning et al., 1993). The purpose of the LCA project was to gain experience of LCA and how this methodology could play a role in developing Jotun's business strategies. This is the first LCA project I performed and it was one of the first LCA projects carried out in Norway following the SETAC (Society of Environmental Toxicology and Chemistry) Code of Practice (Consoli et al., 1993).

The scope of the first project was to compare environmental and health impacts from two paint products in a life cycle perspective. As the project report states: 'As an LCA is both an instrument for assessing products and is a communication tool for strategic decisions in companies, planning, the actors' motivation and composition of the project organisation are vital for success' (Rønning et al., 1993). The project was supported by the management, which was considered as a key factor for implementation of results. The project group consisted of representatives from the following departments; management, marketing, production, purchasing, distribution, R&D and Environmental protection. The project identified intervention for improvement of the two product systems – in accordance with the way an LCA was performed at that time:

- Which environmental impacts contribute most to the overall environmental profile for the given product?
- Where in the life cycle stages do these environmental impacts occur?
- Which actions should be taken to improve the product system?

In addition to the comparison per se, the project resulted in increased knowledge of several LCA methodological aspects like allocation, cut-off criteria, data quality, data collection and weighting.

In 1991, the Nordic Council of Ministers initiated a project on LCA. The objectives of the project were to develop a Code of Practise for LCA built on Nordic consensus, to provide industry and other practitioners with a set of guidelines for LCA. This work resulted in a Nordic Guideline for Life Cycle Assessment (Lindfors et al., 1995a). Ostfold Research was the Norwegian research partner and together with Ole Jørgen Hanssen, I was a project member. The project identified important topics to discuss and form guidelines for system boundary setting, cut-off criteria, allocations, data quality and impact assessment methods (Lindfors et al., 1995b, Lindfors et al., 1995c, Rønning. 1994). In this context, the Jotun paint project served as input to this work as the project covered a broad set of methodological challenges.

At the same time, Statoil (the Norwegian State Oil Company) and Jotun initiated a project, where the intention was to improve coating systems for offshore installations. One of the main purposes was to develop new coating systems with significantly better environmental and health properties at lower costs, than the best existing coating system from Jotun at that time. In this part of the project Jotun Paints and Statoil chose to carry out an LCA of a reference system and two new systems. Ostfold Research foundation was invited to participate in the project after the first year, when environmental and health aspects were given higher priority in the project. This was considered as a prestigious project, and was even stronger linked to and rooted in management business strategies. This project began in 1993 and lasted until the end of 1994, Rønning et al (1995).

In addition to LCA, Life Cycle Cost (LCC) was introduced as a parallel method for assessing the economic life cycle consequences of a new offshore coating system. Thus, this project is an example where the purpose was to use LCA as part of decisions for product development and at the same time introduce LCC as a complementary assessment tool. Based on experiences from this project, Jotun decided to integrate these methods in general in their long-term product development, whereas Statoil decided to integrate the experiences in their guidelines for maintenance practice.

The project was then integrated as a part of the Nordic Project on Environmental Sound Product Development (NEP-project) as a case-project in method development. The main purpose of the NEP-project was to develop methods, decision tools and educational programmes for integrated life cycle assessment, product development and system engineering for practical application in the industry.

The NEP-project was initiated in co-operation between the Federation of Swedish Industries (SI) and Østfold Research in 1993, based on experiences from projects with product related environmental impact studies in Sweden and Norway (Ryding, 1995). Several companies had started to work with life cycle assessments (LCA) of the environmental profile of their products, to increase their knowledge about environmental and health impacts of products in a 'cradle to grave' perspective. These companies were front-runners, and their customers and other stakeholders required more information and better products with respect to environmental impacts. In development of the LCA method, the least documented part of the method at that time was the 'Improvement phase'[1]. Through the NEP project, the Nordic industry and research centres intended to make a substantial contribution to the methodological basis for application of LCA in product development and product management (Hanssen et al., 1996, Hanssen, 1997).

After these destinations in the first part of my 'journey' with LCA, I became increasingly involved in LCA as a tool for analyses related to environmental impacts in the building industry, and my thesis focus upon building and construction in particular. I have experienced many of the challenges and opportunities LCA has faced at different times and in different contexts. LCA has been (and is?) a contested and controversial approach both regarding the scientific validity and reliability, not at least in the building sector. In addition, these controversies became related to environmental policies regarding this sector in particular. This took place in several countries when LCA analyses were introduced as an instrument to legitimize the eco-friendliness of specific building products – the so-called 'Construction Materials War, see chapter 1.3. The scientific and political questions referred to as this 'war' constitutes the backdrop of my work with LCA in the sector.

In 1994, the Cement producers in the Nordic countries (Sweden, Norway and Finland) established a joint LCA project as a response to the growing claim that one construction material is better than another with respect to the environmental friendliness of a building. This was the departure point to develop and apply LCA in the construction industry through projects for various business organisations and public bodies. For my part, these projects were important as a research field to study the development and use of LCA methodology, and later for studies of how results and knowledge based on LCA were used in companies. I have chosen to focus on the

[1] In an early phase of developing the ISO 14043:2000 Environmental management - Life cycle assessment - Life cycle interpretation, the fourth phase of LCA was Improvement phase and later changed to Interpretation.

projects that show how the development of knowledge on LCA - in both theory and practice - changed during the years.

The first projects were implemented in collaboration with manufacturers of cement, concrete and light clinker. Here the aim was to increase their knowledge of their products in a product life perspective. Later, the 'Leca International Environmental Project (LIEP)' was the most extensive project associated with this section of the construction industry (see 6). As one response to this, the Norwegian Cement and Concrete Industry invited the Wood Industry Association and the producer of masonry and masonry-related products to participate in a common project. I was the leader of this project, which was the beginning of an explorative journey in the use of LCA to analyse environmental performance in the building sector. Part of this was to perform critical analyses of the way LCA was being used in the 'war' that I have briefly described above. In various ways and in different projects and commissioned work, I have analysed the importance of comprehensive analyses with LCA as a key element.

In 1997 the NIMBUS project was established as a joint Nordic project that aimed at developing methodology and a system for a Nordic EPD programme. The project was initiated by Ostfold Research in partnership with the Confederation of Norwegian Enterprise (NHO) and the Federation of Swedish Industries, and was financed by the Nordic Industrial Fund and participating companies. The project was implemented in 1997-2001 in two phases, a pilot phase in 1997-98 (Møller et al., 1998) and the main project in 1998-2001 (Hanssen et al., 2001), with representation from Denmark (dK-Teknik and the Confederation of Danish Industry), Sweden (IVL Swedish Environmental Research Institute, Chalmers University of Technology, Gothenburg University and the Federation of Swedish Industries) and Norway (NHO and Ostfold Research). The main project proposed a common Nordic format for EPD, and collaboration in organisation to ensure similar systems in the Nordic countries for companies operating across Nordic borders (Hanssen et al., 2001). This project placed the Nordic countries at the forefront of developments in the field in an international context, but its proposal for a coordinated EPD system for the Nordic region was not accepted. However, the proposal for a common Nordic format was adopted in Norway and has provided the basis for the development of the Norwegian system of environmental declarations through the Norwegian EPD Foundation, which was established by the Confederation of Norwegian Enterprise (NHO) and the Federation of Norwegian Construction Industries (BNL) in 2002.

To summarise, the first five years of my journey were dedicated to methodological developments of LCA and to get LCA integrated in product development. However, gradually the political implications of these analyses – as reflected in the 'wood and concrete war' - became visible.

Later, I worked with LCA both in relation to specific environmental analyses of products and services, and in developing and standardising the method. Appling LCA in the service sector and the service divisions in manufacturing companies was a major part of my research around the start of this millennium (Økstad and Rønning, 2002, Økstad et al, 2002), Modahl and Rønning, 2006). This perspective was later referred to as organisational LCA and our research was based on the first efforts in the life cycle community on organisational footprinting that took place in the 1990s (Taylor and Postlethwaite, 1996; Finkbeiner et al., 1998; Clift and Wright, 2000).

My research also includes how the concept of Factor 10 could be applied in the service sector in collaboration with Håg (seating solutions) and Telenor (mobile operator), Sommerfeldt et al. (2006), developing methods for climate accounting in the service sector for appr. 100 Nordic Choice hotels (Rønning and Brekke, 2008, Rønning and Brekke, 2009), development of environmental life cycle based indicators for public procurement (Rønning and Vold, 2005) and even LCA of a human being (Rønning et al., 1999).

In addition, I have been involved in developing standards at international and national levels. A recurrent theme in this work has been the reciprocal influence between specific analyses and international standards. I have seen the challenges involved when international standards meet specific environmental analyses of individual products, where the LCA concept meets 'reality' and is to be used in specific building processes and in drawing up policies. On the other hand, I have experienced the struggle to develop standards that can both satisfy academic requirements and be useful in practice.

During my period as research scientist, perspectives on environmental problems, and strategies to analyse them by LCA approaches, have changed significantly. My thesis therefore focuses on the complexity of the analytical methods used in the LCA tool applied in the construction sector. In order to describe various challenges in the development of LCA, I have chosen some LCA projects to illustrate the challenges and solutions in the projects where I have been involved in the development of standards and the scientific basis for LCA. The selected projects have been limited to those that concerned sustainable buildings or building materials. These were analyses that I consider as key points in my professional development related to LCA, and they also led to a critical (re)assessment of how analyses should be performed.

1.2 LIFE CYCLE PERSPECTIVES – A BRIEF OVERVIEW

Environmental problems and resource depletion have been challenges for the business sector and governments for the past 30-40 years. During these years, political strategies have changed, and environmental concerns have become an important focus for business and industry in the Western world. While environmental issues have become part of the political and business agenda, also analytical and policy approaches to environmental problems have changed character. There are at least three factors behind these changes:

Firstly, environmental policy has become *institutionalised* as an independent policy area. Whereas environmental policy was formerly regarded as a policy field in opposition to the established political and administrative institutions, it is now an integrated part of the political-administrative system in most Western countries. Most governments have an environmental minister, together with an administrative system and legislation related to this policy area.

Secondly, *the actors involved* have changed in accordance with the institutionalisation of the policy area. In the 1960s and 1970s, just a few environmental political activists and a small number of business people were involved, while today many stakeholders in business, politics and the media are engaged in the design and implementation of environmental policies.

Thirdly, the *development of knowledge* has changed radically in terms of how we analyse and seek solutions to environmental problems. Environmental perspectives are now more comprehensive, more fragmented and more technologized. In accordance with this, knowledge issues must be addressed explicitly.

These three factors have changed people's perspectives on how to solve environmental problems. Historically, most of the industrialised countries, in their efforts to reduce pollution and waste generation, have tried to achieve success with different strategies. Several authors have described these different strategies.

Remmen (2001) divides the developments of new knowledges, approaches and actors in three phases: The first one –in the 1970s – was dominated by the filter strategy, in which the problem was defined as 'emissions', the solutions were 'end-of-pipe', the incentives were characterized by 'compliance', and the major actor in the development of these strategies were the environmental authorities (Remmen: 54). The second phase - in the 1980s – the approaches changed substantially: *'Since the mid-80s the discourse on pollution prevention and the understanding of cleaner technology have changed from cleaner production processes over environmental management to cleaner products'* (Remmen: 55). While the 'cleaner production processes' approach broadened the scope by defining the problems as both emissions and waste from the companies and resource consumption, the solutions preferred were technical demonstration projects, and dissemination and diffusion of solutions, and the number of actors involved in the strategy increased as production engineers, consultants and environmental authorities now took part. Since the beginning of the 1990s, a third phase has evolved, characterized by an environmental management approach. Here models of management included environmental considerations, as well as the ISO 14001, EMAS and other environmental standards that were developed during this period. The problems were defined as emissions and resource consumption, and organizational preconditions. The solutions were continual (incremental) environmental improvements, resting to a large extent on environmental management systems, being controlled and supervised by international standardization actors and regulations by national environmental authorities (Remmen: 57).

In this thesis, the third phase is of particular interest. The environmental management approach has, according to Remmen, some obvious advantages: This approach ensures – at least formally – that environmental efforts are becoming systematic activities with specific procedures and instructions and a dynamic activity with focus on continuous improvements, and a focus on organizational conditions for these improvements within companies. However, there are environmental activities are secured potential weaknesses and challenges in the environmental management approach as well: first of all '*companies may fail to keep up the momentum and maintaining the system so the dynamics of environmental activities are secured'* (Remmen: 57). Thus, the environmental management approach rests heavily upon maintaining the strategies by implementation of the approach. One of the major strategies in this third phase was – and is – LCA. The strengths and weaknesses mentioned by Remmen, is one important aspect of my discussion on the LCA approach in this thesis.

Hanssen and Abrahamsen (2012) describes the same period as follows:

1. **The diluting strategy**, based on tall chimneys into the air and pipelines into lakes, rivers and the sea. This strategy was used in the 1950s and 1960s. The opinion at the time was 'if the pollution was spread over a large area, it would do no harm'**.**
2. **The filter strategy**, based on end-of-pipe installations. In the 1970s and the 1980s, this strategy was a widely applied solution to most environmental problems. However, these solutions often transfer or transform one environmental problem to another (from water pollution to hazardous waste).
3. **The recovery/reuse strategy** from the 1980s, where many environmental activities were carried out and produced results such as: recycling of paper, glass, etc. However, this strategy does not deal with the process or problem itself, but often focuses only on used products and the recovery of raw materials in waste products.
4. **The cleaner production (CP) strategy** emerged in some countries from the late 1980s, and was the dominant pollution prevention strategy in industrialised countries in the 1990s. This strategy is based upon reducing environmental problems by source reduction and focuses mainly on industrial processes inside the factory.
5. **Product-oriented environmental strategies.** Just as the 1980s witnessed a shift from end-of-pipe technologies to cleaner production, environmental strategies in the 1990s shifted the focus from processes to products. In 1990, Lindhqvist and Lidgren (1990) introduced the concept of Extended Producer Responsibility

(EPR) in Sweden and later it took form as a policy approach that give producers a responsibility – financial and/or physical – for the treatment or disposal of post-consumer products, OECD (1996). Besides, LCA was introduced as a broader perspective on environmental awareness: life cycle consideration of environmental problems related to their products along the value chain – both inside and outside the company; life cycle management (LCM).

As the focus shifted from only focusing on Cleaner Production (CP) in one company to life cycle management (LCM) in value chains along the value chain – both inside and outside the company - focus on preventive environmental strategies in integrated industrial network increased. Industrial ecology (IE), focusing on functional or geographical systems was then introduced, Erkman (1997). The industrial ecology perspective has been defined as a *'systems-based, multidisciplinary discourse that seeks to understand emergent behaviour of complex integrated human/natural systems'* (Allenby, 2006). From a system perspective, CP, LCM and IE have different system boundaries for what to include in assessments and the complexity increases form left to right, as shown in Figure 1.1, Hanssen and Abrahamsen, 2012, Finkbeiner et al. 1998.

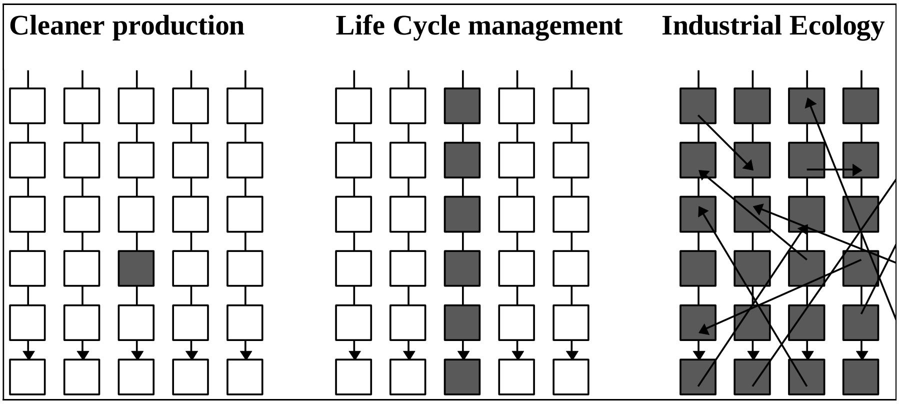

Figure 1.1 From Cleaner Production to Industrial Ecology, Hanssen and Abrahamsen (2012).

It is in this field of tension between individual companies, product chains and companies in the same industrial sector that the challenges discussed in this thesis take place. Although, the focus will be on LCA in the construction sector.

According to Guinee et al. (2011), LCA and life cycle thinking (LCT) have become 'the core element in environmental policy or in voluntary actions in the European Union, the USA, Japan, Korea, Canada, Australia as well as upcoming booming economies such as India and recently also China' (Guinee et al., 2011:90). In line with this, life cycle perspectives and particularly LCA have developed in different directions - in terms of applications, analytical depth and breadth. This means that determining what LCA ‘is’ is not straightforward.

The framework of LCA has been developed to be able to capture the inflows and outflows from activities in all life cycle stages associated with products, product systems and services and all environmental impacts related to these inflows and outflows. It considers the entire technical system related to a product from ‘cradle to grave’, i.e. from raw material acquisition to final waste treatment of waste products (ISO 14040:2006, ISO 14044:2006). The concept of LCA will be discussed in more detail in 3.

LCA was originally based on analyses of individual products and on comparisons of alternative products. This (relatively simple) approach was seen in the US, where the first LCAs were related to Coca-Cola’s packaging strategy (plastic bottles vs. cans), in the UK, and in the Netherlands (Hunt and Franklin, 1996; Köppfer, 1997; Gabathuler, 1997; Finnveden et al., 2009). Pesso (1993) argued that *‘On one side stand the 'inventory makers', who consider that no decision can or should be taken until 'all' the information is gathered; on the other side are the 'streamliners' who argue that swift decisions can be taken on the basis of a few select inventoried parameters, which in some cases can cover only a small part of the life cycle.’*

The original construction-related LCAs in the initial stages around 1990 were following the ‘streamliner’ strategy and were typically based on the assumption that non-contextual comparisons where system boundaries were set in such a way that only parts of buildings’ or other construction works’ life cycle were analysed (Fossdal, 1995; Upton, 2008; Guggemos and Horvath, 2005). Later on, the scope was expanded from merely documenting the consequences of choices made to also including the planning of future buildings or other civil engineering works.

The first LCAs of construction products and construction works were published in the early nineties, Cole and Roussau (1992), Buchanan and Honey (1993), Cole and Kernan (1996), Fossdal (1995), Mørkved and Opdal (1990). The Canadian timber industry was involved at an early stage and thus gained an advantage over other material manufacturers. The results of the Canadian studies generally showed that wood was more environmentally friendly than other building materials (Cole and Kernan, 1996). Since many of these studies were based on LCA, building material manufacturers began to show an interest in performing LCAs themselves. Part of the rationale for these analyses was that these manufacturers wanted to counteract the perception implied by the Canadian studies that wood was the most environmentally friendly building material.

In Norway, the interest in environmental impact from different construction products based on LCA increased significantly in the construction sector. As early as 1994 the Norwegian Building Research Institute published a report comparing three different residential buildings. One of the conclusions was that timber framed buildings had a better environmental profile than steel and concrete framed buildings, (Fossdal, 1994).

The process that followed the initial analyses of wood and the later comparison with other building materials had implications for both industrial and environmental policies. There was a strong link between these two policy areas, and powerful business interests became keen to ensure that their products were not labelled as less environmentally friendly than alternative building materials. The processes triggered by these assessments have in many contexts been referred to as a 'war' between different products, especially between wood and concrete as building materials. The 'Wood and Concrete War' was largely a conflict between business interests concerning the knowledge base for the priorities to be taken as environmental considerations gained prominence in industrial policies. This is an important backdrop for my research questions, theoretical perspectives and selection of cases. Thus, the 'war' and its background need to be clarified, see chapter 1.3.

1.3 'THE WOOD AND CONCRETE WAR' AND OFFICIAL NORWEGIAN POLICY

1.3.1 OFFICIAL NORWEGIAN POLICY

The 'war' referred to here was basically concerned with the *knowledge base* for claiming that certain building materials had precedence as more environmentally friendly than others. Parliamentary Report No. 17 (1998-99) 'Value Creation and the Environment - Opportunities in the Forestry Sector' was the first time this issue had been raised in connection with Norwegian environmental and industrial policy. As the title of the report indicates, a policy to strengthen the forest industry was linked to environmental policy considerations. The report stated that sustainable production and consumption, climate challenges and energy use are closely interrelated, and that the production and use of wood has valuable direct and indirect effects in meeting these challenges. Here, for the first time in a political context, a comparison was made between wood and other building materials:

'....At the same time, the use of wood to replace materials such as steel, aluminium and concrete leads to lower greenhouse gas emissions, while bioenergy to replace fossil fuel also reduces CO_2 emissions. The lifetime of wood, its potential for recycling and its biodegradation in ecological cycles make it a favourable material. The Government believes there is a potential for increased environmental benefits in utilising it better.' (Parliamentary Report No. 17, 1998-99, chapter 2.4.2)

On this basis, the report stated that the Government would place greater emphasis on the role of forestry and wood products in fostering more sustainable production and consumption, and would work internationally to ensure that forestry measures are an important element of environmental efforts. It was also stated that it was important to change people's priorities in choosing building materials:

'There is also in Norway a great need for increased communication between the forestry sector and other groups. The Government believes that forestry and environmental policies must focus on energy use, material utilisation, waste management, etc. and encourage sustainable production and consumption in which wood products play a key role.' (ibid., chapter 8)

However, this report contained no references to product's service life or life cycle assessment. The arguments were primarily related to forestry policies, and the environmental policy aspects mentioned dealt with ways of maintaining and strengthening the forestry industry. The basis for claiming that wood was the most eco-friendly building material was thus an exclusive focus on analyses of wood products, without any direct comparison with other building materials.

The perception that wood was the most environmentally friendly building material was accepted by the Government of Norway (and other countries) - as the quote from Report No. 17 shows. The timber industry thus gained a political stamp of approval, which was based on both the results of the LCAs performed and also on the more intuitive understanding that wood - being a clean and renewable product - would be the most environmentally friendly material in buildings. LCA was thus portrayed as a 'scientific' basis for aspects of public environmental policy.

The debate about wood versus other building materials became explicit and more strongly focused when the Official Norwegian Report NOU 2006: 18 'A Climate Friendly Norway' was released by the Ministry of the Environment on 4 October 2006. The committee behind the report undertook a broad review of environmental policy issues, based on analyses of global trends, international environmental policies and Norway's recommended role in environmental and climate policy issues. The committee, headed by Jørgen Randers, had considerable prestige and achieved great influence in setting the premises for the Norwegian environmental policy debate. The report also dealt with the construction industry, especially energy efficiency in buildings. It focused particularly on requirements for stricter building standards, environmental labelling and subsidies, among 15 priority measures in Norwegian environmental policy. Now the question of the environmental performance of different building materials was also addressed directly: in a separate section, there was the headline: *Wood or cement in the building sector - which should we choose?* (Box 6.7, p. 68). The text read as follows:

'Increased use of wood could reduce greenhouse gas emissions, if it replaces other more harmful materials in the building sector. The environmental gain in e.g. a change from concrete to solid wood may be roughly estimated at 0.4 tCO2 equivalents per ton of increased wood consumption. Similar trends would apply to a change from light steel to solid wood and a change in light timber frame structures from wood to solid wood, although the gain here is somewhat lower at 0.3 and 0.25 tCO2 per ton of increased wood consumption, respectively.

If construction methods in new buildings were restructured with a moderate increase in wood consumption (an increase in the use of wood to 40 percent of the technical potential), we could achieve an annual saving in greenhouse gas emissions of about 0.3 MtCO2 equivalents. This is equivalent to 20-30 percent of the environmental impact related to the production of new buildings in Norway. This can be compared in size with the reduction that could be achieved with a 30 percent decrease in energy consumption in new buildings. And these measures are not mutually exclusive. Here it is a matter of choosing both.'

In addition to the savings involved in the transition to wood and wood products in new buildings that could immediately be credited to the national emission accounts according to the principles of the Kyoto Protocol, wood also binds CO_2 through photosynthesis, and buildings would thus serve as storage facilities for CO_2 (see box 6.6).' (ibid., p. 68)

However, the report only referred to one source of these calculations (Berge and Stoknes, 2004). This report also contained no references to LCA or other kinds of analysis that reflected a lifecycle perspective.

This changed, however, during the next few years, both in developments in environmental science and in the political debate. In Parliamentary Report No. 39 (2008-2009) 'Climate Challenges - Agriculture as Part of the Solution' (Ministry of Food and Agriculture), both the discussion of the eco-friendliness of various building materials and the use of LCA/life cycle assessments had become key aspects of the design of (parts of) the environmental policy. Although the report discussed environmental aspects of food production, there was one particular point where the choice of building materials was seen as important in agriculture: whether one could replace steel - the most common material for buildings used in food production - with wood. The comment in the report was: '*Wood in constructions should increasingly replace less climate-friendly materials'* (ibid., p. 56). It was claimed that increased use of wood was important in relation to climate change, both because wood binds carbon and because the production process leads to fewer emissions than the production of other materials.

Interestingly, LCA was presented here as an important knowledge base for environmental policy considerations:

'LCA (Life Cycle Assessment) assesses environmental aspects and potential environmental impacts (such as the use of resources and environmental consequences of emissions) throughout the product lifecycle, from procurement of raw materials, through manufacturing, use, final treatment, recycling and disposal (i.e. from cradle to grave).' (p. 76)

However, there was still scepticism about how LCA could be used, and it was also stated that:

'Results from life cycle analyses must be interpreted critically. This is because the environmental impact may vary according to the factors and conditions used in the calculations. Production methods and processes may vary over time, and it can be difficult to illuminate a problem by including all the factors in the value chain. Life cycle assessments also do not capture the costs of an action, which is an obvious weakness'. (p. 76)

Despite (or perhaps as an argument for) the lifecycle perspective, the Government argued that *'The manufacture of wood products consumes little energy compared with alternative products and leads to low process emissions'* (ibid., p. 76). This was partly explained by the fact that waste products from the forestry and wood product chain can be used as bio-energy and replace fossil fuels, and wood products can also be used as bioenergy at the end of their useful life. Measures to increase the lifetime of wood products will help prolong the storage of carbon. In the description of the knowledge base for this conclusion, the report referred to a review by the Norwegian Forest and Landscape Institute, commissioned by the Ministry of Food and Agriculture, which summarised Nordic literature on the environmental impact of using wood. Here it was stated that in 65 percent of the studies (15 studies) in which wood was compared with other materials, wood was the best environmental option. In 30 percent of the studies (7 studies) there was no or little difference and in 4 percent (1 study), alternative materials were best. Reference was also made to research at the Norwegian University of Life Sciences, based on comparative LCAs in Sweden, which supported the use of wood as the most favourable option with regard to greenhouse gas emissions:

'When wood is used instead of steel, it saves 36-530 kilos of CO_2 equivalents per cubic metre of timber. When wood replaces prefabricated concrete, it saves 186-2124 kilos of CO_2 equivalents per cubic metre of timber. Wood is also significantly more beneficial in terms of greenhouse gas emissions than vinyl, linoleum, slate, carpet flooring, plastic pallets and plasterboard. Wood additionally provides less waste and lower emissions of sulphur dioxide (SO_2). Wood is also cheaper or the same price as other materials. The construction and operation of buildings accounts for roughly 35 percent of global greenhouse gas emissions. On the path towards a low carbon society, significant steps must be taken to reduce these emission figures. One such step could be to increase the proportion of renewable wood raw material in building constructions.' (p. 75-76)

The reports presented above all indicate that wood is a more environmentally friendly building material than other materials, including concrete and steel. In addition to the industrial policy arguments used as a basis for this, reference was eventually also made to more direct comparisons, based on LCAs. The reference to LCA as an analytical method in Parliamentary Report No. 39 (2008-2009) reveals a somewhat ambiguous attitude to LCA as a basis for environmental policy decisions. On the one hand, we see a desire to explain and clarify the strength of LCA as an analytical tool, but on the other hand, it appears that the Government does not want to commit itself too strongly to this tool - which may partly be explained by criticism of the elements included in the calculations. It is also conceivable that it was undesirable to let a potentially unfavourable result of LCA analyses for wood products stand in the way of important initiatives in industrial policy. *(I have no data to support this, and will not pursue this argument further here).*

The political documents presented above show that LCA was given a more important role as a basis for environmental policy considerations. 'Lifespan perspectives' are mentioned in several places. The calculations made (of energy use/emissions, etc.) without LCA being mentioned, demonstrated a preference for wood in industrial and environmental policy. This was later confirmed by Canadian and Nordic studies that were referred to and used as an argument for the prioritisation of wood. However, the discussion of the eco-friendliness of the various building materials was also subject to political considerations. This led to a new comprehensive parliamentary report in 2011 dedicated to the construction industry, with a particular focus on environmental requirements for buildings. Parliamentary Report No. 28 (2011-2012) 'Good buildings for a better society. A progressive building policy' was the first time a separate report to parliament represented a 'comprehensive' policy in this area. Here the choice of building materials was subject to an exhaustive evaluation, including environmental considerations.

In a separate section on 'Material use and environmental impact', it was stated that:

'All construction products are made of material with an environmental impact ..... The building and property sector is the largest consumer of material resources in Norway. The construction industry uses several thousand different products, and the use of new materials in buildings increases with the rate of construction and renovation. There are also great quantities of materials and construction products in existing buildings. The environmental impact of the use of materials in buildings could be enhanced by using products and methods that reduce resource use, energy consumption, the use of substances hazardous to health and the environment, and the type and quantity of waste. In addition, the environmental impact of materials will depend on how the materials affect the operation of buildings, how often materials are replaced, maintenance requirements and the lifespan of buildings. A life cycle assessment of a building will provide good information on the total environmental impact of the materials in the building.' (p. 66).

The report also gives a general positive assessment of wood as a building material:

'Wood is and has been much used as a building material in Norway. Wood from sustainable forestry is an environmentally friendly material with many applications. ....There is a considerable untapped potential for increased use of wood in this area, and a great need to develop new solutions (p. 65)'.

This description, with its direct reference to a lifespan perspective and 'life cycle assessment' implies a continued focus on wood as a high priority building material, also from an environmental perspective. But, unlike the former political signals, as formulated in the reports mentioned above, and despite the favourable views referred to there, the report does not present an entirely unequivocal recommendation of wood as the most environmentally friendly building material:

'The manufacture of wood products, compared with many other products, is less energy-intensive and produces fewer process emissions. How environmentally friendly wood products depends on the type of wood, its origin, the production method and how it is treated. Most harvesting and production of wood for use in buildings in Norway is of spruce and pine. In general, such production is very environmentally friendly and requires little energy. Wood, as a natural material, is often coated with paint or varnish or impregnated, involving substances harmful to health and the environment. Such surface treatment can change the environmental qualities of wood products. New environmentally friendly methods of pre-treating wood products to increase their lifespan are continually being developed.'

Such formulations, which appear to be arguments for prioritising wood from an environmental perspective, also allow for a more nuanced approach in what became known as the 'Wood and Concrete War' in environmental science circles at the time. This is mainly evident in the focus of the new report on the need for more information:

'Since it is difficult to obtain good environmental information, the Government will take steps to ensure greater access to such information. In the longer term, this will lead to more environmentally friendly production of products, facilitate assessment of the environmental impact of products by consumers, and increase the use of environmentally positive products.'

One of the most important measures in the report is to ensure the availability of such information. This will be achieved through an increased focus on environmental product declarations. Here, rather specific requirements and expectations are formulated:

'The construction industry has taken the initiative for environmental product declarations (EPD) as documentation of the environmental impact. EPD Norway administers the scheme, which is an international system. EPDs document resource

use, energy use, climate impact, pollution and for some product categories also the content of health and environmentally hazardous substances.'

In the summary of government policy in this area, it is stated (as 2 of 15 points):

- 'The Government will consider whether the next revision of the construction regulations should stipulate that the environmental impact of construction products must be documented with an EPD, an official ecolabel or equivalent.
- The Government will work for the intensification of efforts to introduce EPDs and encourage EPD Norway and the Norwegian Foundation for Environmental Labelling to cooperate on common documentation requirements. (…)'.

A timeline for the official Norwegian environmental policy documents for the construction sector described above is illustrated in Figure 1.2.

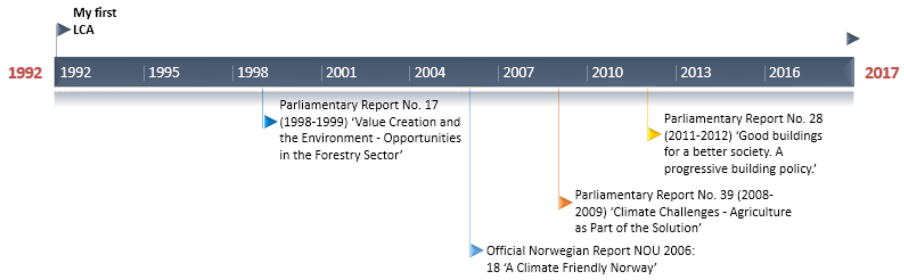

Figure 1.2 Timeline for Norwegian environmental policy documents for the construction sector.

1.3.2 RESPONSES FROM BUSINESS AND SCIENTIFIC COMMUNITIES

As shown above, the Norwegian version of this controversy was linked to the Government's priority of wood as 'the most eco-friendly material' in Parliamentary Reports No. 17 (1998-1999) and No. 39 (2008-2009). The political overtones of these issues were mainly the desire to strengthen Norwegian agriculture by developing forestry as part of this industry. Against this backdrop, a 'stimulation fund' of about NOK 100 million, called the Wood Programme, was established by Innovation Norway, with the aim of stimulating the Norwegian forestry and timber industries. The claim that wood was a greener building material was a key factor in the rationale for this initiative, and it was largely based on the report by Berge and Stoknes, who argued in favour of wood on the basis of an LCA they had conducted (Berge and Stoknes, 2004).

Both Ostfold Research and researchers at SINTEF Building and Infrastructure were critical to the documentation used in this analysis, finding it insufficient in terms of the requirements needed in order to use an LCA-based analysis as a basis for giving priority to a particular construction material. This meant that the perspectives and assessments of Ostfold Research, SINTEF and some other Norwegian research groups were drawn into the 'war' we are referring to. The Ministry of Agriculture's strategy to invest in wood as the 'most eco-friendly material' was refuted in the belief that there was no scientific basis for this priority.

This involvement took place primarily through the work of 'Bygg uten grenser' ('Building Without Borders'), a sector organisation created 'to inspire and inform about the appropriate use of brick and concrete' to safeguard the interests of this sector, also in environmental issues (byggutengrenser.no). This organisation represented virtually all suppliers in the Norwegian brick and concrete industry. As an interest organisation, its goal was to inspire and inform 'about the endless possibilities present in brick or concrete construction' (ibid.). On the basis of the reports by Ostfold Research and SINTEF Building and Infrastructure (Rønning and Hanssen, 2007, Engelsen et al., 2007). Building Without Borders claimed that the Government's commitment to wood in construction was not in line with research on the eco-friendliness of building materials based on LCAs. Building Without Borders, in their submission to the Commission on Low Emissions, showed that both SINTEF Building and Infrastructure and Ostfold Research refuted the allegations of the environmental impact of concrete in the report. Therefore, Building Without Borders sent the reports by Ostfold Research and SINTEF Building and Infrastructure to the Ministry of the Environment together with its comments. Here, Building Without Borders stated[2]:

'Both institutes point out errors in references to concrete in the report. These references are excerpts from a report written by the architects Stoknes and Berge in 2004, commissioned by the timber industry, which largely deals with the production phase of concrete and not its entire lifetime. There is also no reference to the actual report.

We find it strange that the Commission on Low Emissions should choose to rely on such a report rather than approaching the institutes with the most updated knowledge in the field.'.

[2] http://www.byggutengrenser.no/aktuelt/05/02/04/samlet-mur-og-betongbransje-klager-sponheim-inn-esa

Subsequently, Building Without Borders, on behalf of the brick and concrete industry, submitted a complaint about the Ministry to the Norwegian Competition Authority. Here, it was stated that the Minister of Agriculture and Food, Lars Sponheim, had used the Wood Programme to support associations and individual companies in the timber industry for more than NOK 100 million. In October 2004, the Competition Authority stated that support for sector organisations and individual companies in the timber industry through the Wood Programme could distort competition. However, the Competition Authority did not proceed with the case because the distortion appeared to be intentional, based on national forestry policy objectives.

However, this was not accepted by Building Without Borders, which then adopted a more powerful instrument. Under the heading 'Unanimous brick and concrete industry complains about Sponheim to the ESA[3] (Building Without Borders communicated that the brick and concrete industry had submitted a complaint about the Ministry and Lars Sponheim to the European Supervisory Authority (the supervisory body of the EEA Agreement) for systematic distortion of competition in the construction industry. The brick and concrete industry thus complained to the ESA about the Ministry and Sponheim for a breach of EEA rules on public financing. The EEA Agreement prohibits state funding in any form, which distorts or threatens to distort competition by favouring certain companies or industries (byggutengrenser.no).

In their description of the process, Building Without Borders stated that the Ministry of Agriculture and Food considered the Wood Programme to be 'fine' because it fulfilled political objectives related to environmental and regional policies (also the view of the Competition Authority). Bjørn Mørck, the then CEO of Norcem and chairman of Byggutengrenser.no, argued, for his part, that the Wood Programme was based on the wrong premises and that the way it was presented would create an imbalance in the construction industry[4].

He argued that 'Sponheim has made agricultural policy out of vital parts of the Norwegian construction industry, and this is completely unacceptable. The political objectives that the Ministry highlights to legitimise the subsidies are quite untenable. Nobody can prove that the use of wood versus brick and concrete is environmentally beneficial if the materials are considered over their whole lifetime'[4].

Mørck added that what made the Wood Programme particularly critical for competition in the construction industry was that financial support '*is accompanied by moral and verbal support from the Minister of Agriculture .... Sponheim has made*

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[3] The EFTA Surveillance Authority

[4] http://www.byggutengrenser.no/aktuelt/06/05/17/byggutengrenserno-fornoyd-med-esa-gransker-treprogrammet

many strong statements criticising our industry, but the worst aspect is the misleading information relating to environmental and employment issues' (…).

The ESA decision supported the brick and concrete industry. In its assessment, the ESA wrote that: '… in the opinion of the Authority the Wood Scheme does not comply with certain of the rules for granting regional aid, aid for research, development and innovation, and aid to small and medium-sized enterprises. Consequently, the Authority has concluded that the Wood Scheme was not compatible with the EEA Agreement' (ESA press release, 23.1.2008).

The process described here not only provides an insight into what I have described as the 'Wood and Concrete War', but also illustrates the political framework for the projects I shall consider here. The question of wood vs. other building materials was - and still is - a controversial battlefield internationally. An example to show that this 'war' has not yet ended is the corresponding 'war' in Canada. Here too, it has been a political strategy to prioritise wood, through an initiative called 'Wood First' At the Converge 2013 forum, which brought together leaders from the Canadian building materials and construction industries in Vancouver, B.C. on October 16 2013, it was stated that: *'…Members of Canadian concrete and steel construction associations are angry and upset about a campaign by the wood industry to persuade provincial and federal governments to give wood preferential treatment over other building materials*'. Ed Whalen, the president of the Canadian Institute of Steel Construction (CISC), also stated: *'…We are not complaining anymore, we are going to war'*. Further: '*Governments that decide to implement Wood First or treat one material over another, they will see us at the table. The wood industry has awoken the sleeping giant' (Source: October 16 2013 posting in the Journal of Commerce)*[5].

Ostfold Research played an important part as one of the key contributors to the processes described above, and I was one of those strongly involved in the initiatives of Ostfold Research concerning the environmental friendliness of construction materials during these years. A particular challenge in this situation was to safeguard the scientific perspective - how LCAs must be performed according to specific criteria to prevent their use to promote certain interests without a sound scientific basis. This is the backdrop of my selection of cases in Part 2.

[5] The Ontario Wood First Act passed second reading in the provincial legislature in April 2012, which included changes to the building code that could have allowed 6 storey wood buildings to be constructed. The act died in committee when Premier Dalton McGuinty resigned on October 15, 2012 and obtained a prorogation of the Ontario legislature.

1.4 RESEARCH QUESTIONS AND METHODS

Theoretically, LCA is a hybrid method that represents an attempt to combine different scientific perspectives and traditions. As I will discuss in 2, LCA has become a popular ‘travelling concept’, in spite of - or maybe because of - its theoretical hybrid status (Røvik, 2007). Methodologically, this implies a challenge in creating a credible data basis for the analysis of environmental impacts. Similarly, LCA has been linked with other analytical tools - to address the complexity of the issues covered by the term ‘industrial ecology’ (Hajer, 1995). Furthermore, practical use of LCA reveals a number of challenges related to the link between analysis, data and context. As I will describe in more Part 2, these challenges and how they have been met by scientists is the theme of this thesis. The thesis should be regarded as a ‘meta’ analysis of the methods the LCA concept is characterized with at different stages in the evolvement of the concept. Reporting from my ‘travels’ with LCA thus implicates that I am focussing upon those factors that have had impact upon the dynamics of scientific methods and the context of these dynamics at different points of time during the ‘journey’ I have undertaken.

As indicated, the challenges facing LCA both theoretically and in practice have been met with efforts to clarify and elaborate LCA since the concept was first introduced. *The aim of this thesis is to show how LCA as an analytical tool for environmental assessments has evolved from its introduction to its present status*. Here, the focus is on LCA in the construction industry, which is the field I have been most involved in with regard to analysis and development of methodology. More precisely, this thesis will discuss the development of LCA as a basis for environmental assessments by focusing on three interrelated aspects:

- the changes, refinements, modifications and additions that have been made in LCA knowledge during the time I have been engaged in the development of the tool,
- how LCA has been linked with other related analytical tools to ensure ‘comprehensive’ evaluation of the eco-friendliness of products and production systems
- the importance of the ‘context’ of, and actors involved, in the evolvement of LCA in this sector, e.g. political and economic environments which (potentially) have influenced the processes I am studying.

The basis for my choice of theme is the experience I have gained through my ‘journey’ with LCA as a knowledge field, and the various analytical tools linked to LCA. These developments show that LCA has become an important basis for making decisions in environmental policy, that an increasing number of actors have become involved in the development of LCA, and that the trend towards ‘industrial ecology’ has resulted in an increasingly broad and complex field.

The selected cases for this PhD thesis involve a variety of different views on how analyses should be designed, which aspects to include or disregard, and how to safeguard scientific integrity in work on environmental assessments. The interplay between scientific, political and economic interests is – directly or indirectly – being represented in the analytical work in the cases presented in Part 2.

The point of departure for the thesis is the first LCAs that I conducted in the construction sector in the early 1990s, and culminates with the (provisional) end to my LCA journey in 2017. In recent years, I have led the global ISO work to revise the international standard 'Core rules for environmental product declarations of construction products and services' (ISO 21930:2017). Thus, my 'journey' involves both the initial phases of life cycle thinking and present-day global standardization work. Between these two points in time, I have performed a number of LCAs and worked to develop standards for LCA - based on experiences from LCA's encounter with reality.

The main question about the evolution of LCA as an analytical tool in the construction sector, as well as the three research questions – reflects LCA as a dynamic analytical tool. The focus on 'evolution' points to LCA as not being a static, 'objective' scientific phenomenon. Rather than resting upon scientific knowledge embedded in engineering and technology – where a positivist ideal from natural science is the ideal - LCA should be seen as evolving at the crossroads between social and natural science(s). In the literature on scientific knowledge these ideals are often considered as contradictory; the objects for natural sciences are principally not responding to social phenomena, while in social sciences the study of human ideas and actions make the researcher part of the study, as explained by hermeneutics. Here, social actors, being politicians, governments, economic actors as well as actors representing scientific communities or perspectives are the main focus (Johannesen et al 2016, Skjervheim 2000). Therefore, I have formulated the three research questions; in order to study these phenomena in particular.

A backdrop for studying these issues is the global debate over which knowledge(s) should be decisive for how to develop sustainable societies. As indicated by social theorists like Hajer, who discussed the development of 'ecological modernization', there is a tendency to adapt 'technological fixes' such as'recycling schemes, energy conservation, an eco-tax.', Hajer (1995:84). LCA might easily be regarded as another technological fix – with the controversies and dilemmas this involves both from 'within' (the LCA 'community' of scientists, politicians, business interests etc.) and from the 'outside' (e.g. social scientists studying environmental politics).

So, when this thesis is referring to 'my travels with LCA', it reflects the evolvement of the LCA tool at the crossroads between these approaches to scientific knowledge. On one hand - as a 'tool' – LCA necessarily is expected to be 'useful' in social settings, embedded in political, economic and organizational environments. This I discuss as LCA becoming (or not becoming) *'manageable'*. On the other hand, LCA also has to be scientifically 'sound' as a valid instrument as seen from a natural science/engineering science point of view. This I refer to as LCA being scientifically *'valid' or scientifically 'credible'*.

On this background, the main research question is:

What has characterised the evolution of LCA as an analytical tool in the construction sector?

The main research question is a general one. I have mentioned some key characteristics of LCA: firstly, LCA typically involves the ambition to classify and calculate environmental effects on a broad basis for all links in the value chain. This implies that the analysis must address *complicated and complex problems*. This takes place in LCA through the interconnection of different knowledge bases (linked to calculating various environmental impacts, as outlined above) to result in a 'comprehensive' picture which must be valid both in sub-analyses and as a whole (as a basis for concrete decisions based on overall environmental effects). Many of the actors involved will be keen to protect their own interests in such a process.

Secondly, LCA was developed as a *standardised analytical tool* based on global standards as a constantly recurring process. As indicated above, for the past 30 years LCA has been subject to standardisation processes in Norwegian, Nordic, European and global contexts. This also means that LCA is a field in *dynamic development, where standards are modified, adjusted and altered* in the context of experiences with their application in specific analyses.

Thirdly, LCA is in many contexts *coupled with other analytical tools*. Despite its generic ambition, there are many other relevant aspects of decisions apart from environmental effects that will also have to be taken into account in actual decision-making situations, such as economic or local physical considerations. How such a coupling takes place will also influence the way LCA as a tool is used in practice.

These basic features of LCA mean that there are ongoing challenges related to the use of the tool. In my view, these challenges must be clarified as the basic premises for the developments in LCA. The point is to highlight a simultaneous increase in both the acknowledgement of the complexity and the ambitions for the application of LCA. This also involves a need to clarify the challenges in creating a credible knowledge base for the implementation of LCA. This in turn requires clarification of how to deal with this complexity in a credible manner.

Related to the main research question, three supplementary research questions were formulated in order to analyse further LCA as a tool, the relation to other environmental tools, and the importance of the actors and the context for these changes:

Related to the main question, three research questions have been formulated in order to analyse further LCA as a tool, the relation to other environmental tools, and the importance of the actors and the context for these changes:

1. How has LCA been subject to changes related to new knowledge during the years it has been used in the construction sector?
2. How has LCA as analytical tool been linked to other relevant analytical tools?
3. How have the dynamics between different actors involved in the construction sector (e.g. scientists, political authorities and business interests) developed in the studied period?

1.5 THESIS OUTLINE

This thesis is divided into three parts:

Part 1 deals with themes, issues, the theoretical basis of the thesis, context, design and methodology, the LCA concept and standardisation in the construction sector.

In Chapter 1, a brief introduction to LCA and my previous research are presented and I will discuss the political and conceptual framework for my projects in the construction sector - what has been termed the 'Wood and Concrete War'. This industrial and environmental policy conflict provides the backdrop to the projects I was involved in at different times. Finally, the background for and the research questions are presented as well as the scientific perspectives and research method used.

Chapter 2 reviews the theoretical perspectives used. The framework of this thesis is theories about how complex problems are faced, with an emphasis on processes that seek to 'tame' complexity. The theoretical basis for the analysis in the thesis concerns how we can understand the dynamics of the change processes undergone by LCA as an analytical tool. This theoretical foundation is based on social theories about 'complexity' and the development of 'standard solutions', as those terms have been used in the analysis of phenomena similar to LCA.

3 is a review of the LCA concept. This chapter is published as a book chapter, Rønning & Brekke (2014). This chapter is partly a description of the concept itself and partly a discussion of some of the challenges faced in the development of the analytical method(s). It is based on a systematic review of the various phases in the development of LCA methodology, particularly in connection with my main focus on LCA for

buildings. This includes a state-of-the-art study on the status and role LCA has had, based on a review of the international literature.

4 gives a presentation of the complex set of standards for LCA in the construction sector and hereby EPD, which has been the most widespread attempt to simplify the presentation of LCAs for practical application.

Part 2 deals with the projects conducted within the framework of my ‘travels with LCA’, which demonstrate the basis for the focus on the knowledge base of LCA, the links between LCA and other measurement tools, and the dynamics between different actors involved in the construction sector. The projects have all been published previously as reports, articles or book chapters, and some selected publications on these cases are attached to the thesis.

The concluding Part 3 is where the three research questions are answered and a discussion of the more general lessons related to the issues derived from the theoretical basis of the thesis. Finally, some general features of the development of LCA, and the challenges this tool will face in the future are presented.

2 THEORETICAL PERSPECTIVES – LCA AS A GLOBAL CONCEPT

2.1 THEORIES OF COMPLEX SOCIETAL PROBLEMS

Life cycle perspectives and LCA as analytical tool, address environmental problems in ways that are intended to be comprehensive and scientifically valid. This is a challenge, since environmental problems are often complex to analyse, and hard to find viable solutions to. In organisational theory, this type of problems has been called 'wicked problems'. The term 'wicked problems' was first used in academic contexts by Rittel and Webber in 1973. At the time, both were professors at UC Berkeley, primarily engaged in urban planning. It was in connection with the huge, seemingly intractable problems of big cities in the US that the term was first used. It referred to problems of physical planning, communications systems and growing slums, together with other economic and social problems that the cities were experiencing at that time. In the 1973 article, the two authors generalised from the problems they observed to more a general phenomenon in modern societies. They distinguished between what they called 'tame' and 'wicked' problems.

'Tame' problems are considered as problems that are by nature manageable through rational decision making, using existing knowledge, and dividing complexes of problems into smaller parts. The emergence of rational, standardised and technology-based approaches is referred to in the literature as suitable to deal with these 'tame problems' (Rittel & Webber, op. cit.). This does not mean that the problems are 'simple'; they can be complex and challenging to solve, as Rittel and Webber state: '*Tame problems are not necessarily simple - they can be very technically complex - but the problem can be tightly defined and a solution fairly readily identified or worked through (...)*'**.** The main point is that the solutions require a clear-cut definition of the problem, along with knowledge of how similar problems have been solved before. Engineering is frequently mentioned as an example of this: although it requires advanced knowledge in a variety of technical disciplines, this knowledge of the available solutions is 'built in' to the definition and prior delimitation of the problem. These are problems that can be solved through this kind of rational process, as when the chosen solution leads to the desired environmental effects.

The use of the term wicked problems by the two authors implied that they believed there were certain problems in society which by their very nature could not be 'solved' in the way that tame problems could (potentially) be dealt with. They identified a number of characteristics of wicked problems. In a short version, Rittel and Webber mentioned the following ten points:

1. There is no definite formulation of a wicked problem. Wicked problems are difficult to define clearly.
2. Wicked problems have no stopping rule. Wicked problems have many interdependencies and are often multi-causal.
3. Solutions to wicked problems are not true-or-false, but good-or-bad. Attempts to address wicked problems often lead to unforeseen consequences.
4. There is no immediate and no ultimate test of a solution of a wicked problem. Wicked problems are often not stable.
5. Every solution to a wicked problem is a 'one-shot operation; because there is no opportunity to learn by trial-and-error, every attempt counts significantly. Wicked problems usually have no clear solution.
6. Wicked problems do not have an enumerable (or an exhaustively) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan. Wicked problems are socially complex.
7. Every wicked problem is essentially unique. Wicked problems hardly ever sit conveniently within the responsibility of any one organisation.
8. Every wicked problem can be considered to be a symptom of another problem. Wicked problems involve changing behaviour.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem resolution. Some wicked problems are characterised by chronic policy failure.
10. The planner has no right to be wrong.

The basic challenge here is that the knowledge base is often incomplete or conflicting and the various sub-problems are intertwined with other sub-problems. Goals and success criteria are also difficult to define. Solutions to wicked problems are therefore not right or wrong in the sense that one has solved the problem or not, but could rather be described as better or worse in that the problem appears to have decreased or increased (Einstein, 2007; Hansen, 2011).

The term 'wicked problems' has gradually gained acceptance, both in (social) scientific communities and as a basis for political strategies in different areas of society. It has been used in connection with international crime, poverty and unemployment (Nerby et al., 2012), and certain health problems (e.g. concurrent mental health and substance abuse problems) (Head and Alford 2013), and relevant in this context - global climate change and environmental problems (Australian Public Service Commission 2007:III). Some governments have even developed their own policy strategies for those societal issues they define in their national context as 'wicked' - for example, in 2010 the Australian government drew up a strategy document where environmental problems were one of the policy fields referred to as 'wicked' (Australian Public Service Commission 2007:III).

How is this theoretical approach relevant in the present analysis? Three factors make it relevant: the first is the general societal problem involved in environmental problems, as outlined above. The scope and character of these problems make it difficult to agree on what the problems consist of, how far it is a global problem and/or many local problems, how to define the problems, which knowledge bases are most relevant, and which solution strategies are most effective. The complexities are also connected with the fact that a variety of actors have an interest in how environmental problems are defined and how they should be addressed, and will attempt in different ways to influence the design of the tool. The most interesting aspect in relation to the analysis of LCA is more specific: Rittel and Webber - and the literature on wicked problems that has followed their work - have mainly concentrated on how to 'respond' to such problems.

2.2 LCA AND ENVIRONMENTAL CHALLENGES AS WICKED PROBLEMS

In a white paper on 'Tackling Wicked Problems', the Australian government maintained that climate change is an example of wicked problems: '*Climate change is a pressing and highly complex policy issue involving multiple causal factors and high levels of disagreement about the nature of the problem and the best way to tackle it'* (Australian Public Service Commission 2007:III). Based on the theory of wicked problems, it could be claimed that every single environmental challenge (such as a building) will have a unique combination of challenges, goals and resources. This means that decisions about which solutions to choose in specific situations must address the particular challenges of the building 'as far as possible', and should be a unique and individual process in every single case. Overall, this creates an image of an unstable and uncertain decision process. This contrasts strongly with the view that environmental challenges require authoritative, standardised solutions based on the taming strategies outlined above. These different approaches to the problems faced also affect the development of LCA as an analytical method and as a basis for political strategies. How this happens will be addressed in the next chapters.

LCA may be considered a generic assessment, where the complexity of the considerations involved has been accepted, along with the fact that different fields of knowledge must be combined. This method implies either a weighting of various factors to be included in the analytical models, or a prioritisation of the factors considered most important for the relevant actors. Within this framework, the two main strategies outlined above are applied, and that there is underlying academic and strategic disagreement about which is most effective: either the tendency towards 'taming', delineation, simplification and standardisation, or on the other hand ambitions of individualised assessments, where the totality and complexity of the specific context of the analysis is taken into account.

Because of the complexity of the problems LCA aims to reduce the environmental problems two parallel processes have taken place, both of which intend to ‘tame’ the problems involved in LCA. Both involves an attempt to standardise, delimit and simplify the tool. This is presently particularly related to ISO standardisation work, together with the focus on EPD, which is designed to be a simplified, more easily communicable version of the more comprehensive, more technical LCA.

2.3 STRATEGIES TO ADDRESS WICKED PROBLEMS

Rittel and Webber mention two main responses: ‘negotiation/compromise’ and ‘taming’. A negotiation strategy is a pragmatic attempt to find (temporary) compromises when a solution cannot be found and that agreement cannot be reached on the most appropriate knowledge base to create solutions. This is a solution strategy often used in politics - but may also be used in cases of disagreement in scientific knowledge, as when different approaches make it impossible to arrive at a clear and unambiguous scientific result.

Many studies of the working methods of international organisations or of international scientific recommendations in various areas of society show that negotiation and compromise are often the result when representatives of different approaches cannot agree on the existence of clear scientific ‘evidence’ in a particular area.

‘Taming’ is a strategy that implies that 1) problems are split into smaller problems, 2) there is an attempt to gain acceptance for the idea that solutions will be found, and 3) these solutions may provide the basis for knowledge bases, which by nature may help to find the right answer. This necessitates identifying technological solutions, i.e. those based on ‘rational’ calculations (Rittel & Webber 1973). As I see it, taming may, however, be based on an awareness of the complexity of the problems one is dealing with. But it can also be imagined that the actors involved have a more optimistic perspective, which does not recognise the complexity and the ‘wickedness’ of the problems, or that they are only familiar with the technological aspects of solving them. Although the departure points may vary, the result will always imply a focus on technological, rational calculations. One point is that societal problems that could well be considered wicked tend to be defined as tame, so that the same approaches are used as with problems that really are tame as defined above.

The literature on wicked problems has discussed the strategies that can/should be applied to issues such as those we have outlined above (Roberts, 2005; Australian Public Service Commission, op. cit.; Head & Alford 2013). According to the literature, there are various preferred solutions (e.g. network building (Ferlie et al., 2010), ‘Taming’, however, involves an attempt to find solutions using the rational model we have presented above. In practice, this means trying to divide into sub-problems to deal with them one by one.

Alternative strategies to taming may be better adapted to the realities represented by wicked problems: interaction, dialogue and adaptation to a complex situation through:

- linking different fields of knowledge and actors,
- 'authoritative' (quasi-)solutions where other actors give up some influence to create opportunities to act in a complex world.

A third alternative is to let market mechanisms work - in this case, one accepts that market mechanisms through supply and demand and pricing will ultimately create a balance between the various considerations.

2.4 DESIGNING ENVIRONMENTAL STRATEGIES AS STANDARDISATION PROCESSES

The theoretical basis of this thesis is the assumption that global standards can be understood as strategies based on complex decision-making processes. Standardisation is simplifying decision processes, and coordination among actors by establishing a reference value, which will (or rather is expected) to be making order and structuring actions when facing complex problems. The basis for standardisation is understood as an 'ideal' rational decision-making process (Brunsson and Jacobsson, 1998, Bolman and Deal 2009). The first step in such a 'ideal' decision process is data collection that will lead to a delineation and definition of the problem ('diagnosis'). Based on the diagnosis established, an assessment is performed to find the 'best' solution. This analysis is based on a clear perception of the objective of the measures to be implemented. In environmental work, this will often be to 'reduce environmental impacts', 'cut CO2 emissions' or similar. In the analysis itself, experts connect their knowledge and experience to the diagnosis. This leads to a clarification of the possible measures that exist and a choice is made among these. Such a choice must be based on scientific evidence showing that the measures work.

In technology, analytical methods are based on the natural sciences, experience and rules of thumb. Such studies should preferably be based on a small number of common features, often rooted in standardised 'global' guidelines. This leads to the formulation of relevant specifications which are normative for the measures to be implemented in practice. LCA is an example of a global 'institutionalised standard'. Due to the expansion and status of LCA in environmental contexts together with its 'global' spread through ISO standards and the recommendations or requirements of other international organisations, there is justification for analysing LCA from this perspective.

What has been perceived as the advantage of LCA is that it constitutes a generic and broad analytical basis that is presumed to address the complexity of environmental matters in a broad perspective. This creates a situation where complexity in environmental matters forms part of the complexity of the analysis, and this complexity can also be addressed in specific decision-making situations.

In the current situation, these two views exist side by side, often without any communication of which view is behind specific LCAs. The result is unresolved, sometimes contradictory, perceptions of the status LCA should have with purchasers, clients, political authorities, etc. This thesis is intended to illustrate and clarify some of these basic questions involved in the LCA approach. This will take place through specific analyses of the challenges and dilemmas faced, as these are presented in the articles which form the basis for the thesis.

2.5 TAMING STRATEGIES AND THE ESTABLISHMENT OF INSTITUTIONALISED STANDARDS

Røvik (2007) has devoted several books to theories about how certain organisational concepts gain popularity and are spread in modern (Western) societies. He calls these institutionalised standards, which are thus popular ways to answer difficult questions. Røvik has been interested in analysing such standards in the field of organisation and management, but also mentions that they are used with particular power and commitment in ‘technical’ disciplines. I have therefore chosen to use the term ‘institutionalised standards’ and the related theoretical perspectives as a starting point for my analysis of my ‘journey’ in connection with the development of LCA.

The fact that a standard is ‘institutionalised’ means that ‘within a certain period, it is perceived by many, and often referred to, as the right, appropriate, effective, modern - and even the natural - way of organising things’ (Røvik 2007:13). Each individual standard or ‘recipe’ can be said to be the result of ‘ideas on a journey’, which means that the ideas are spread from the specific basis on which they were first designed, after which, through various processes, they are generalised, transformed, modified or adjusted before they finally emerge as de-contextualised standards. In this way, such standards may appear to be ‘global’ concepts. What makes Røvik’s theories particularly relevant is that such standards are always subject to a dynamic development. Institutionalised standards are established, disseminated, modified and adapted in specific contexts.

In Røvik’s view, this usually follows a common pattern: first the standard is developed in a local context, or by a few actors, such as a group of scientists. The idea that a standard can be developed locally, in order to be used a variety of contexts, means that it must first be de-contextualised. It must be given a form which allows it to be used in different contexts, often as a general tool to solve specific problems. An analysis of this process is described as studying the *genealogy* of the institutional standard - where did it come from, who had the idea, when did this happen? When the standard (‘concept’) is spread, it is often associated with an acronym - such as LCA.

When the standard has been established, and has a general form, it must - in order to be used in various specific contexts - be ‘re-contextualised’. This re-contextualisation involves a translation of the general elements of the standard to be applied to more specific local contexts; this may take place in different ways and with different means. Røvik discusses how institutionalised standards are spread in space and time. What characterises LCA as a standard is that it has been used for about 30 years, but during this time it has spread globally. Røvik refers to this as a ‘super-standard’. He mentions a number of popular organisational examples of this, such as performance-based management, quality circles, total quality management and reengineering. What distinguishes these from LCA is that the latter is not (primarily) an organisational recipe, but rather a ‘technical standard’. In Røvik’s opinion, such standards are not equally flexible in accommodating local translations, but on the other hand they have the potential to become more permanent once they are established. Re-contextualisation implies that concepts need to be translated to be used in specific contexts. The translation also implies an adaptation process which can result in adjustments or modifications of the standards originally presented.

3 THE CONCEPT OF LCA

3.1 INTRODUCTION

The concept of LCA can be understood as stated by Baumann and Tillman (2004): *It means that a product is followed from its 'cradle' where raw materials are extracted from natural resources through production and use to its 'grave', the disposal*. LCA addresses the environmental aspects and potential impacts in this context and the general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences (ISO 14040:2006).

From a number of examples presented in the current literature, it may be seen that even when studying the same kind of construction works or building materials, LCA results may differ significantly. There are a number of methodological options that may potentially influence the results from the LCA: the definition of scope, including the choice of functional unit (the defining reference for the analysis to be performed) and the system boundaries. Further, data selection and collection must be transparent, valid and reliable. The third stage in LCA is impact assessment. In spite of the complexities of aggregating emissions into impact categories, there is currently agreement for several important categories.

In the following chapter, the concept of LCA with its possibilities and limitations in the construction sector will be presented. This chapter is published as a book chapter in *Eco-efficient construction and building materials* edited by Pacheco-Torgal et al. (2014) by Rønning and Brekke.

3.2 LIFE CYCLE ASSESSMENT (LCA) OF THE BUILDING SECTOR: STRENGTHS AND WEAKNESSES

4
Life cycle assessment (LCA) of the building sector: strengths and weaknesses

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Abstract: This chapter discusses possibilities and limitations of life cycle assessment (LCA) in the building sector. Through standardisation, LCA has gained global support as a most important tool for furthering more environmentally friendly choices in the sector. However, there are several limitations of LCA at a macro level such as choice of unit of analysis and at a micro level related to methodological and practical matters. Overall and inherent possibilities and limitations in the steps of LCA analyses are scrutinised. The flexibility of the method gives LCA the power to inform decision makers and the public about the environmental performance of buildings and building products.

Key words: LCA, building material, building product.

4.1 Introduction

What is an environmentally friendly material for building and construction? The question is increasingly being posed by customers, researchers, building owners, politicians, entrepreneurs and others. The answer is that it all depends: on the specific site where the material is to be employed; on the energy sources used in the production of the material; on the lifetime of the material; on the other materials and systems with which the material will interact; and a range of other issues including the assessment method used to answer the question. Life cycle assessment (LCA) is one such method which aims to scrutinise the environmental friendliness of products and services. LCA is now employed in ever more applications from intra-company decisions to large-scale political decisions. However, LCA cannot provide a single answer that can be used in all circumstances but must be adapted to different situations. A decision situation where an engineer is to choose between two well-known materials for an outer wall is very different from a situation where the environmental properties of a material with unknown use in the future need to be assessed. This chapter will describe the possible uses of LCA in the environmental assessment of materials. We will, however, also include a discussion on the limitations that should be taken into consideration when applying LCA in the building sector.

The first section describes the general possibilities and limitations of LCA. Thereafter, possibilities and limitations inherent in the steps of LCA work processes are examined. Finally, a concluding section sums up the information and gives general advice as to how to conduct a critical reading of an LCA study. The chapter is directed towards readers with a superficial understanding of LCA who want to know more about where the important assumptions and methodological choices are located. However, this should also remind readers more familiar with LCA, or even performing LCAs, about benefits and pitfalls. Readers with no knowledge of LCA may gain from reading some basic texts first, for instance the ISO standards 14040-44 (ISO, 2006) or *The Hitch Hiker's Guide to LCA* (Baumann and Tillman, 2004).

4.2 The overall strengths and limitations of life cycle assessment (LCA)

LCA is an environmental assessment method intended to capture the environmental performance of products, services or product systems. It provides a flexible framework for a large number of different analyses, ranging from details in production processes to systemic political decisions. The framework has been developed to be able to capture the inflows and outflows from activities in all life cycle stages associated with a product or product system and all environmental impacts related to these inflows and outflows. One of the greatest advantages of LCA is the ability to avoid so-called 'problem shifts', both with respect to environmental impacts and to life cycle stages. The possibility to compare different analyses and to use LCA in business is ensured by its inclusion in organisations with global outreach. Three issues are scrutinised in the following, namely the possibilities and limitations of:

- running different analyses;
- avoiding problem shifts; and
- widespread use and standardisation.

4.2.1 Different analytical approaches

The applicability of LCA is discussed in relation to different themes and various uses. Regarding themes, area waste management (Ekvall *et al.*, 2007; Blengini *et al.*, 2012), building materials and buildings (Guggemos and Horvath, 2005; Dimoudi and Tompa, 2008; Huberman and Pearlmutter, 2008; Upton *et al.*, 2008; Ortiz *et al.*, 2009) and electricity production (Rossi *et al.*, 2012) have been examined. These discussions partly overlap with other themes, such as policymaking (Tillman, 2000; Bribián *et al.*, 2009;

Pacheco-Torgal *et al.*, 2013), product improvement (Haapio and Viitaniemi, 2008b) and product labelling (Rajagopalan *et al.*, 2012). Different uses require different approaches to modelling systems. In the *General Guide for Life Cycle Assessment – Detailed Guidance* (EU JRC, 2010), hereafter referred to as the ILCD guide, different decision contexts are introduced to explain why it may be sensible to employ different modelling approaches and data sources in an LCA. The guide discriminates between three different contexts, termed: (A) micro-level decision support; (B) meso/macro-level decision support; and (C) accounting. These three contexts are used in the guide to structure the presentation of LCA methodology, showing that they will have consequences for choosing what system(s) to include, and how to include them, in an analysis.

Two main modelling principles exist for LCA: *attributional* and *consequential*. According to the ILCD guide '*the attributional life cycle model depicts its actual or forecasted specific or average supply chain plus its use and end-of-life value chain. The existing or forecasted system is embedded into a static technosphere*' (EU JRC, 2010, p.71). The consequential life cycle model '*depicts the generic supply chain as it is theoretically expected in consequence of the analysed decision. The system interacts with the markets and those changes are depicted that an additional demand for the analysed system is expected to have in a dynamic technosphere that is reacting to this additional demand*' (EU JRC, 2010, p. 71). These definitions may seem overly theoretical but the main difference lies in the former striving to capture the actual data in a product system, while the latter investigates a hypothetical system where data should reflect changes in a product system. Weidema *et al.* (2009) state that '*the term consequential describes a modelling approach that seeks to describe the consequences of a decision*' (p. 6). This should not be confused with the decision context as laid out by the ILCD guide. The keyword in the citation is not 'decision', but 'consequences'. Both the attributional and the consequential approach can support decisions even though the former does not focus on changes incurred by the decision *per se*. A visible difference between the two approaches is the nature of the data used as input to analyses. In the attributional approach, average data should be employed to describe the relevant process, while in the consequential approach, marginal data is more appropriate.

Both these modelling approaches are relevant and necessary and it is futile to argue which one is better in general. The question is rather which one is the best in a given situation. The most important aspect in answering this question is whether or not the analysis addresses the dynamics of change and refers back to the decision contexts described by the ILCD guide.

If one wishes to consider the performance of a material, the study is usually based on an attributional approach, which is the predominant approach in the building sector. But if the goal is to examine the wider system consequences of introducing a new material on a large scale, a consequential approach must be adopted. The framework should allow for reproducibility but also wider scenario building. It should be applicable for strict comparisons of two products fulfilling the *same function* as well as generating an understanding in a *dynamic perspective*. The latter refers to environmental performance in a world where basic systems are changed, for instance a change in transport and energy systems from fossil to renewable sources. The European Commission has initiated strategies to harmonise and explain life cycle assessment methodology, which have led to documents on best practice in LCA (EU JRC, 2010).

The ambiguous, sometimes contradictory, results based upon LCA assessments reflect partly the complexity of the building sector as such, but also, in spite of the efforts to standardise LCA assessment approaches, inherent ambiguities in the LCA methodology as it is presently used. The LCA methodology opens up windows of opportunities to make various choices which will eventually influence the results of the actual studies being performed.

4.2.2 Avoiding problem shifts

Those performing LCAs in the building sector are all potential actors along the value chain, for instance material producers, entrepreneurs, owners, politicians, etc. LCA is used to support different decisions by these various actors in the building sector. It is not obvious to all what the consequences of decisions made at one place in the value chain will be. When reducing one environmental load, the measures may lead to increased emissions elsewhere in the value chain.

This is precisely where the main advantages of LCA lie, in identifying such issues that are not visible at first sight. These issues can be classified into two main categories for product systems:

1. capturing all life cycle stages where impact occurs in order to identify the important stages and associated processes, and
2. capturing several environmental impacts simultaneously to identify the important environmental issues.

A general conclusion and assertion that has been verified is that energy use for operation contributes to 70–90% of the total during the lifespan (Rønning *et al.*, 2001, 2007; Vold *et al.*, 2006; Fernandez, 2008; Barrett and Wiedmann, 2007; Sartori and Hestnes, 2007; Dimoudi and Tompa, 2008; Bribián *et al.*, 2009; Ortiz *et al.*, 2009). As stated, LCA provides the opportunity to include all life cycle stages and at the same time capture the consequences that the introduction of one or more measures at one stage has on others. Due to increasingly stringent political energy requirements and other changes, energy use for the operation is likely to decrease over time as we are heading towards low-energy buildings as a consequence of different measures. Sartori and Hestnes (2007) have performed a literature review where one main conclusion was that low energy buildings are more energy efficient than conventional buildings, although energy use for production of (upstream) materials increases.

On the basis of these findings, energy consumed during production, transportation and construction of a building can be relatively more important in an LCA. On the other hand, we often see that it is not the case that all life cycle stages are included regarding (low energy) building. In addition, the perception and understanding of the term 'user stage' in LCA can be ambiguous as it often only refers to energy for heating and cooling for operation of the building. Thus, as we are heading towards low-energy buildings, the environmental impacts and energy consumption associated with the maintenance, replacement and development phases are of greater importance than the operation of the building. High replacement rates of materials with high embodied energy will have a greater impact on life cycle performance. Thus, including all life cycle stages in LCA will have a vital impact on the ability to capture the effects of introducing measures.

The second category for avoiding problem shift, the capturing of several environmental impacts simultaneously, intends to minimise the risk that introducing a measure to reduce one impact increases another. This seems promising but *several* does not mean *all* environmental impacts, and it is still potential impacts and not effects on people and nature which are calculated. Impact on land use, biodiversity, indoor climate and exposure to toxic chemicals are some examples of those impacts known to occur during the life cycle of a building or building material, but are often troublesome to include in the LCA.

In relation to the low-energy building debate, we observe that environmental assessments of buildings and materials largely take place in the context of capturing embodied energy and greenhouse gases (Statsbygg, 2011). This is an example of choosing not to exploit the strength of LCA.

Capturing a large amount of activities, components and environmental impacts also has pitfalls. It makes analyses complex and difficult to penetrate and merely checking which processes are included can be a cumbersome task, especially since the documentation of the system being studied in many instances is lacking. Of course, it also causes problems for LCA practitioners because of the amounts of data required and the understanding needed of a range of different environmental issues. This is further discussed in the sub-sections below.

4.2.3 Widespread use and standardisation

The LCA method has been subject to standardisation both by ISO and CEN. The process of standardising LCA approaches began in the early 1990s and today the two standards SO14040 and ISO 14044 are generally adopted. In addition, a standard for communication of results from LCAs has been developed, known as Type III declarations or environmental declarations (EPD), ISO 14025. This standard addresses all products while ISO 21930 focuses on EPD for building products. A closely related standard to the ISO 14000 series has been developed: the ISO 15686 series Buildings and constructed assets – Service life planning. These standards are intended to complement the ISO 14000 series by describing how environmental standards may be implemented in building projects.

LCA is referred to as a backdrop and instrument for policy making by the EU Commission and UNEP, respectively. In relation to EU energy and building policy, several new CEN standards for sustainable buildings based upon LCA have been developed. This reflects a growing recognition of the wider systemic consequences of isolated processes undertaken by individual actors in the building sector. For more than two decades LCA has been developed and used as the predominant method for assessing the environmental performance of different building products and constructions during their lifetime.

In order to avoid flaws in assessments due to the interests of actors, the ISO standards include procedural measures to be applied when different products are compared. Ekvall *et al.* (2007) point out that the international standardisation process helps to reduce what can appear to be the arbitrariness of the methodology, but important methodological choices still remain free to be made in the individual study. It all depends on how goal and scope are defined, as discussed below.

From this description of general possibilities and limitations of LCA, we move to the more specific possibilities and limitations inherent in the method.

4.3 Strengths and weaknesses within LCA methodology

Current literature reveals that even if two LCAs apparently study the same kind of building, the results may differ significantly. How can this be explained? Performing LCA analyses of building materials and buildings requires methodological considerations on several dimensions, leading to a variety of explanations of differences in results. In the following sub-sections we will highlight some of the methodological explanations by organising the discussion according to the four phases of LCA as laid out by ISO 14040, namely:

1. Goal and scope definition;
2. Inventory analysis;
3. Impact assessment; and
4. Interpretation (ISO, 2006).

4.3.1 Goal and scope definition

As explained under the general possibilities and limitations of LCA, the goal of the LCA study determines several of the subsequent methodological choices. This may sound alarming – as if LCAs can be tuned to provide whatever results one may choose. However, it is more connected to a realisation that, for example, a study of an existing material in order to improve a production process requires a different approach from a study to guide policy making for buildings in the future.

When the goal is defined and the appropriate analytical method chosen, the next choice concerns the functional unit. In contrast to most assessment methods coupled to the environment, LCA has a product-oriented focus. Other assessment methods such as risk assessment or environmental impact assessment are mostly connected to point sources, i.e. individual production sites. Such methods can therefore reveal nothing about the viability of the production site to fulfil the needs and wants of users of products. LCA offers the possibility to make the assessment more relevant to end consumers.

The first century Roman architect Vitruvius (1960) once said that buildings must be solid, useful and beautiful. In our modern times the need for changing the functionality of buildings has become an increasingly important issue. An office building may be a school building tomorrow or the room solution may not meet the new tenant's requirements. Thus, Vitruvius's statement can be supplemented with 'buildings must be adaptable over time'. In this context Rønning *et al.* (2007) define sustainable buildings as those that *function* optimally for their purpose over time, while using the optimal amount of resources. The sustainable building should:

- function optimally – the users' needs should be met effectively
- be suitable for its use
- be flexible to adapt to changing needs and user requirements over time
- have optimal resource use, i.e. low material and energy consumption, low carbon emissions, etc.

A meaningful and valid description of these qualitative and quantitative aspects when analysing buildings or building materials and products is not possible without an understanding of the function of the product or system with respect to the needs or requirements of the end users. What is 'meaningful' depends on the scope. The functional unit (FU) is a quantified description of the performance of the product systems, for use as a reference unit in this context. Thus, one asks questions that make it possible to quantify both the qualitative and quantitative aspects of the function in relation to end use; e.g. 'what', 'how much', 'how well' and 'for how long'. In this context, the ILCD Handbook gives the following example of a functional unit (EU JRC, 2010): 'Lighting 10 square metres with 3,000 lux for 50,000 hours with daylight spectrum at 5,600 K'.

Given an indoor paint as an example where the scope is to substitute a chemical which will not influence the property of the paint, then one litre could be a suitable FU. But if the FU is to reflect the end use and the functionality when comparing two paints, 'the amount of paint necessary to cover 1 square metre of wall surface with a given quality and always "up to date" colour during 15 years' may be a more appropriate choice. In this case, the functionality (what), quality (how well) and time aspects (for how long) are reflected and quantified by the FU.

Some products are applied in a context where other conditions are guidance factors, rather than the product's capability to fulfil the required functionality. An example could be surface protection of an aeroplane. Due to safety requirements, repainting of the plane is necessary long before the actual need for maintenance connected to the lifetime of the paint. This kind of information is vital both for customers, as they can demand products which fulfil their needs and requirements, and for producers for better understanding their customers' needs as input to product development and marketing.

How can this be applied to building products or materials, or to a whole building during its lifetime? The new CEN standard EN15978:2011 introduces a functional equivalent intended to give a representation of the required technical characteristics and functionality of the building. According to this standard, the functional equivalent of a building or an assembled system shall include at least the following aspects:

- building type (e.g., office, factory, etc.)
- required service life
- relevant technical and functional requirements (e.g., the specific requirements of regulations, client, etc.)
- pattern of use.

Rossi *et al.* (2012) confirm this approach and highlight that each building is a unique product and its characteristics have to be included when defining the functional unit. It is of course a challenge to quantify all aspects related to the function of a material or building. One has to predict the future; what are future environmental impacts as a consequence of building design, user behaviour and changes in use pattern, re-design and other aspects related to adaptability, etc. Rønning and Lyng (2011) discuss how different types of buildings will need different approaches when defining the time aspect and scenarios in relation to the functional unit. The time aspect in this context refers both to the service life itself, which will vary considerably between, for example, an opera building, a warehouse and an office building, and to the service life period, which reflects the need for changes or maintenance during the required service life.

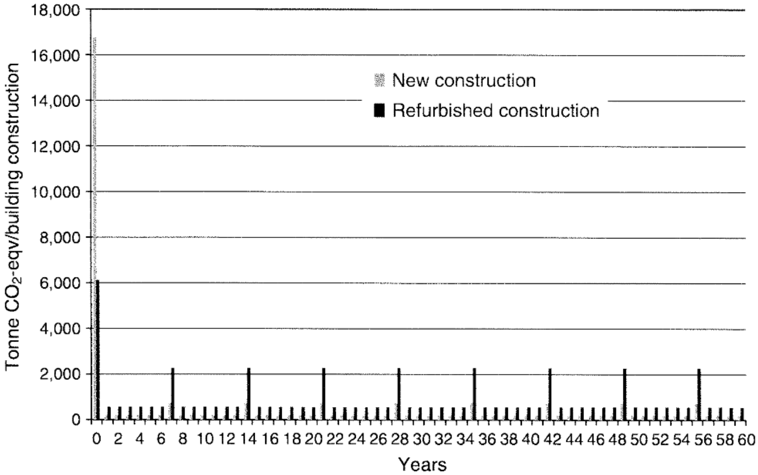
The required service life for which the LCA is undertaken is of great importance for the results as service life is usually relatively long (Erlandsson and Borg, 2003; Haapio and Viitaniemi, 2008a; Klunder, 2002). The choice of service life period (SLP) has a vital influence on the LCA results. The range in SLP is found to be between 20 and 100 years in the literature (Sartori and Hestnes, 2007). The definition of service life is a part of boundary setting in LCA and a premise for defining which life cycle stages and which activities should be included when developing a scenario for the future.

In fact decisions made in the feasibility or planning phase of the building process will affect factors such as the need for heating, maintenance, repair, etc., during the building's lifetime. Such activities will again increase the emissions and resource use from, for example, the production of new building materials and products; this is known as the embodied energy.

There are now strict guidelines for how to develop scenarios. This is done case by case. An example of how scenarios for the life cycle may be developed in an LCA is given in Fig. 4.1 (Rønning and Vold, 2008). In this study, LCA was used as one input to the decision on whether one should renovate an existing office building or demolish it and construct a new building. The state of the building and how it is and will be used were the main focus in constructing the scenario.

Since the average rental period for office buildings in Norway is 7 years, these buildings are subject to extensive rebuilding due to new tenants' needs and requirements. How extensive the rebuilding processes will be depends on the degree of adaptability of the building. In this case the existing building had a very low degree of adaptability and therefore the maintenance and changes required by new tenants needed relatively greater efforts. Thus, the contribution to global warming increased since the amount of materials needed for rebuilding of the poorly adaptable building will be greater than in the case of one with better adaptability.

Total GHG emissions related to the new construction are about 60% lower than in the case of refurbishing the old building, but if only the construction stage is considered, the conclusion will be the opposite as seen in the figure. This case illustrates that the emissions related to the maintenance



4.1 Global warming potential measured as CO_2 equivalents during the 60 years life time for the two constructions (Rønning and Vold, 2008).

and development of a building make a vital contribution to the total emissions during lifetime. If the life cycle stages of maintenance, replacement and development are excluded from the analysis, the total environmental performance throughout the life span of the building will thus be underestimated.

As discussed in Section 4.2 some LCAs define operation as limited to use of energy for heating and cooling (Blengini and Di Carlo, 2010). Others also include lighting and the use of technical equipment and appliances (Scheuer *et al.*, 2003). In the first case one may question whether lighting and use of appliances are in fact included since it is difficult to specify the total energy used for different purposes. Other operation-related activities such as cleaning and inspection of technical equipment form part of the daily operation of the building, but are seldom included in LCAs. At the same time design and choice of materials and equipment will affect the other life cycle stages, e.g. the need for and type of cleaning (Rønning and Vold, 2008).

To summarise, the goal and scope definition phase lays the premises for the LCA by the methodological choices involved. As LCA is an iterative process, the goal and scope will probably change in the course of carrying out the study. This again affects the 'how', 'what' and 'why', and the study will thus potentially be refined. A side effect of the iterative process is that knowledge building related to the system studied can be achieved.

4.3.2 Inventory analysis

The goal and scope definition and the definition of functional unit and system boundaries form a framework for the inventory analysis. In this phase one enables the actors to examine and enhance their knowledge about, for example their own production as data regarding energy use, input of raw materials, loss in production, the functionality of their product with respect to the user's needs, etc. Thus, this phase encourages dialogue among different actors. Also, by defining and collecting data from suppliers, it emphasises the understanding of what defines and causes the product's embodied energy and how accumulated emissions increase. Of course if all the work is performed by an external LCA practitioner, communication and dialogue with clients will be vital for the dissemination of the new knowledge acquired.

To decide which data to collect regarding upstream and downstream processes is an extensive task. First of all, data selection and collection can be approached methodologically from two different perspectives: top-down, based on input–output life cycle assessment (IO-LCA) analysis or bottom-up, based on process life cycle assessment (P-LCA).

Input–output (IO) models represent the monetary transactions between industry sectors in mathematical form. IO models indicate what goods or services (or output of an industry) are consumed by other industries (or used as input). Hendrickson *et al.* (2006) exemplify this as:

> consider the industry sector that produces automobiles. Inputs to the automobile manufacturing industry sector include the outputs from the industry sectors that produce sheet metal, plate glass windshields, tires, carpeting, as well as computers (for designing the cars), electricity (to operate the facilities), etc. In turn, the sheet metal, plate glass windshield tire, etc. industry sectors require inputs for their operations that are outputs of other sectors, and so on. Each of these requirements for goods or services between industry sectors is identified in an IO model.

Thus, one captures infrastructure and other indirect emissions which would otherwise be excluded.

The factors that make the IO-LCA method an efficient and robust tool also limit its use for life cycle assessment. The results of an IO-LCA analysis represent the impacts from a change in demand for an industry sector. The given industry sector consists of several industry types. Thus, the data is not describing a specific industry and if the industry concerned is not representative of the sector or the sector is not homogeneous, this approach to modelling leads to uncertainty rather than providing accurate or holistic information. Only a limited number of environmental effects are included. The information is based on publicly available data for monetary flows and emissions measured and reported from different industries. The IO data are not modelled annually and a limited number of countries have statistics available in this form. One consequence is that an IO model for one country is used as a data source to describe other not necessarily comparable countries.

The second and most commonly used approach is the P-LCA. This approach calculates emissions and energy use based on the inflows and outflows from activities and process units in all life cycle stages associated with a product or product system and all environmental impacts related to these inflows and outflows. In other words, it is based on a traditional mass and energy balance approach. In the building sector P-LCAs have been the most common approach. Also in P-LCA, data selection and collection represent challenges for several reasons. Firstly, the construction sector does not have a tradition of evaluating their projects on a mass basis, only in economic terms. There are thus no key figures or experience-based calculations to lean on in this respect. Secondly, in a feasibility phase it will generally not be known which materials will be chosen. Last but not least, environmental data are not available for all building materials and components.

Based upon experiences both from P-LCA and IO-LCA, a third approach, 'hybrid LCA', has been developed. This approach avoids the 'narrow' system boundaries in P-CLA and thereby the omission of contributory factors outside these boundaries. Hybrid LCA combining P-LCA and IO-LCA models has demonstrated its value as a complementary tool to traditional inventory methods in LCA to overcome the lack of data and to include embodied emissions (Guggemos and Horvath, 2005; Sharrard *et al.*, 2008). Here process information collected in physical life cycle inventories is linked with monetary flows in economic models.

The selection of data is of vital importance for the LCA results. In the early days of LCA it took months of effort to access and collect both specific and generic data. Today, various databases and tools for calculating emissions are available to facilitate the performance of an LCA, and because producers are now often familiar with LCA, there is a greater willingness to share data. However, missing data has been and still is a challenge in LCA. If two products are to be compared and some of the data is lacking for one of the products, the conclusions may be the opposite of what is actually the case.

The development of databases has been a great success for developing and distributing data. One often distinguishes between specific data, for example from an individual producer, and generic data which can be an average of all producers in a region or from a database (e.g., Ecoinvent). Some of these data are common to many building products and this availability makes the LCAs based on these data more comparable. On the other hand, databases must be updated and not a source for preserving outdated data and knowledge.

Even when updated, several data sets in the same database may address the given activity or material. This is the case for electricity, and as it is widely used in relation to buildings and building materials, the choice of electricity model will have a vital influence on the results of the LCA. Various mixes of energy sources for producing electricity are available in databases. These sets of data give huge variations in GHG emissions from the use of electricity (Raadal *et al.*, 2011). Then, as presented in Section 4.3.4, simulation of the effects of different choices of data representation is one way of overcoming this limitation.

The process of 'defining scenarios' is and always has been to some extent a part of the design process, both for buildings and even when improving or developing new building materials. The LCA approach provides the opportunity to capture these issues through both qualitative and quantitative knowledge, which is then systematised and utilised in defining scenarios that quantify the activities. It is of course challenging to quantify and collect data for all materials, energy use, etc., in a way that correctly and realistically predicts scenarios for the given case. As an example, technical service life for building products is vital when developing new building materials or products. Studies of service life in practice show it often differs significantly from the service life predicted by producers (Bjørberg, 2009; Haagenrud, 2006). This is both a possibility and a limitation depending on how the actors approach it. On the one hand, if defining incorrect scenarios means that one does not take into account when and how maintenance or replacement might occur, this may weaken the robustness of the results. The lack of data may be overcome by simulations of different assumptions. On the other hand, investigation of service life in practice will increase knowledge of why changes in the life cycle occur and may be vital input to, for example, product development.

In the method of life cycle costing (LCC) these aspects are often handled and defined as scenarios for operation, maintenance and development, and expressed in monetary terms. Combining LCC and LCA enables the identification of the different building materials, energy use, maintenance, etc., for defining the scenarios given in an LCC model. But, in order to quantify the inputs, a slightly different approach from that of LCC must be implemented. When a developer performs an LCC assessment, the costs from historical projects often form the basis. Likewise, the existing LCC web tools are based on experience and historical data in order to give the output as monetary values.

The comprehensiveness of LCA is undoubtedly one of its main advantages. However, it also creates the need for a huge amount of data as all elements are ultimately interconnected. The data needed are of various origins and at different levels. The selection of data is of vital importance for the results. As more studies are performed using more data sources, the availability for future projects will increase.

4.3.3 Impact assessment

The impact assessment part of an LCA serves to aggregate the inventory data to aid interpretation by assessing the potential impacts of a life cycle. The main advantage of aggregating emissions into impact categories is to reduce the large number of emissions into a much smaller set of categories. The first step is classification where the question is 'Which emissions contribute to which impact categories?' The second is characterisation: 'How much do the different emissions contribute to the given potential impact expressed by the impact categories?' Potential impact is presented as, for example, 'acidification potential' and not 'how many fish will die' as a consequence of the given number of SO_x emissions. One does not take into account the buffer capacity of the river or lake. The third step consists of weighting, where the question is: 'Which potential impacts are most important?'

Although the actual assessment of environmental impacts must take place after the inventory is finished, the choice of impact categories must be made in the goal and scope stage. As discussed in previous sections, LCA captures several environmental impacts simultaneously. It gives the possibility to map the influence one measure has on several impacts. For example, reducing energy for operation by increasing the insulation properties of a material may lead to a reduction of greenhouse gases or global warming potential in the user phase, but increase the use of chemicals in the production phase.

Climate change and climate mitigation are on the political agenda and are highly focused in both international and national environmental policies. This again is reflected in business priorities, also in the building sector. Thus, LCA often focuses on a limited number of impact categories, e.g. global warming potential (GHG emissions) and embodied energy. The risk of a unilateral focus on one environmental challenge is that others are ignored. Which life cycle stage contributes most to a given impact category will differ from one category to another. In the context of the low energy debate which will involve a stronger focus on, for example, building material selection, the use of non-renewable resources may become a more critical factor in LCA than today. Again, depending on scope, ignoring impact categories may lead to a suboptimal understanding of the most important environmental aspect and where in the life cycle it occurs.

Human activities have impacts on the environment which may not easily be quantified in an LCA. Examples of such impacts are noise, encroachment during construction periods, effects on the ecosystems and indoor climate. Given the significant consumption of resources in the construction sector, impact categories related to the depletion of non-renewable resources, such as land use, are also particularly relevant for building-related LCA studies (Rossi *et al.*, 2012). However, databases and calculation tools used for inventory analysis or to assess environmental impacts may not be available for all potential impacts or applications. Moreover, even if they are available, there are several models for calculating one given impact. This is problematic as it requires specialised knowledge to select and use the methods correctly.

When all impacts are calculated, what is the most important one? There is no definite answer to this. It all depends on which impact is given more weight than others and by whom. This is to a large extent a matter of interests and values. The comprehensiveness of LCA and its ability to capture several impact categories is one of its main advantages. Furthermore, as more studies are performed with improved data sources and models, availability for future projects will improve.

4.3.4 Interpretation

The benefits of an interpretation step in the LCA are primarily to help the reader to understand and identify the most significant issues. In relation to the previous three LCA phases, examples of general questions to be asked are:

- *Goal and scope definition*: Is analysis in accordance with the defined goal and is the goal in accordance with the needs of intended users in order to achieve appropriate decision making, both at political and technical level? Do system boundaries include all relevant life cycle stages and do they cover the relevant geographic area? Are realistic scenarios defined? Is the functional unit defined satisfactorily?
- *Inventory items*: What are the most important items and where in the life cycle do they appear?
- *Impact categories*: Are all relevant impacts included and do they give the same conclusions?

The answers are complex and entangled since LCA modelling allows for considerable variations in terms of calculation methods and the results obtained may thus also vary. The intended application of the study, how the system boundaries are determined (which phases to include/exclude), the assumptions made, cut-off criteria, the available data and the quality of the data, and finally the intended audience, will all affect the results. They may also be influenced by the values and perspectives of the LCA practitioner and whoever commissions the LCA. These limitations are also not unique to LCA. As stated by Ekvall *et al.* (2007), several methods for environmental systems analysis have been developed to support different types of decisions, and most of these involve similar problems.

This makes it important that these aspects are documented and assessed in the interpretation step. In the interpretation the robustness of the choices can be tested by simulation of, for example, other data, system boundaries, calculation methods, characterisation factors, etc. This not only strengthens the results of the LCA, it may also give vital input to choose the best solution for optimising the system. Even the flexibility in methodological choices may weaken the credibility of LCA at first sight; one should not underestimate the importance of the process of performing the LCA itself. It is here one has to understand the product or system and actors in a broader context. When methods for future studies are integrated in the LCA, the methodology not only assesses scenarios, but Ekvall *et al.* (2007) state that it also assists in *developing* the scenarios that are to be assessed. This is in accordance with the experiences of Rønning and Vold (2008) where LCA was used to communicate choices in a feasibility phase.

LCAs are mostly used for documenting the consequences of already established choices and decisions or completed construction projects, and are to a lesser extent used as a planning tool for simulation of consequences of different choices in various phases of the construction process or throughout the lifetime of a building.

The environmental performance of a building or an individual building material depends on many factors, such as how it is designed, what it is made of, where it is located, how it fits into the surroundings and how it is used. These factors must be considered in the interpretation phase in a comprehensive way in order to determine if the environmental profile of a building or an individual building material is 'satisfactory' with respect to the scope defined. However, what is considered satisfactory is generally not defined, and will at all times reflect political targets, environmental guidelines, the ambitions of the developers, etc. At the same time, these factors will often partially explain the results; for example, the design will affect the use of energy for heating or the amount of materials needed.

Several studies conclude that when performing LCAs of buildings for planning purposes, especially regional planning, one should include transport activities related to the use of the building. Transport may contribute as much as 50% of the total energy use (Norman *et al.*, 2006; Selvig and Cervenka, 2008). Cole (1999) found that worker transportation could account for 10–80% of total construction energy. However, in current LCAs the transport of users is typically overlooked (Stephan *et al.*, 2012), while the transport of construction workers is not insignificant and is excluded in most studies (Blom *et al.*, 2010). On the other hand, LCA standards do not require transport of users (or workers) to be included in LCAs as a consequence of localisation.

The interpretation phase in LCA is at first sight aimed at the individual building or material which is being examined. Haapio and Viitaniemi (2008a) have performed a literature review on different calculation tools for environmental evaluations based on LCAs of entire buildings. This study shows that LCA results are dependent on the tool used, and that a comparison between results from different tools is impossible and not recommended by the authors.

However, there are a number of LCA studies that compare building materials, such as wood versus concrete or steel (Upton *et al.*, 2008; Guggemos and Horvath, 2005). The functional units may be equal, but the system boundaries are often not comparable as some of the life cycle stages are excluded. The argumentation for the exclusion is not always clear. However, some argue that 'energy for heating is equal for both buildings'. This is clearly a weakness when comparing building systems based on different building materials, especially when comparing results for two different LCAs. On the other hand, if the transparency is satisfactory one may draw general conclusions and knowledge from such studies.

Rajagopalan *et al.* (2012) state that LCAs are too case-specific with respect to functional unit, system boundaries, specific scenarios for a specific type of building, etc. Thus, an LCA cannot be replicated and general conclusions are not transferable to other building projects. On the other hand, the flexibility of LCA enables a large number of different analyses. Often the results are intended to be communicated to a wide audience. Thus, the results and outcome of the LCA have to be presented with a certain transparency and clear interpretation to ensure that the audience understands that figures and results may vary depending on the intended use of the LCA.

4.4 Conclusions

The use of LCA as an assessment tool has become common as the holistic model for assessing energy and environmental performance of buildings or building materials. Presently, it has become the main approach for answering the question of which material is most environmentally friendly for constructions and buildings. The fact that LCAs are used in applications from intra-company decisions to large-scale political decisions indicates that LCA has gained broad acceptance by actors in the building sector. During the last 20 years the method has been improved and refined, and has been subject to a number of strategies in order to create global standardisation of the method.

The comprehensiveness of LCA is undoubtedly one of its main advantages. The comprehensive approach offered by the LCA approach makes it possible, at least at a theoretical level, to confront a number of issues relating to how to assess complex problems by including value chains with vast amounts of data from different sources. At the same time, the approach addresses a number of potential and actual environmental impacts. Likewise, it allows a number of actors to become involved in efforts to create environmentally friendly solutions based upon scientifically grounded knowledge and methods. Results from LCA analyses point out the most important environmental problems, and where in the life cycle these problems should be identified. Informing about LCA approaches is thus an arena for communication and learning about environmental issues, offering input to different decision makers about when and how in the life span of a product environmental problems and possible improvements might occur.

As indicated by several authors, despite (or maybe because of) the holistic approach LCA offers, inherent ambiguities in the methodology represent limitations as it is presently used. This is becoming obvious in the current work on standardising LCA methodology. The limitations can be identified at different levels of analysis: at a macro level, the ambitions of global standardisation are confronted with the complexities and ambiguities of the building sector. Here, there is a need for 'translation processes', by opening up the standardisation formats to local and contextual characteristics. At the micro level, there are several pragmatic obstacles to using the full potential of LCA: there is not enough time to capture all relevant data, not sufficiently sophisticated methods to capture all relevant environmental impacts, no consensus (or too many methodological choices) to determine which environmental impacts are more important than others, not enough harmonisation to compare results even for the same material across studies.

From a number of examples presented in the current literature, it may be seen that even when studying the same kind of building or building materials, LCA results may differ significantly. As illustrated in the discussion above, there are a number of methodological options that will potentially influence the results from the LCA. In our presentation we structured these options according to the stages in the LCA method. As we see it, several conditions must be fulfilled in order to reduce the variations in the results from the LCA method. Firstly, a clarification of goal(s) will be necessary as a starting point. Secondly, the definition of scope, including the choice of functional unit, is the defining reference for the analysis to be performed. Here, the system boundaries must be defined in an unambiguous way. Thirdly, data selection and collection must be transparent, valid and reliable. The fourth stage in LCA is the impact assessment. In spite of the complexities of aggregating emissions into impact categories, there is currently a large extent of agreement for several important categories. Finally, in the interpretation stage the results of the LCA must be related to the goals and scope of the analysis.

In summary, we argue that in order to ensure more use of life cycle considerations, focus should be on the challenges along two axes: on the one hand, to strengthen the credibility of the underlying data and calculation methods of LCAs, and on the other hand to facilitate the use of results in actual construction processes, companies' product development and overall priorities at the national and local levels. Clarification of which environmental information decision makers need in the various phases of the construction process is vital in this context. However, we would claim that LCA provides a wealth of possibilities. The flexibility of the method coupled with already existing models and data give LCA the power to inform decision makers and the public about the environmental performance of products and services to a considerable extent.

4.5 References

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4 A COMPLEX FRAMEWORK OF STANDARDS

4.1 INTRODUCTION

In 2, LCA was perceived as an ‘institutionalized standard’, i.e. established as an analytical tool designed to address certain values and goals for how it should be used in practice. According to Røvik (2007), a typical feature of institutionalised standards is also a dynamic relationship between contextual testing, de-contextualisation and re-contextualisation. This process can be described as a first phase to try out new tools and analytical methods in specific situations, after which de-contextualisation takes place through the establishment of general, universal rules (i.e. standards) for how the concept should be applied. The standardisation process involves these rules being institutionalised and given a status as norms for the application of the concept (which is why the term ‘institutionalised standards’ is used). As shown in the introduction, this will therefore involve authoritative actors - often governments or so-called sub-political actors with international support. Finally, feedback, re-contextualisation and the application of the standards will reveal that the standards must be ‘translated’ for (new) specific situations where they must be maintained in practice.

LCA as an analytical tool has been subject to processes that have many similarities with the typical descriptions of institutionalised standards. A number of international bodies have been involved in these processes, and the result is an extensive and complex status in terms of the different actors involved and standards developed at different levels and for different purposes within the framework of the LCA concept.

The international standardisation of Environmental Management has resulted in the ISO 14000 series. Within this series a number of Environmental Management tools are treated. The focus of ISO 14001 Environmental Management Systems is organisations, while ISO 14040 series LCA deal with products. In principle, they are different, since the life-cycle approach analyses one production chain from ‘cradle to grave’ or even back to the cradle, while a management system according to ISO 14001 analyses organisations only until the 2015-edition. This will be elaborated in 6.

4.2 LCA-RELATED STANDARDS - A BRIEF OVERVIEW

In 1990-1993, SETAC (the Society of Environmental Toxicology and Chemistry) shaped the development of LCA in a series of workshops culminating in a ‘Code of Practice’ (Consoli et al., 1993). In parallel, the Nordic Council of Ministers initiated a project on LCA in 1991. The objectives of the project were to develop a Code of Practice for LCA based on a Nordic consensus, to provide industry and other practitioners with a set of guidelines for LCA, mainly in 'key issue identification' LCAs and to influence the international discussion on the subject. This project resulted in the Nordic Guidelines for Life Cycle Assessment (Lindfors, 1995).

After the harmonisation of LCA by SETAC, the international standardisation process was initiated in 1993, but it took seven years for the first series of LCA standards to be published (ISO 14040, ISO 14041, ISO 14042, ISO 14043). The first series of ISO LCA standards superseded the SETAC 'Code of Practice', the Nordic guidelines and several national standards and, according to Köpffer (2014) has become the 'uncontested model' of an environmental life cycle standard. The series ISO 14040 was revised once and condensed into two standards, ISO 14040:2006 and 14044:2006.

ISO 14040:2006 describes the principles and framework for life cycle assessment LCA. This standard does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA. ISO 14044:2006 specifies requirements and provides guidelines for life cycle assessment (LCA) including the following: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements. These have all been of importance for the diffusion of LCA worldwide, and according to Finkbeiner (2013) represent the constitution of LCA.

As mentioned, standardisation work for LCA took several years before the first standards were published in 2000. During this period, LCA studies were used in a variety of contexts, including external communication and marketing. A need therefore arose for specific standards to communicate LCA results in a credible manner. This standardisation process started in the late 1990s; one important result was the standard for environmental product declaration (EPD).

Type III environmental declarations (ISO 14025:2006) are EPDs which provide quantified environmental data using predetermined parameters that are based on the ISO 14040 and ISO 14044 standards and, where relevant, additional environmental information. Thus, EPD is a standardised, quantitative and in addition, externally verified life cycle assessment of products, which uses common boundaries for products fulfilling the same function (ISO 14025:2006). In short, EPD is an executive summary of an LCA.

Whereas the structure of LCA as a science-based method for environmental assessments was unchallenged, new developments led to 'new' approaches and spin-off standards along two axes, involving a demand for more flexibility and/or more detailed requirements than ISO 14040:2006 and ISO 14044:2006 could offer. These were:

- to reduce the life cycle impact assessment to one impact category like carbon footprint (ISO/TS 14067:2013) or water footprint (ISO 14046:2014)
- to expand the environmental LCA by linking it to e.g. LCC (life cycle costing), S-LCA (social LCA), and eco-efficiency assessments (ISO 14045) or LCSA (life cycle sustainability assessments), combining LCA+LCC+SLCA

In addition, a technical specification that provides additional requirements and guidelines for the application of ISO 14040 and ISO 14044 to organizations (O-LCA) was published in 2014 (ISO/TS 14072:2014). In 2015, the UNEP/SETAC Life Cycle Initiative published the 'Guidance on Organizational Life Cycle Assessment' (UNEP, 2015). This report builds on existing key publications and initiatives, such as the Greenhouse Gas Protocol Initiative (WRI and WBCSD, 2011), and makes a particular attempt to align with ISO/TS 14072:2014, and with ISO 14040 and ISO 14044.

4.3 STANDARDS IN THE CONSTRUCTION SECTOR

4.3.1 BACKGROUND

For more than two decades, Life Cycle Assessment (LCA) has been developed as a tool for assessing environmental aspects of different construction work and building products during their lifetime. The main drivers have been the two factors of 'push' and 'pull'. On the one hand, in using LCA, actors at an early stage in the value chain, such as manufacturers of construction materials, have learned that there is a long way from the factory gate to the decisions on the choice of materials in construction works. Therefore, the construction industry, especially in Europe, has been advocating the development of common standards for LCA and EPD.

In parallel to the standards in the ISO 14000 family, the ISO Technical Committee 59/SC17 - Sustainability in buildings and civil engineering works - has developed several standards for construction products and construction works intending to complement the ISO 14000 standards by providing specific requirements for construction products and services and construction works see Figure 2.2.

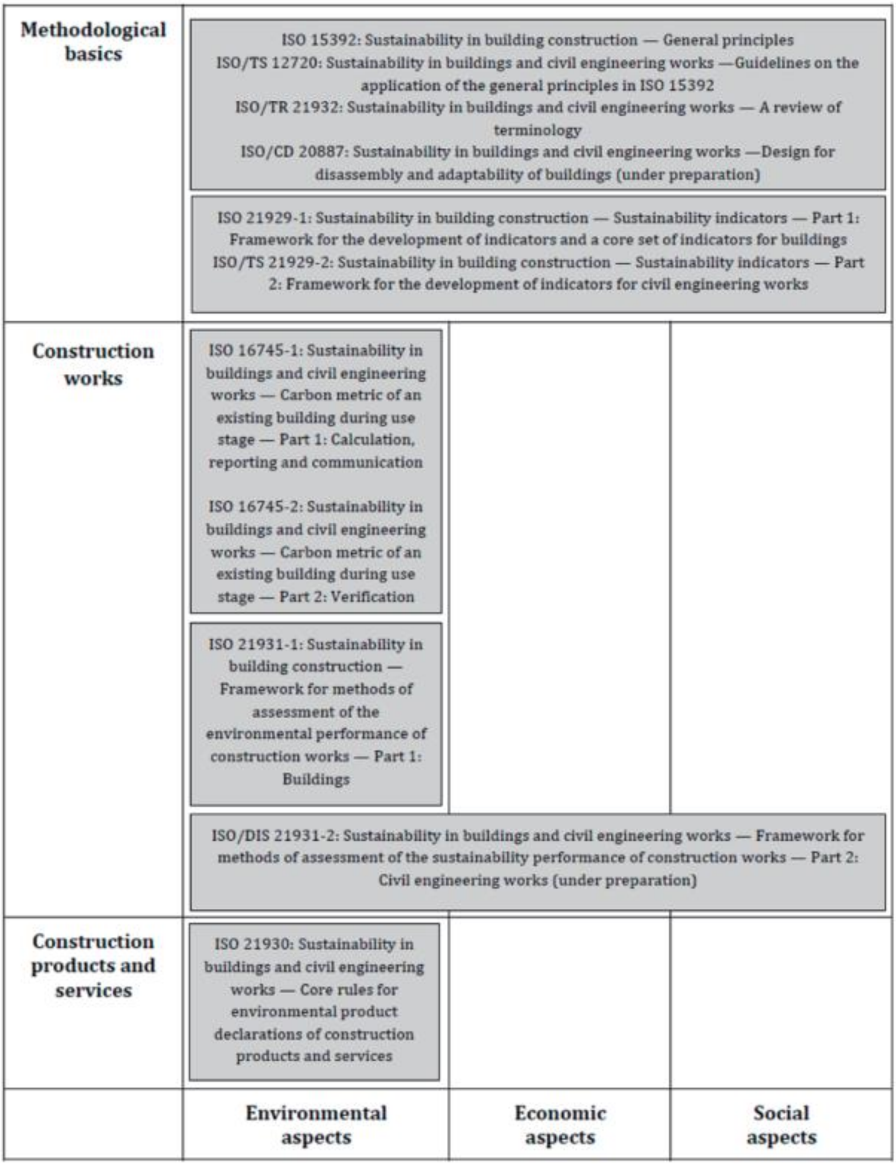


Figure 4.1 Suite of related international standards for sustainability in building construction and construction works, ISO 21930:2017.

These series of standards are based on the core LCA standards ISO 14040:2006 and ISO 14044:2006 and the EPD standard ISO14025:2006. In addition, they follow the concept of LCSA (life cycle sustainability assessments), which is based on the three pillars LCA, LCC and SLCA.

However, the pillars of economic and social aspects have only been developed and published on a framework level as ISO standards.

In parallel to the ISO 14025 standard, a standard for construction products was developed, ISO 21930 (2007). The justification was a need to make the methodology more stringent and applicable only to construction products. This standard has been the basis for the development of EPDs nationally and internationally since 2007. The development of both standards was initiated in the late 90s and EPDs were published before the standards were available.

In 2004, the European Commission produced a mandate to develop horizontal standardised methods for assessing the environmental performance of buildings. This work was initiated under the European Committee for Standardisation (CEN), and the committee TC350 ‘Sustainability of Construction Works’ was given the responsibility.

The goal of the Commission is to provide a method for the voluntary delivery of environmental information that supports the construction of sustainable works including new and existing buildings (not all construction works will be included). One way to achieve this goal is to provide environmental information on the construction products and the materials that are used. This results in voluntary Environmental Product Declarations (EPD). To ensure that comparable environmental information is generated and used, without creating barriers to trade, national schemes need to be based on a common European programme founded upon European or international standards for EPD (European Commission, 2004).

At that time, the European Commission considered that the ISO standard ISO21930:2007 for EPDs of construction products was inadequate since it could lead to trade barriers and did not provide a sufficient basis for comparison. Besides, as the ISO standards for construction works were not sufficiently developed, more specification was needed that also reflected EU policies, e.g. the Construction Products Regulation (CPR) that lays down harmonised rules for the marketing of construction products in the EU, or waste legislation.

This mandate led to the development of a series of European standards that follow the same structure as the ISO-standards. Standards created by CEN/TC 350 provide a system for the sustainability assessment of construction works using a life cycle approach. Horizontal sustainability assessment quantifies impacts and aspects of the environmental, social and economic performance of construction works. Within the sustainability system, standards cover rules for how to handle sustainability performance at the framework level, building level and product level, see chapter 4.3.2.

4.3.2 STANDARDS FOR CONSTRUCTION WORKS IN EU

In Europe, calculation standards have been developed for all three pillars that together intend to assess the sustainability performance of buildings: the environmental (EN 15978:2011), social (EN 16309:2014) and economic (EN 16627:2015), see Fig. 2.4.

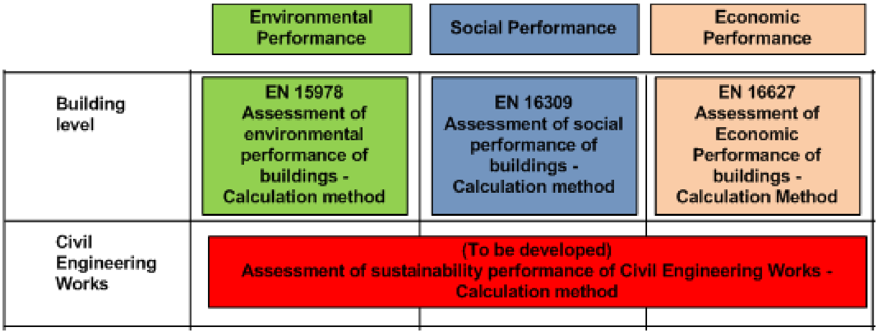
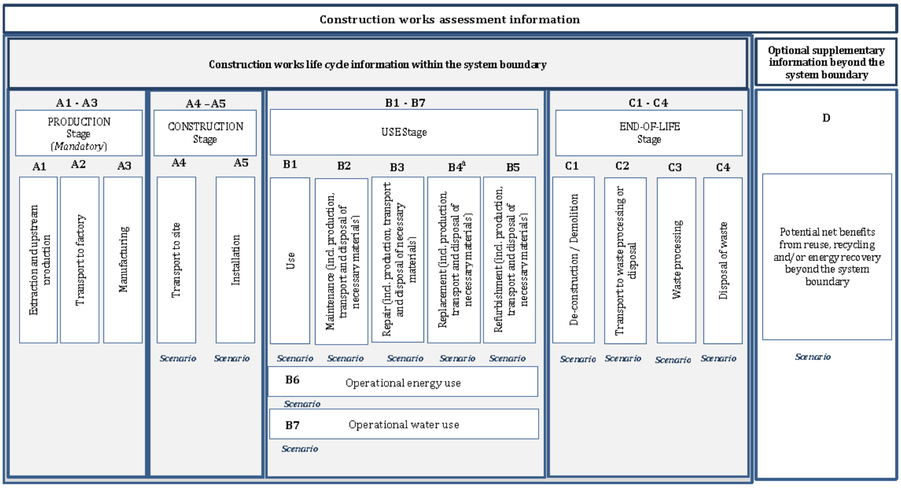


Figure 4.2 Suites of European standards at building level

EN 15978:2011 specifies the calculation method, based on LCA and other quantified environmental information, to assess the environmental performance of a building, and presents the means for the reporting and communication of the outcome of the assessment. The standard is applicable to new and existing buildings and refurbishment projects. The assessment includes all building-related construction products, processes and services, used over the life cycle of the building. Interpretation and value judgments of the results of the assessment are not within the scope of this standard. There is an ongoing standardisation work on developing similar standards for civil engineering works both at International and European level.

The setting of the system boundaries both for ISO and CEN standards follows the ‘modularity principle’: where processes influence the building’s environmental performance during its life cycle, they must be assigned to the module in the life cycle where they occur, all environmental aspects and potential impacts are declared in the life cycle stage where they can be attributed, see Figure 4.3 (ISO 21930:2017).

The life cycle of a construction product and a construction works is divided into four life cycle stages, which include a number of information modules (see Figure 4.3). These life cycle stages describe the entire product system of any construction works.



[a] Replacement information module (B4) not applicable at the product level.

Figure 4.3 Common four life cycle stages and their information modules for construction products and construction works and the optional supplementary module D, ISO 21930:2017.

The approach to the building assessment covers all stages of the building life cycle and is based on data obtained from EPDs, their information modules, and when appropriate other information necessary and relevant for carrying out the assessment of the environmental performance of the building. Figure 4.4 gives an overview of CEN standards at product level. EN 15804 – Core rules for the product category of construction products - provides the set of rules, requirements and guidelines that shall be applied to the development of an EPD for construction products.

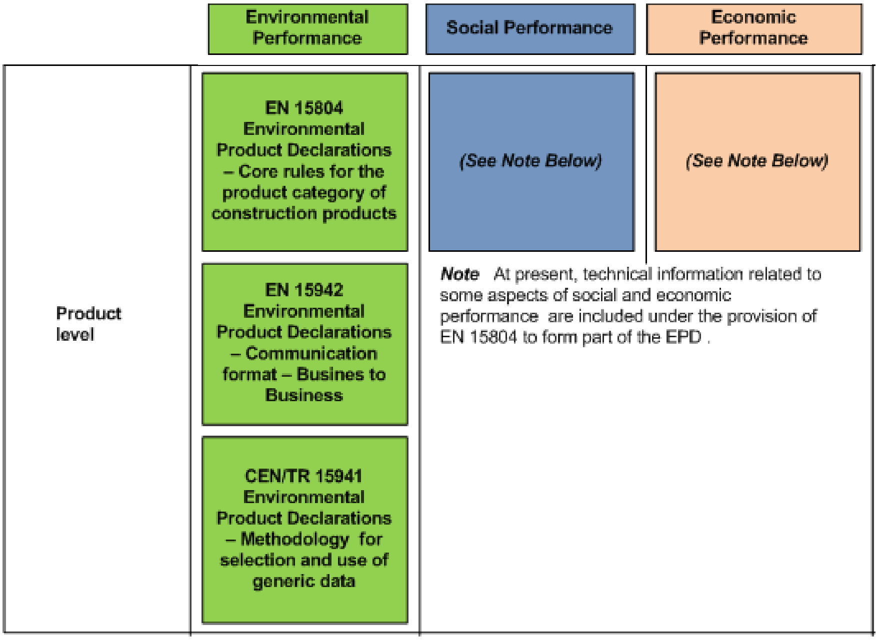


Figure 4.4 Suites of European standards at product level, CEN/TC 350

How do these standards linked between product and building level? This modular set up of the LCA underlying an EPD allows easy organisation and expression of data packages throughout the life cycle of the construction product. This approach requires that the system boundary for each of the life cycle stages, as well as the information modules, included in the EPD are transparent, well defined, and applicable to any construction product.

An EPD of a construction product provides information modules for the assessment of the environmental performance of buildings (EN 15978, ISO 21931-1), and civil engineering works. The EPD is expressed in a form that allows aggregation (addition) to provide complete information for buildings. The EN 15804 standard does not deal with aggregation at the building level nor does it describe the rules for applying EPD in a building assessment. The assessment at building level is covered by EN 15978.

It is mandatory that EPDs shall give information on 'cradle-to-gate' (information modules A1-A3) for construction products. In addition, EPDs may contain scenarios or technical information about construction products as a basis for defining scenarios at building level. In Figure 4.5 the link between product level and building level is illustrated.

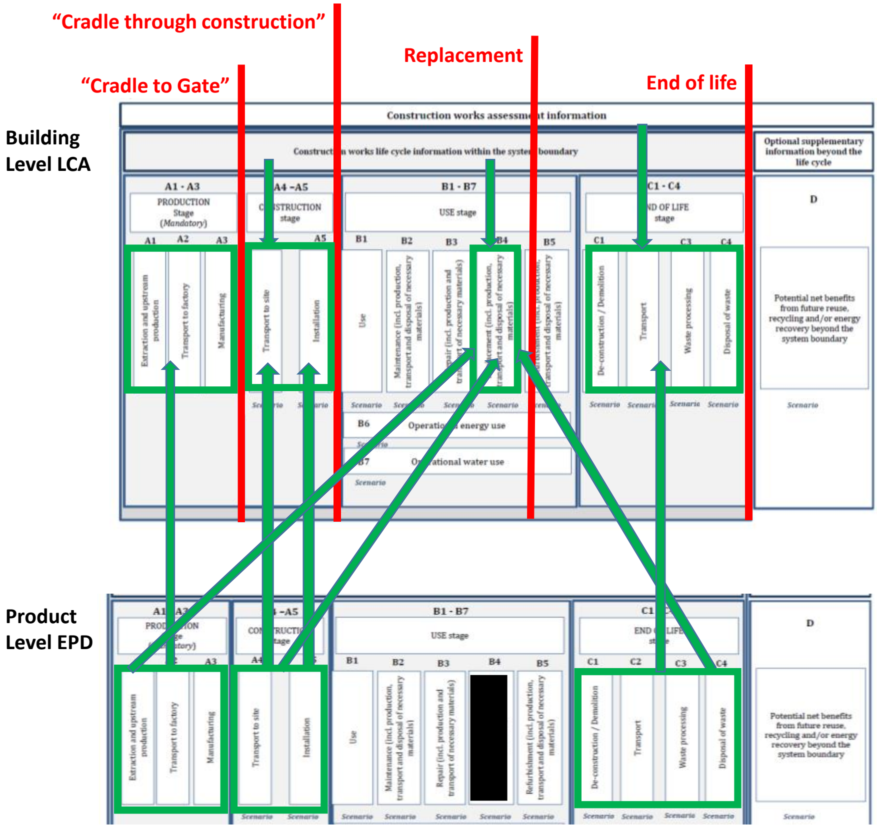


Figure 4.5 Link between product and building level. Adapted from Lützkendorf (2016).

As illustrated, information from an EPD regarding information modules A1-A3 (cradle-to-gate information for the product) is the information used at building level for the different construction products that represent the building. Then the EPD may contain information regarding how the construction product is transported to construction site (A4), how it should be installed in a given context (A5), how often it needs to be replaced and how this could be done (B4), and how the scenarios for waste processing for both the replaced product (B4) and for the product after end-of-life of the building (C1-C4). As mention, information modules A1-A3 are mandatory and the scenarios after gate are optional. As a construction product may be used for several purposes and different intended use, the scenarios at product level will always be guidance. At the end, the scenarios at building level take form in the context the building design take place by actors the not necessarily represents the manufacturer.

As illustrated in Figure 4.5, severat EPDs and other information will be 'added up' to make the full LCA of the building. Thus, only comparison of construction products EPD has be carried out in the context of the construction works.

EN 15804 specify that '*comparisons are possible at the sub-construction works level, e.g. for assembled systems, components or services for one or more life cycle stages. In all cases of comparing construction products, the principle that the basis for comparison of the assessment is the construction works level shall be maintained by ensuring that the same functional requirements are met and:*

- *the same functional requirements as defined by legislation or in the client's brief are met, and*
- *the environmental performance and technical performance of any assembled systems, components, or products excluded are the same, and*
- *the amounts of any material excluded are the same, and*
- *excluded processes or life cycle stages are the same, and*
- *the influence of the product systems on the operational aspects and impacts of the building are taken into account.*'

To ensure comparability, it is important that products within the same product group or products that solve a specific function, have used the same 'calculation rules' and assumptions. To sum up; ISO 140440 and ISO 14044 give rules for how to perform LCA for all products and services. ISO 14025 is the corresponding standard that established the principles and specifies the procedures for developing EPD for all products and services, while EN 15804 or ISO 21930, both give core rules for 'all' construction products and services. They include rules for all stages until the end of 'cradle-to-gate' that apply to all construction materials, and guidelines for the creation of scenarios in the construction phase, use phase and end-of-life (A4-C4, see Figure 4.3). The latter must be detailed specific for each product category; e.g.; windows, insulation or concrete product, by so called product category rules (PCR). PCR define the rules and requirements for the EPDs of a certain product category. Thus, to perform an LCA of a building, knowledge regarding a broad set of standards are required.

PART 2 - EMPIRICAL CASES

Part 2 describes and discusses some of the projects I have been involved in before and during the period of this thesis. ‘Case’ is used to describe that these chapters are intended to indicate that they do not present a complete description of all aspects of the projects referred to.

The political and academic controversy around the eco-friendliness of construction materials, which I outlined in Chapter 1.3, was particularly relevant as a background to the projects I will review in this section. Some of the selected projects were at an early stage of the application of LCA in the construction industry, and were thus forerunners. Some were conducted in the context of the area of conflict they could easily become a part of, and with an awareness of this potential conflict. A timeline for the dynamics between the official Norwegian environmental policy documents presented in chapter 1.3 and the projects I present in the following chapters is illustrated in Figure 4.6.

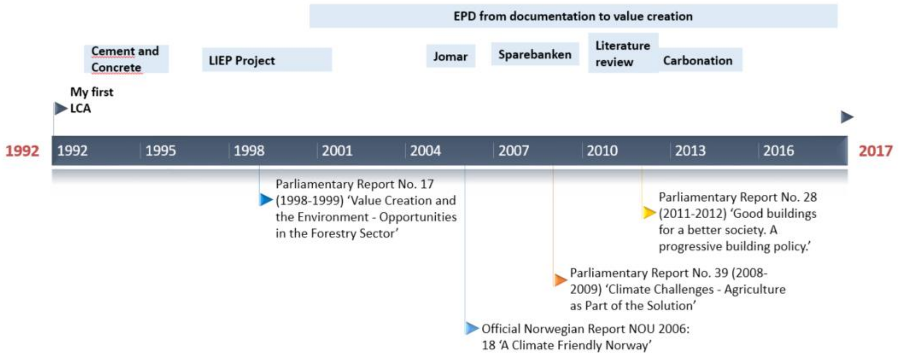


Figure 4.6 Timeline for selected projects and Norwegian environmental policy documents for the construction sector.

The main purpose of the case chapters is to demonstrate the issues that were in focus at the particular time related to the research questions given in chapter 1.4. These issues, together with the project activities referred to, concern the knowledge base, the new knowledge added in the project, and the actors involved. The cases were chosen because they can shed light on the dynamic development of the knowledge base, manageability and involvement of the actors at various points in time in the development of LCA in the building industry. One of the aims of presenting a case is to show the dynamics between knowledge and the actors involved in this knowledge development/transfer. How did new actors become involved in the project analysis and documentation and what knowledge did they call for?

In chapter 5 ‘Introducing LCA in the cement and concrete industry’, the point of departure was a scientific discussion concerning the idea that ‘one construction material was better than others’. At that point in time, the discussion mainly engaged scientists working with LCAs and organisations in the construction industry. Their interest lay in building knowledge of LCA methodology to be used in the increasing discussions in the construction industry. At this stage, there was also an interest in using LCA perspectives in product development.

This was further reinforced by the ‘LIEP Project’ discussed in chapter 6 ‘LCA in business strategies’. Also in this project, the external discussion on the credibility of LCAs formed the basis, but the focus was increasingly on how to implement ‘life cycle thinking’ in product development, sales and marketing, i.e. in the companies’ own strategies.

In chapter chapter 7 ‘LCA in building assessment’, I discuss the Jomar Project, which mainly concerned developing the theoretical and practical methods in LCA involving links between LCA, LCC and other standards already implemented by actors in the construction process.

In chapter 8 ‘LCA in practice’, I discuss a further project based on the results of the Jomar Project dealing with the choice between conversion and demolition of a large commercial building: a bank. The project was primarily an illustration of how LCAs - based on the approach developed in the Jomar Project - could be applied to practical evaluations, using a manageable analytical method.

In chapter 9 ‘Integration in policy’, I discuss a literature review to reveal the knowledge platform for LCA commissioned by the Ministry of Local Government and Regional Development, that served as input to Parliamentary Report No. 28 (2011-2012) ‘Good buildings for a better society’. At that time, the Government was focusing on LCA methodology and particularly the development of EPD, while downplaying the issues that had been central in the so-called ‘war’ concerning the eco-friendliness of construction materials.

In chapter 10 ‘Adding specificity to calculations’, I present efforts to include specificity to calculations to improve environmental profile for construction products and how the credibility of analysis from a scientific perspective enhances by including interdisciplinary expertise knowledge related to the chemical processes involved (carbonation of concrete).

The last case, chapter 11, ‘Development of EPD as institutional standard’, gives an overview of the evolution of EPD through different phases of its evolvement.

5 LCA IN THE CEMENT INDUSTRY

5.1 INTRODUCTION

This chapter deals with the first LCA-related project in the cement and concrete industry in the Nordic countries. The project was initiated mainly as a response to the issues raised in relation to the “wood and concrete war”. In 1994, cement producers in the Nordic countries (Sweden, Norway and Finland) established a joint LCA project as a response to the growing claim that one construction material was better than another with respect to the environmental friendliness of a building. In addition, regulatory requirements mainly focused on emissions from manufacturing plants, which also was a disadvantage to the cement industry.

As an actor in an early stage of the value chain, the cement industry found it important to highlight the qualities of cement-based products. One challenge involved in LCA was that it compared one construction material with another without considering them in the general context of the building. This might for example involve a comparison of two outer walls with different functions. Due to this, an actor in an early stage of the value chain had to understand and document such factors. This was the focus of the project: how to address the discussions and allegations that one building material was better than another.

The Nordic cement project was a collaboration between cement producers (involving six production sites) and researchers from the three Nordic countries: Chalmers Industriteknik (Sweden), VTT (Technical Research Centre of Finland) and Ostfold Research. The purpose was to increase knowledge of LCA by performing case studies where entire construction works were assessed, with a focus on how to use LCT to improve cement production and concrete product systems. Thus, a common Nordic cradle-to-gate model for cement production was important and the six cement production sites formed the basis for the model. In addition, LCAs of two concrete applications, road paving and building material, were performed. These two applications were compared with asphalt and steel respectively as a basis for internal discussions on product improvement.

I will not present all the results here, but highlight the important aspects for my understanding of what LCA ‘is’ and how this contributed to my further work on the method. This chapter is based on the report *‘LCA of cement and concrete - main report’* (Vold and Rønning, 1995).

5.2 APPROACH AND RESULTS

The project was organised by using workshops as a venue for knowledge building and sharing, where the researchers presented the results from their analyses. Concrete producers and concrete associations were invited to these workshops.

A common ‘cradle-to-gate’ model for all six cement plants was created. ‘Cradle-to-gate’ implied that the following were excluded: transport from factory gate, concrete production and the use and disposal phases of the building the cement was used for. Here the results were presented as an average for a ‘typical Nordic cement product’. An average based on the three Finnish and the two Swedish plants was used as a basis for calculating the cradle-to-gate data for cement, which were then used in the LCAs for concrete used for road paving and as a building material.

The study followed both the LCA guidelines as described in the SETAC Code of Practice (Consoli et al., 1993) and the Nordic guideline on LCA (Lindfors et al., 1995). Some methodological aspects are highlighted below. See Vold and Rønning (1995) for further details.

The functional units for the two cradle-to-gate studies were defined as follows:

- production of 1000 kg of cement
- production of 1 m^3 of concrete

The cradle-to-gate analysis from this study was used as basis for the LCA studies of concrete as road paving (Häkkinen and Mäkelä, 1996). The functional unit was defined as 1 km of paving of a main road, assuming a volume of 20 000 vehicles per day for 50 years. The assessment included production, use and disposal, while the influence of fuel consumption by traffic, noise, lighting requirements and dust formation were also taken into consideration.

Three methods of valuation were applied: Environmental Priority Strategies (EPS) in product design (Steen and Ryding 1992), the Ecological Scarcity Method with Norwegian and Swedish data (BUWAL) (Baumann, 1992) and the effect-category method (CML) adapted to Swedish conditions (Baumann and Rydberg, 1994). In addition, land use and exposure to noise at the production site were assessed.

Figure 5.1 illustrates the relative importance of the different environmental impacts related to cement production according to the three valuation models.

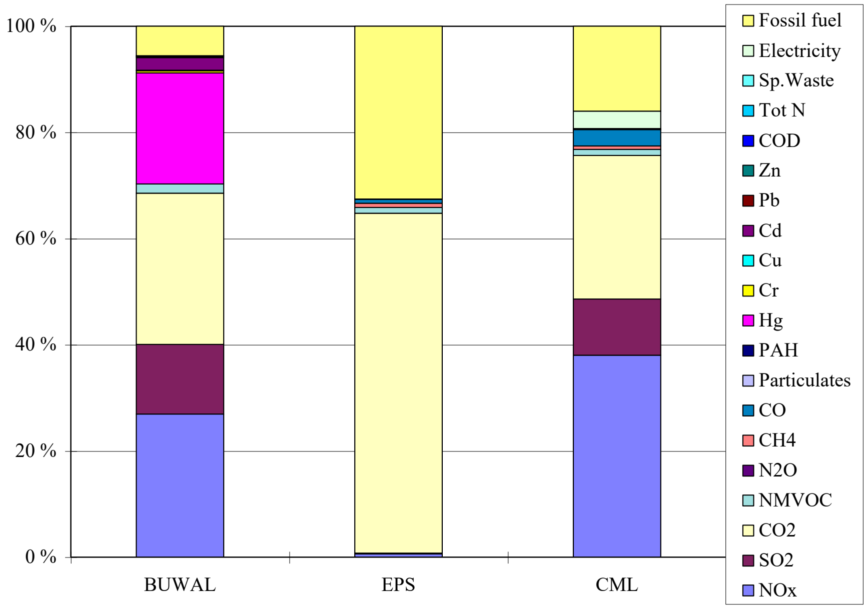


Figure 5.1 Environmental impacts according to the three valuation models for average Nordic production of cement (given in 100% of the total). Source: Vold and Rønning, 1995.

According to the BUWAL model, the emissions of CO_2, NO_x, Hg and SO_2 were considered to be of greatest importance in the production of cement. According to the EPS model, the emissions of CO_2 and the use of fossil fuels are of most importance. Finally, according to the CML model, the emissions of NO_x, CO_2 and SO_2 and the use of fossil fuels were most important. CO_2 emissions were related to the calcination process and from fossil fuels used in the clinker burning process, while SO_2 and NOx emissions were mainly related to burning of fossil fuels.

Hg and other heavy metals are natural contaminants in limestone and coal. Due to high temperatures, parts of the most volatile heavy metals will be released during the clinker burning process. One of the valuation methods, BUWAL, identified Hg as an important factor.

The data from LCAs of asphalt and concrete road paving were assessed using the same evaluation methods as for cement. The differences between asphalt and concrete road paving were not significant except for BUWAL, where Hg was identified as a significant emission.

LCA allows for the consideration of ‘all’ the environmental impacts associated with a product system. This project wanted to focus on some indicators which we at the time had little experience of including in an LCA, but which the industry itself perceived as important, as its stakeholders were concerned about them.

LCA allows for the consideration of ‘all’ the environmental impacts associated with a product system. This project wanted to focus on some indicators which at the time was not focused in LCA, but which the industry itself perceived as important, as its stakeholders were concerned about them.

One of these aspects was the use of land for cement production, since limestone quarries occupy land, and are accordingly also an important indicator. Thus, this indicator was included in this study, even though it was not derived from LCA.

The method used to assess the use of land was based on the work by Heijungs et al. (1992). This method classifies land use in five different categories before any activity on the land, during the activity and after termination of the activity:

1. Area unaffected by human activity.
2. Natural area, slightly affected by human activity.
3. Cultivated system (e.g. agricultural area, forestry area, cultivated land).
4. Built-up area (roads, houses, railways, industry).
5. Spoiled area, i.e. an area where human activity has largely reduced its environmental value or biological production capacity.

The types of transformations for the different activities in cement production are given in Table 5.1.

Table 5.1 Classification of land use in different category land use before, during and after occupation of land for limestone mining and cement production.

Type of activity	Before activity	During activity	After termination
Limestone mining	2	4	3
Cement production	2	4	3 or 4

It is possible to reclaim most of the occupied land back to a less affected category after the activities have been terminated. Land use was considered to be of less environmental importance in this study compared to the emissions presented above, but the industry and the LCA practitioners wanted to gain experience of including indicators not derived from LCA.

Another indicator not derived from LCA assessed in this study was noise. Noise impact was calculated as 0.22 person noise hours per ton of produced cement. This figure is based on measurements taken in the neighbourhood of the facilities. The number of persons affected by noise levels higher than 45 dB(A) at night and 55 dB(A) during daytime was recorded.

To put the figures into perspective, in Norway, 50 000 to 100 000 persons are affected by noise >55 dB(A) caused by industry. In the Norcem Brevik neighbourhood only 20 persons are affected by more or less constant noise >55 dB(A). Noise from cement production was therefore not considered as important due to environmental concerns, but was part of a stakeholder dialogue with the company.

One consequence of participation in the Nordic project was that Norcem (the Norwegian cement producer) subsequently took an active part in the Nordic NIMBUS project, which aimed to develop methodologies for EPD (Møller et al., 1998, Hanssen, et al., 2001), see chapter 1.1. This work provided input to the ISO work with EPDs and contributed to the development of ISO 14025. The Norwegian and Swedish EPD programme operators, EPD Norway and Environdec, were established in connection with the NIMBUS project.

Norcem has prepared EPDs for many of its products since then and is actively using these today to document the environmental characteristics of different types of cement, Vold et al (2016).

5.3 DISCUSSION

The project presented here was clearly part of the development of knowledge of LCA in the industry, while also being in the early stages of this development in Nordic scientific communities. The project therefore represented a learning process for both the industry and the scientific communities involved. There were two objectives: to enhance knowledge and to discover potentials for improvement through the analysis of specific concrete products (such as road paving), where LCA analyses were performed in ‘textbook fashion’.

In order to enhance the credibility of LCA for cement and concrete products, it was an advantage to establish a detailed Nordic model of cradle-to-gate analysis. This was despite the fact that the different cement producers were basically competing in the same market. The established model is still being used.

At this point, the last phase of the LCA method as presented in ISO 14040 was ‘improvement’ (later replaced by ‘interpretation’). There were no clear guidelines on how this could be integrated into existing external methods for product development or improvement. This project identified areas for improvement related to cement production and used simulations of alternative solutions to show how these could reduce one or more potential environmental impacts of cement production.

Cement production is an energy-intensive process, which uses coal and other fossil fuels. Measures to reduce fossil energy consumption and hence greenhouse gas emissions were a high priority. As cement production requires a high temperature, it is suitable for incineration of types of waste that other incinerators cannot handle. This, together with knowledge of the environmental consequences of alternative energies provided by LCA, led to a considerable reduction in CO_2 emissions from cement production.

The fact that cement production had high CO_2 emissions was well-known to the project participants. But, the importance of mercury emissions as demonstrated by weighting came as a surprise. Weighting was an important aspect of an LCA study at the time, but has somewhat lower priority today.

In addition to the emissions associated with the combustion of fossil fuels, CO_2 is released when limestone is burned in the calcination process. Similarly, some of this CO2 will be absorbed by the concrete in what is known as carbonation. This project attempted to include carbonation. Carbonation was well known as a phenomenon in the industry, but was not equally well known and accepted in other industries. Thus, the cement and concrete actors feared that the inclusion of carbonation might on the one hand derail the discussion of whether LCA is a suitable documentation method and on the other hand weaken the credibility of the studies conducted by the cement industry. More than 20 years passed before carbonation was ripe for inclusion in LCA. See 10 where this is presented in the project 'CO2 uptake by concrete carbonation'.

As mentioned above, the project proposed ways of considering product improvements both in production and after the factory gate. Analysis of concrete products used in road paving and as building material enhanced the participants' understanding of the emissions created in the life cycle of the product systems and their extent in relation to other materials and inputs.

One rationale for the project was also the previous experience that the system limits involved in an LCA only allowed for a partial analysis of the product systems, which also formed the basis for the 'wood and concrete war'. This also became a challenge in this project. How should the system limit of a road surface be determined? The project participants realised that maintenance should be included. But, what about emissions related to driving? What about street lighting or groundwork for the road?

Through such discussions and the use of simulations, the project team realised the importance of an open approach to such issues in order to arrive at practicable solutions for improvements, not only for concrete but also for interaction with other products. One such example was road marking (Häkkinen and Mäkelä, 1996). Paints for road marking adhered better to asphalt than to concrete; this meant that concrete roads required more frequent maintenance. This led to a dialogue with producers of road marking paints to develop products more suited to concrete surfaces.

Another example was street lighting. Here concrete had an advantage over asphalt, since a concrete surface is brighter, thus reducing the need for lighting. From a systems perspective, both these examples showed the importance of defining system boundaries sufficiently broadly to capture important aspects which can lead to system improvements. With regard to the lighting for the defined stretch of road in this case study, energy for lighting accounted for as much as 50-70 percent of total energy consumption (Häkkinen and Mäkelä 1996).

Viewed in its entirety, the project was primarily about knowledge development, focusing on issues within the established framework concerning how LCA should be performed. There were no links to other management or analytical concepts that focused e.g. on product development. It became clear to the researchers and to me that this was necessary in order to benefit from the improvement potentials identified by LCA. The number of actors taken into account was also somewhat limited. For example, the development of scenarios for the operation and maintenance of roads would be an important part of an LCA. An interesting point is therefore that the actors who perform such work did not participate in the project. It was initiated by the cement industry, while the concrete industry that produces the building materials had a more peripheral role. In retrospect, such participation would have been important to enhance knowledge of these stages in the life cycle. This was a typical feature of the early days of LCA in the construction industry; only actors in the early stages of the value chain were concerned about these issues.

This project raised awareness that a broad perspective on actors is vital to ensure that reliable knowledge is developed and applied, and that a stronger link to already established processes and work methods in companies is needed in order to bring about improvements. The latter point was a major driver for the development of more recent LCA projects that I was involved in and that is described in more details in the following case.

6 LCA IN BUSINESS STRATEGIES

6.1 INTRODUCTION

During the late 1990s, Leca companies in several countries had faced new challenges; there was an increasing focus on the environmental aspects of their manufacturing processes and products. The greater focus on greenhouse gas emissions and fossil energy consumption was seen as a potential threat to the manufacturers of Leca products, which depend heavily on coal in most companies.

Some Leca companies had thus initiated a pilot project where the whole life cycle of certain chosen products was assessed. LCA was introduced into these projects, and seemed to promise a new and more holistic insight into environmental challenges for Leca products. However, just as in the cement and concrete industry, those involved found that the focus was on a comparison of construction materials, without taking the building context into account.

Based upon the experiences gained in the pilot project, the Leca companies in Europe decided to continue their activities in a broader perspective in a common project: the Leca International Environmental Project (LIEP). This project started in 1999 and ended in 2002. Figure 6.1 shows the companies involved in the project. They were all members of Leca International (now EXCA), a member organisation for all light weight aggregate (LWA) manufacturers in Europe.

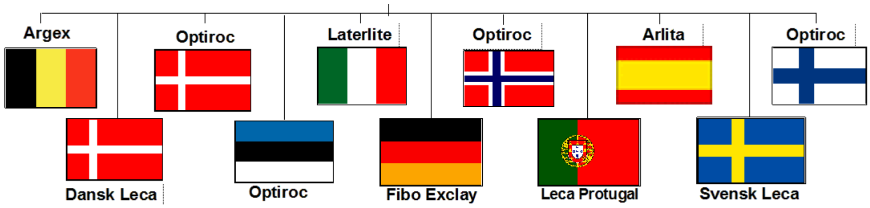


Figure 6.1 Participating companies in the Leca International Environmental Project.

The main objective of the project was to *'address the business opportunities for Leca products with respect to environmental challenges in the European region, by developing, documenting and marketing eco-effective solutions based on Leca products'* (Rønning et al., 2002). The aim of the main project was to be realised through:

- building up expertise and capacity in the European Leca companies concerning product-related environmental issues, and how to carry out LCA projects

- contributing to the development of product-oriented environmental strategies for the different Leca companies in Europe
- improving data quality and gaining experience of the application of a common data model and data format for registration, management and presentation of LCA data from the production and application of Leca products
- developing specific formats for and examples of communication of environmental data for Leca products and companies for different actors in the market.

The main philosophy for the project was:

- From manufacturing and process focus towards product and systems focus
- From threats and risks towards opportunities
- From being a problem generator to being a problem solver

A further focus was to ensure that this knowledge became established in the companies concerned. Typically, several employees of each company were involved, representing production, sales and marketing. In addition, the project was firmly established at management level in the various companies. The project was linked to the European trade organisation Leca International, and the participants were competitors in the same market, but the approach adopted led to the perception that the common external challenge was a strong motivating factor to initiate the project.

From a methodological point of view, the question was how LCA would make a contribution to what was then known as Integrated Product Policy (IPP). Our starting point was thus methodology for environmental management systems (EMS) and how a product oriented environmental management strategies (POEMS) could be included in this. As described in 4, methods for environmental management systems were documented by the ISO 14000 series and offered several options for POEMS practices in organisations. However, a number of questions remained which were not discussed in the standards, such as: which of the tools should be applied to which kind of environmental management problem, and what are the synergies and antagonisms between these tools? Thus, it became necessary to supplement LCA with other tools and methods to provide a basis for decision-making. It was central to identify where and how these other tools should be used to augment the findings of the LCA.

The project activities were structured as follows and I will use those to show how different methodological approaches were applied in this project:

1. Documentation
2. Communication
3. Business strategies

This chapter is in part based on the following reports and paper:

Rønning, A., Hanssen, O.J. (1998), *Product Oriented Environmental Management Strategies. An Input to Strategic Discussions in Leca International Companies,* Ostfold Research Foundation, OR.61.98, Fredrikstad.

Rønning, A. (1999), Leca International Environmental Project – Report from pilot project *OR.19.99*, Ostfold Research Foundation, Fredrikstad.

Rønning, A., Vold, M., Nyland, C. A. (2001), *As a producer in an early stage in the value chain – how to effect decisions in the user phase?* The 9th SETAC Europe Conference, Leiden.

Rønning, A. (2002), *Environmental Performance Indicator (EPI),* OR.28.02, Ostfold Research Foundation, Fredrikstad.

Rønning, A.; Hanssen, O.J.; Nyland, C.A. (2002), *Leca International Environmental Project - report from the main project*. Ostfold Research Foundation, OR.27.02, Fredrikstad.

6.2 RESULTS

6.2.1 DOCUMENTATION

A common cradle-to-gate LCA model for 1 tonne and 1 m^3 of Leca products for manufacturing plants in Europe was established. This model served as a basis for plant-specific cradle-to-gate data used as input for LCAs of different Leca products used in different applications. In addition, this model was used for benchmarks between the different plants. The results from 1999-2002 for total energy consumption, CO_2 and SO_2 emissions were presented on the project website.

Each company chose one application relevant for its market as the object of an LCA. Figure 6.2 shows an overview of the different applications for which an LCA was conducted.

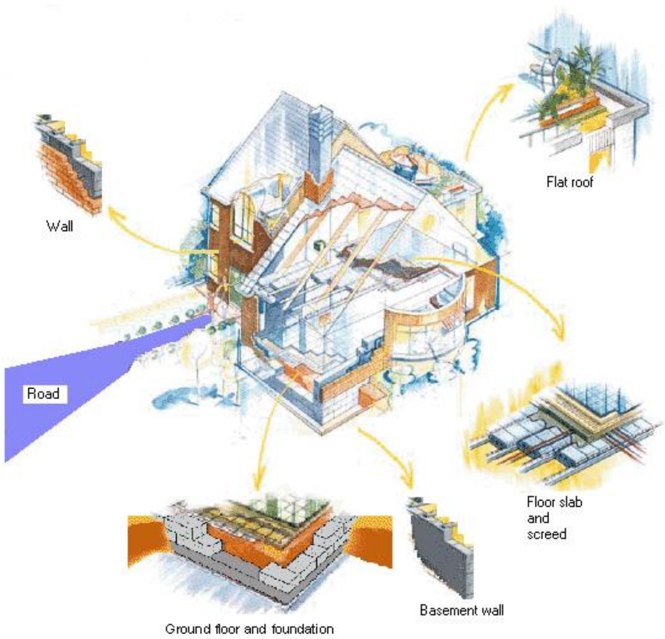


Figure 6.2 Overview Leca products, Rønning et al. (2002).

The environmental aspects of Leca products (both LWA and LWA-based products) were documented in the form of LCA studies. The LCA highlighted the most important environmental impacts related to the given product and where in its life cycle these potential impacts occurred. Based on these, several simulations were carried out to illustrate the effect of improving the product system by changing e.g. the type of energy carrier or type of raw material, or by increasing the insulation rate. In addition, some comparative studies of competing products were performed to learn about their advantages or disadvantages.

One of the cases was Leca blocks used in foundation walls. The functional unit was defined as 1 metre of foundation wall constructed (including reinforcement), maintained, and finally demolished after 100 years. In Figure 6.3 the results from the LCA describing use of energy are presented for 1 metre of foundation wall. As the figure shows, the use of energy is mostly linked to the production of raw materials, about 86% of which is related to Leca block production.

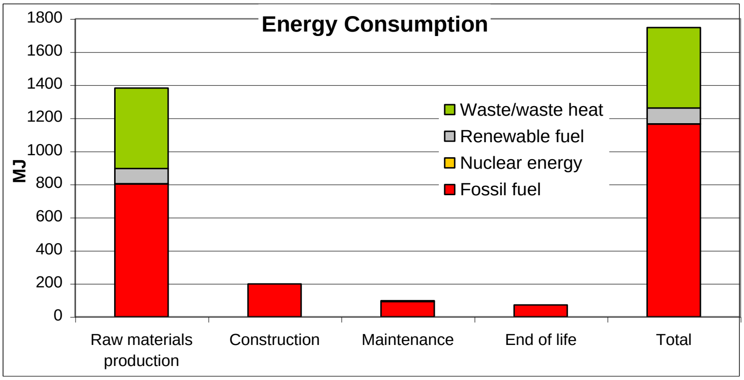


Figure 6.3 *Energy consumption for producing raw materials, constructing, maintaining and demolishing 1 metre of foundation wall.*

LCAs provided this kind of information as the basis for choosing between different building materials for foundation walls. However, when considering insulation properties, information about heating the basement is relevant. In Figure 6.4, the use of energy for heating a basement (90 m^2) is compared to the use of energy required for producing the construction materials for the basement walls. The basement has 38 metres of wall, which means 38 times the values given in Figure 6.3. Thus, the functional unit should include the insulating performance, measured e.g. by U-value.

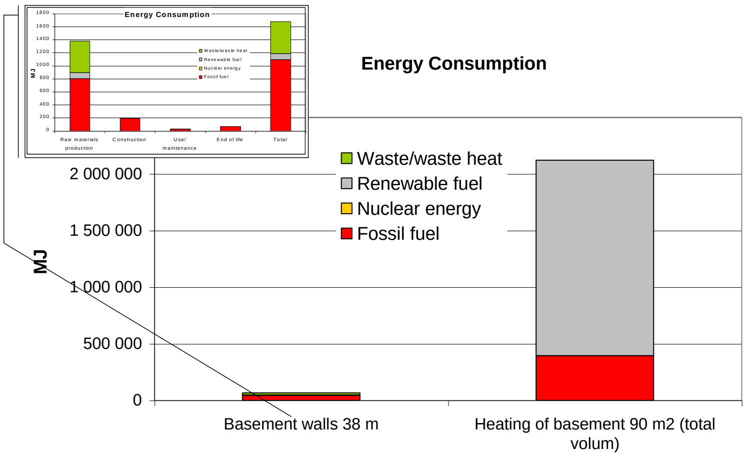


Figure 6.4 *The energy consumption for heating a 90 m^2 basement compared to the energy consumption required to produce building materials for the basement walls (excluding windows and doors, etc.).*

When considering a basement made of Leca blocks, over 95% of the energy consumption is related to heating the basement during its lifetime. From a producer's point of view, it should be important to focus not only on the use of energy for producing the product (cradle-to-gate), but information about the use of energy in the user phase as a consequence of choice of construction materials.

How was this information interpreted in the project? The figures as presented in Figure 6.4 could be regarded as a way to turn the focus towards the user phase. What happened was that the participants focused on the following question: 'In what way can Leca products influence the use of energy in the user phase and contribute to a reduction of the total energy required for heating?'

Figure 6.5 shows the reduction of energy consumption for heating the basement when changing to a solution that has insulation properties greater than the required value (i.e. lower heat transfer rate, or U-value).

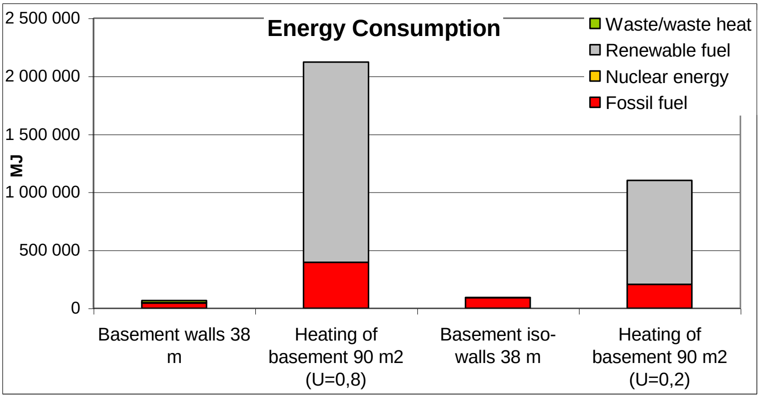


Figure 6.5 *Energy consumption for heating of 90 m^2 basement with two different U-values compared to energy consumption for producing the building materials in the basement walls excl. windows and doors etc.*

As seen in Figure 6.5 the use of energy for heating was reduced. On the other hand the use of energy for producing Leca-blocks (Iso-blocks) with better insulation properties was higher than for conventional blocks.

All results were documented and presented online at the project website, which is still available. At the website was also a library with results related to the topics described in Figure 6.6.

LIBRARY

- Environmental Product Declarations (EPDs)
- Environmental Performance Indicators (EPIs)
- Life Cycle Assessments (LCAs)
- Benchmarking
- Energy simulations
- Competitors' products
- Product Specific Requirements (PSR)

Figure 6.6 Overview of the library content, Rønning et al. (2002)

6.2.2 COMMUNICATION

The activity 'communication' focused on developing strategies for both internal and external communication, the former related to knowledge building, education and management and the latter for marketing of Leca products. An online, partly interactive, website became the solution. The website consisted of an educational part that was both theoretical and interactive, as well as project results, including information on how to interpret the results.

A 'learning centre' was developed, where the participants in all companies could learn about LCA, EPD and EMS on courses that included introductory theory (related to practical examples) and a multiple-choice tests. In addition, guidelines on how to develop LCA, EPD and EPI in practice were developed. Finally, there was a section on how the results from the specific studies could link to the different companies' environmental strategies and how to develop and implement these strategies.

Figure 6.7 Learning centre, Rønning et al. (2002)

EPDs became the tool for communication of the LCA results. The EPD development was based on the technical report under development by ISO (ISO/TR 14025:2000) and the Nordic adaption of this ongoing standardisation process, the NIMBUS[6] project (Møller et al., 1998). At that time, no product category rules (PCRs), then known as product specific requirements (PSRs), were available for Leca products. Thus, PCRs and the format for EPD were developed for external communication both with respect to cradle-to-gate EPDs and for those applications documented by LCA.

Based upon the way LCAs were performed and the EPD systems at that time, the Leca producers feared that the basis for comparison would be the construction materials and not Leca products in their context. This would then imply an incorrect decision from a life cycle perspective. The clients would choose the conventional wall solution and not the one with better insulation properties.

Another example of a product studied was a screed separating floor, which is a comparatively lightweight product. Because this particular floor system is lighter than other floors with the same load bearing capacity, the construction as a whole needed fewer materials as reinforcement, load bearing construction materials, etc.

On the basis of the knowledge acquired through this project, the marketing staff were able to highlight the importance of system perspective in discussions with customers, as illustrated by the two examples above. On the web site, all EPDs were available. There was also an interactive 'user guide' where all tables and figures in an EPD were explained. This tool was used by marketing staff in dialogue with e.g. customers and architects.

6.2.3 BUSINESS STRATEGIES

6.2.3.1 LCA in EMS and POEMS

Product-oriented environmental management strategies (POEMS) and life cycle assessments were new approaches to environmental management in companies. At the same time, there was an increasing focus on market-oriented, preventative policy and regulatory measures. Both national authorities (e.g. in the Netherlands, Sweden and Norway) and the European Commission began to develop integrated product policies for the environment.

To meet these challenges, the response from the LCA environment and for me in this project was to merge LCA and other tools used in companies, such as EMS. Figure 6.8 shows the activities involved in an environmental management system.

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[6] NIMBUS - Nordic Project for Implementation of Environmental Product Declarations Type III in the Business Sector

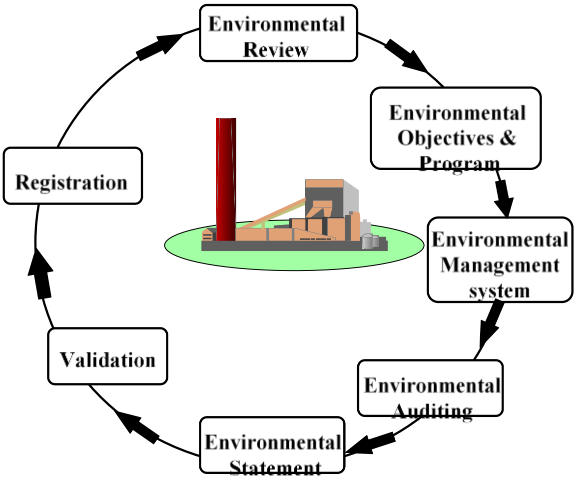

Figure 6.8 Components of an Environmental Management System.

The main difference between a product-oriented environmental management system and more traditional management systems was that the whole life cycle of products and business activities of companies were considered. This means that the number of activities involved in a system increases, as well as the number of actors, internally and externally.

Environmental reporting was an important part of a POES, and was required as a part of the EMS scheme. This reporting was to use Environmental Performance Indicators (EPIs), based on significant environmental aspects and assessment of stakeholders' interests.

The use of environmental performance indicators was one method to develop eco-efficiency indicators for the total organisation, to be used both internally in decision-making and management systems, and as the basis for external communication and reporting. The method was at that time under development by ISO and resulted later in an international standard (ISO 14031:1999).

Stakeholder dialogues were arranged locally at the production sites in different countries and analyses of market needs and requirements were performed.

Thus, environmental performance indicators provided the basis for setting environmental objectives and were used as part of environmental reporting. EPIs were developed at both company and product level on the basis of LCAs and the indicators were integrated into the existing environmental management system in the participating companies, as shown in Figure 6.9.

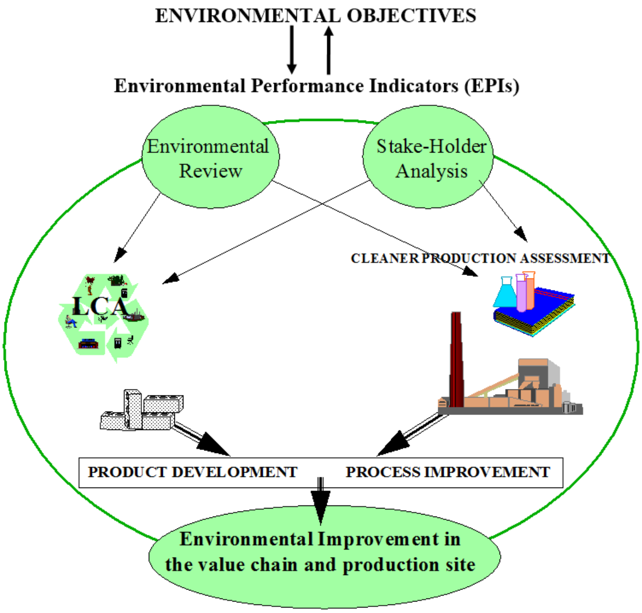

Figure 6.9 An overview of the relationship between the different elements of an EMS (Rønning et al., 2002).

The environmental review, which is a stage in an EMS, considered both the products (LCA) and the actual production site (cleaner production assessment, safety, and health and environment documentation) in developing EPIs.

An aspect of using indicators, whether environmental or economic indicators, was that they should not only be used for reporting, but also for managing purposes. In sum, in this project, EPIs were used for:

- **Formulation of objectives:** Focused on essential areas, based on important environmental impacts and stakeholders' needs. Identification of actions for improvement in relation to both production process and products.
- **Description of results:** The indicators provided a measure of the company's achievements and showed developments over time.
- **Reporting, internal and external:** EPIs were used for annual reports or other types of report.

6.2.3.2 LCA in business strategies

There are several types of strategic decision processes that are important from a POEMS viewpoint. In this project, the focus was on the portfolio of products and how to improve the environmental profile of these products throughout their life cycle and increase their market share as environmentally ‘better’ products. Several companies had made LCA studies of their product types and used this information as a basis for decisions to turn to more ‘green’ products and services (Christiansen et al., 1995; Hanssen et al., 1995). Another type of strategic decision that may be integrated with LCA is the location of production plants in relation to raw material suppliers, energy suppliers, transport infrastructure and important customers.

In the initial phase of the product development process, it is vital, from an environmental perspective, to assess which products are interesting to improve. A review of the entire product range can provide the company with an overview of the products which can be improved most effectively. Figure 6.10 shows how different products were defined this context.

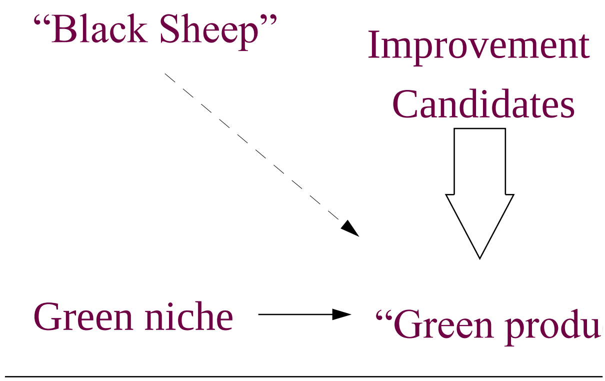

Figure 6.10 Profitability in a life cycle perspective as a function of environmental load, Rønning and Hanssen, 1998.

As seen in the figure, the products with relatively high environmental impacts and high profitability are the most interesting for improvement purposes (improvement candidates). Some products had low environmental load and had a low market share (green niche). The discussion was it possible to introduce those products in the market by green marketing. Last, a company is likely to have less strategic interest in further development of products that have high environmental load and low profitability (the black sheeps).

As part of this project, it was decided that this environmental strategy evaluation methodology would be tested. This exercise was expected to show the potential application of this tool in strategic discussions. One products from one of the participating companies is chosen to illustrate this approach.

The purpose was to link environmental aspects of products and processes to the economic and business strategy development of the company. The environmental strategy matrix would thus give the company input into discussions about the allocation of resources to marketing and product and process development, in order to improve the total performance of the company.

The ‘environmental strategy matrix’ was the main tool used to evaluate and improve the strategic environmental performance of the company. It is an adjustment of the Boston matrix to environmental management systems (Peters, 1990, Stern and Stalk, 1998). The matrix has two axes, one for environmental quality of products and one for economic value of products. The latter indicator could be turnover per year, expected market growth per year, annual net result per year or added value per year for each of the products or product types, depending upon the scope of the study (focus on different economic aspects).

In the main project, seven products with equal functionality (screed solutions) were evaluated. One m^2 of intermediate floor was used as the basis for evaluations (or the FU = Functional Unit). Four of the products are produced by a Leca company (A, B, C, and D), whereas three products are competing solutions (E, F, and G).

The six environmental impact categories listed below were used as the basis for the evaluation. These were chosen both because they were significant for the products considered, and because there was relatively good data available for both LWA production and final products:

- Total energy consumption (MJ/FU)
- Consumption of fossil energy (MJ/FU)
- Emissions of CO_2 from fossil energy (kg/FU)
- Emissions of SO_2 (g/FU)
- Waste to landfill (kg/FU)
- Total material consumption (kg/FU).

The four products from the Leca company (A-D) are compared with the competing products for screed solutions in Figure 6.11. The matrix shows that all four products from the Leca company have a better environmental performance than the three competing products. B is the best solution and A is the product with the lowest environmental quality among the Leca products.

As seen from the matrix, the best environmental solutions are the ones with the lowest economic value (B, D), whereas the solutions with the best economic performance are those with the lowest environmental quality (F, G).

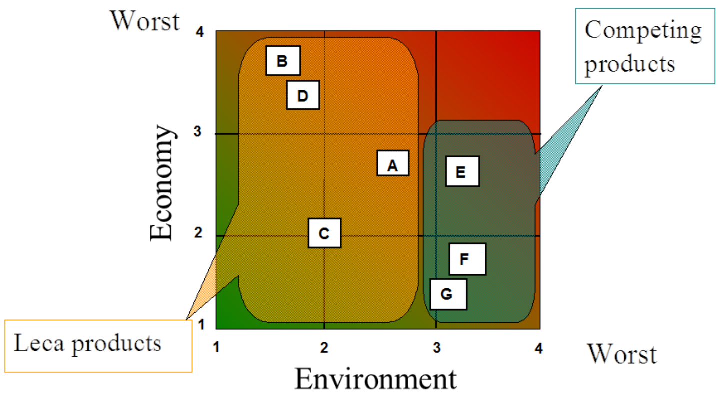

Figure 6.11   Environmental strategy matrix, Rønning et al. (2002).

The following conclusions were made:

1. LWA production and Leca products had good environmental profiles compared to other competing products.
2. The results could be used for setting specific targets for how large a share of the company's turnover should be covered by products with high environmental profiles (value < 2).
3. This target could be an important element in defining specific sales targets for products B and D, which had high environmental performance, but low turnover.
4. The share of turnover target could also be important for the development of product A. Product A should have the potential to achieve an environmental performance score of less than 2 (more like the other products, B, C and D). This could be done by reducing the use of energy, or increasing the share of renewable energy sources. Based on results from LCA, the most efficient measure was to make changes to other components of the product rather than the LWA, i.e. the type of cement used, as this product was a combined product.

6.3 DISCUSSION

LIEP was a comprehensive and ambitious project involving eleven production sites from ten countries with different business cultures and economic environments. Basically, the enterprises all competed against each other in the European market. However, the need to develop unified environmental strategies was seen as essential to meet the common challenges in the market and related to official policy requirements. Environmental policy in Europe and the Kyoto Agreement were important factors in this respect.

While the European Leca International organization initiated and supported the project, the actors involved in the implementation represented various departments within each company. As described, the participants from each company were representatives from management, at least two employees from the production sites and two from the R&D or product development department, who also had knowledge of the market.

The project offered an opportunity to demonstrate how LCA could be linked to other environmental or management tools relevant for production and marketing in the companies in the field, and also how to apply LCA in combination with these instruments in decision making at company level.

One of the concerns and challenges for Leca manufacturers was their energy-intensive production. The production of LWA requires high temperatures and they were therefore dependent on fossil fuels, especially coal. By using LCA in production (a cradle-to-gate analysis), we demonstrated the importance of not analysing emissions from the factory in isolation, but also the size of the production emissions with regard to different energy sources when substitution was considered. A common model for what to include when developing an LCA for LWA products was created. This was done in order to ensure that Leca manufacturers could eliminate a source of uncertainty represented by different approaches and also that the model was commonly agreed upon in case of any external criticism.

The project developed cradle-to-gate EPDs, along with EPDs for a variety of applications such as wall, ceiling and flooring solutions and for road construction. In terms of LCA methodology, these cases did not involve challenges with regard to modelling to gate. It was, however, more challenging to obtain good information on the use and disposal of the products.

The project enabled an analysis of the life cycle for a number of construction products when used in different buildings in different countries. This increased knowledge about LCA methodology applied in different economic and cultural environments, e.g. how to decide system boundaries and how to obtain relevant data. The project also informed the actors about the importance of life cycle perspectives in general and illustrated how LCA approaches needed to be elaborated to represent a knowledge base for the use of building materials in different contexts.

A reason for the establishment of this project was that analyses of entire buildings were at the time not commonly addressed in environmental analyses. Generally, there was a lack of knowledge about how to perform such analyses, while this was regarded as a necessity by the LCA scientific community. The whole life cycle should be considered in comparative studies to prevent drawing conclusions based on a limited part of the life cycle. Several LCA studies of buildings had shown that the material production and distribution phase only contributes about 10% of the energy consumption in the total life cycle of the buildings, whereas the user phase provides up to 90% (Borchsenius, 1998*).* As the user phase contributes greatly to the total use of energy and environmental burdens of buildings, Leca producers wanted to get more and better data for e.g. how their products influence energy needs in the user phase, scenarios for maintenance activities, surface finishing, wall structure, lifetime of products, maintenance cycles and the demolishing of building structures. These types of information were valuable as input to product development, and resulted in e.g. increased insulation capability.

Another lesson learned was that the actors realised that there was limited if any dialogue between Leca companies' representatives and decision makers in the context of specific building projects, i.e. entrepreneurs, architects and building owners. In addition, as far as they knew, no building projects at that time had environmental measures included in their plans. Establishing the "learning centre" increased knowledge about these issues both among the companies and the researchers involved. During meetings in the project organization and in other sessions, issues and questions regarding LCA methods and discussions on the results of the analyses in each company were documented. Through a transparent process of learning by simulations, focusing upon consequences of analyses and contextual issues in the individual company, a number of challenges for the LCA approach were illuminated.

7 LCA OF BUILDINGS

7.1 INTRODUCTION

Heidelberg Cement was part of the Nordic cement and concrete project, see 5. After the Nordic project ended, Heidelberg Cement continued to work systematically to develop and apply LCA. The company participated in a large Nordic project (NIMBUS, see chapter 1.1), in which Ostfold Research and other Nordic research communities worked on developing methodologies for EPD (Møller et al., 1998; Hanssen et al., 2001). This project was the beginning of Heidelberg Cement's development of EPDs for their different cement qualities.

Still after 10 years of experience with LCA in the construction sector, the focus was on comparing construction products and materials per se and not in a building context. Thus, Heidelberg Cement and Ostfold Research initiated in 2005 a project with an overall goal to develop an assessment method for LCA at building level to ensure a comprehensive input for decision making, with a focus on environmental and resource aspects in a life cycle perspective. The project was established in the period of the "wood and concrete war", when various political actors and studies were made in this context, see chapter 1.3.

As a departure point (phase 1), an assessment of different actors' need for a decision-making model was performed. The assessment was based upon a survey among actors (municipal and state developers, entrepreneurs, advisors and housing cooperatives), interviews with selected actors in the building sector, and literature reviews of LCA tools (Vold et al., 2006).

The main findings in phase 1 were:

- The respondents were found it important to take life cycle thinking into account in decision making
- EPDs were considered to be an indicator for companies concerned about environmental issues, rather than the companies actually using the information given in an EPD
- Producers of construction products do all focus on how to be sure that the properties of their products affecting the user phase are considered when designing buildings. Thus, a need for a consensus-based model for LCA was identified
- Environmental calculations should be based on the same accounting system as used in life cycle cost assessment (NS-3454).
- There was hardly any knowledge of existing LCA models or tools among the actors

- A literature review revealed that LCA tools that claimed to include service life in their assessments were based on national data for climate conditions and energy needed for heating and cooling in the country where they were developed.
- In these tools, production data for building materials was often country-specific and not applicable to Norwegian conditions.

Based upon the results from phase 1, the objective for phase 2 was to develop a construction product or material ‘neutral’ holistic model as a basis for calculations of the environmental profile of entire buildings (the Jomar[7] model). Representatives from Maxit AS (formerly Norsk Leca), Cementa (a Swedish cement producer) and the construction services organisation Norsk Byggtjeneste were invited as the steering group for the project. In addition, Multiconsult was invited as an expert on LCC.

In this chapter, I will first describe how the Jomar model was developed. This work was based on existing standards for assessment of buildings in terms of cost, design and service life planning. This was, in other words, an attempt to link to various methods with a different knowledge base than LCA and EPD; these methods were quite well-known and to some extent implemented in the construction industry.

7.2 MODEL DEVELOPMENT

7.2.1 DEPARTURE POINT FOR MERGING METHODS

As mentioned in Chapter 4.3, CEN TC 350 began started working on standardising methods for assessing the environmental performance of buildings based on the ISO 14040 and ISO 14044, and the standard from the ISO 21900 series. Thus, at the starting point of the project described here, there were no commonly accepted LCA methods or specific standards for LCAs of buildings available. However, a series of standards closely related to the ISO 14000 series had been developed, ISO 15686 *Buildings and Constructed Assets – Service Life Planning*. This series of standards addressed the development of the service life of a building component, building or other construction such as a bridge or tunnel.

One of these standards, ISO 15686-6:2004 *Buildings and Constructed Assets - Service Life Planning - Part 6: Procedures for considering environmental impacts,* aimed to complement the ISO 14000 series by describing how environmental standards could

[7] Why Jomar? In attempts to find a good project name, the choice fell on the boy’s name Jomar, which had its name day on the day of the initial meeting.

be implemented in building projects. Figure 7.1 shows the relation between life cycle stages, data sources and service life planning as shown in ISO 15686-6:2004.

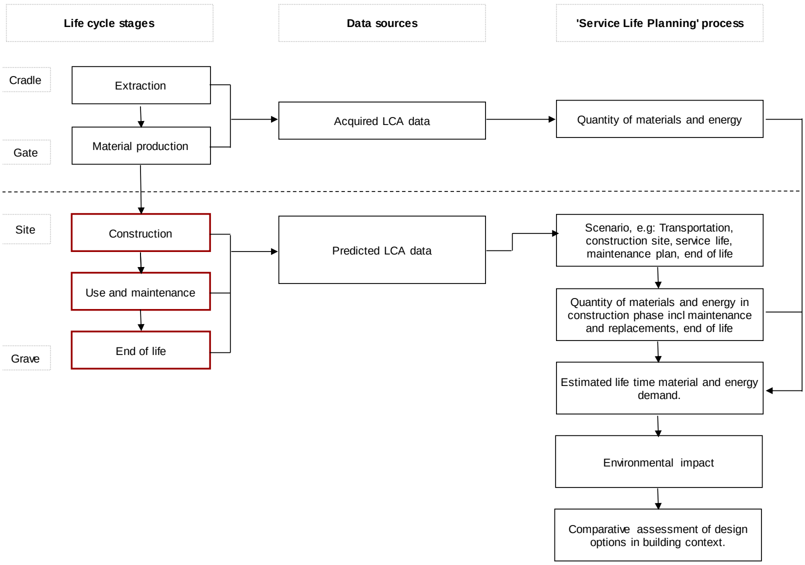

Figure 7.1 *The relation between life cycle phases, data sources and service life planning (ISO 15686-6:2004).*

This standard gave a comprehensive illustration of the system to be included in an environmental assessment of a building, but it was not very clear on how the scenarios for construction, use, maintenance and end of life should be described or what kind of data should be used.

One main finding from phase I was that the focus of environmental considerations had been predominantly on the life cycle stages above the dotted line in the figure. In other words, the specific materials or construction products had been environmentally assessed, but the combination of them and the use phase were rarely assessed. Possible explanations were that data describing scenarios were not available or that the actors had no incentives to include these aspects in their assessments.

On the other hand, some actors referred to LCC as an approach they either used or intended to use in the planning of building projects. The methodology of LCC for constructions had been used for estimating the total costs over the construction's anticipated functional lifetime (Bjørberg, 2004), and further developed in a Nordic project on LCC assessment of buildings (Bjørberg and Haugbølle, 2005). The findings from the Nordic project served as the starting point for the Jomar model in addition to the Norwegian standard NS 3453:2000 Life Cycle Costs for Building and Civil Engineering Work - Principles and classifications

7.2.2 MERGING ELEMENTS FROM LCC AND RELATED STANDARDS

The concept of LCC facilitated decision making based on costs over the whole lifetime, in place of decisions based on capital costs. Here was a clear parallel to LCA: instead of calculating the environmental impacts of the construction product or elements, the loads over the entire life cycle were considered. This approach was also linked to the service life planning given in Figure 7.1. The question was how the LCC approach could provide input to the missing detailed description of scenarios in life cycle planning in an LCA context.

Therefore, LCC had to be scrutinised more thoroughly. An overview of the method was made. LCC incorporated the initial capital costs, the demolition costs and the entire annual costs of managing, operation, maintenance and development, MOMD (NS 3454:2000), see Figure 7.2. Here, the similarities to LCA are seen in the way the results are presented. In addition, we found that life cycle costs could be discounted as net present value (NPV) of lifetime costs. The annuity costs could also be presented as a fixed annual annuity. The relationship between life cycle costs, lifetime costs and annuity costs is illustrated in Figure 7.2.

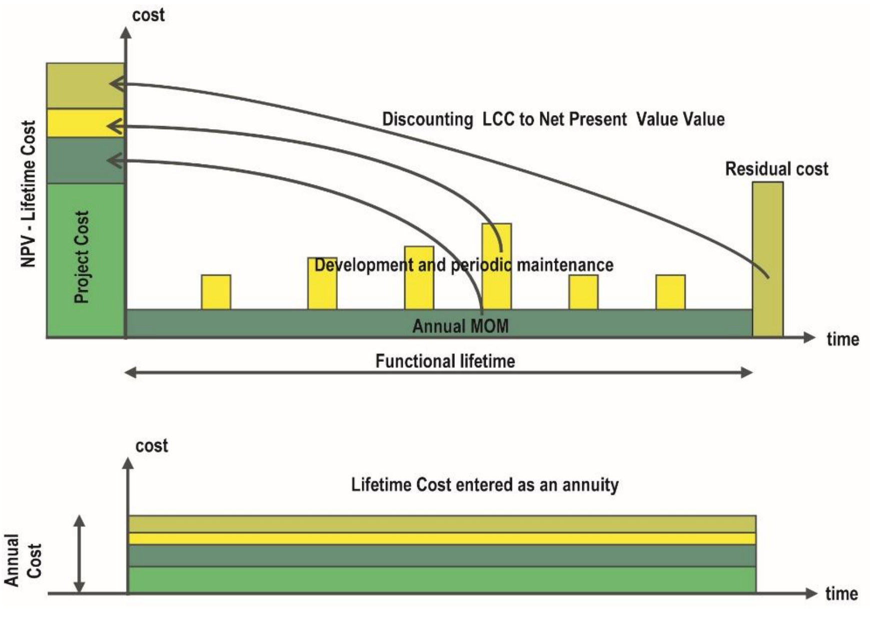

Figure 7.2 Life cycle cost theory (Source: Rønning et al., 2007 adapted from Lindberg, 2002).

At this point, the LCC approach and the Norwegian standard NS 3454:2000 clarified to a certain extent which life cycle stages to include, but not how to structure them or which data to use for developing scenarios, see Table 7.1. However, the standard referred to a set of other standards that needed to be incorporated.

Number	English name	Norwegian name
NS 3451:2006	Table of Building Elements	Bygningsdelstabell
NS 3453:1987	Specification of Building Costs	Spesifikasjon av kostnader i byggeprosjekt
NS 3454:2000	Life Cycle Costs for Building and Civil Engineering Work - Principles and Classifications.	Livssykluskostnader for byggverk – Prinsipper og struktur

Table 7.1 Overview of Norwegian LCC-related standard

The relation between the standards with reference to the timeline of a building's life is presented in Figure 7.3. The detailing of the elements in the LCC accounting system were based upon the standards given in Table 7.1.

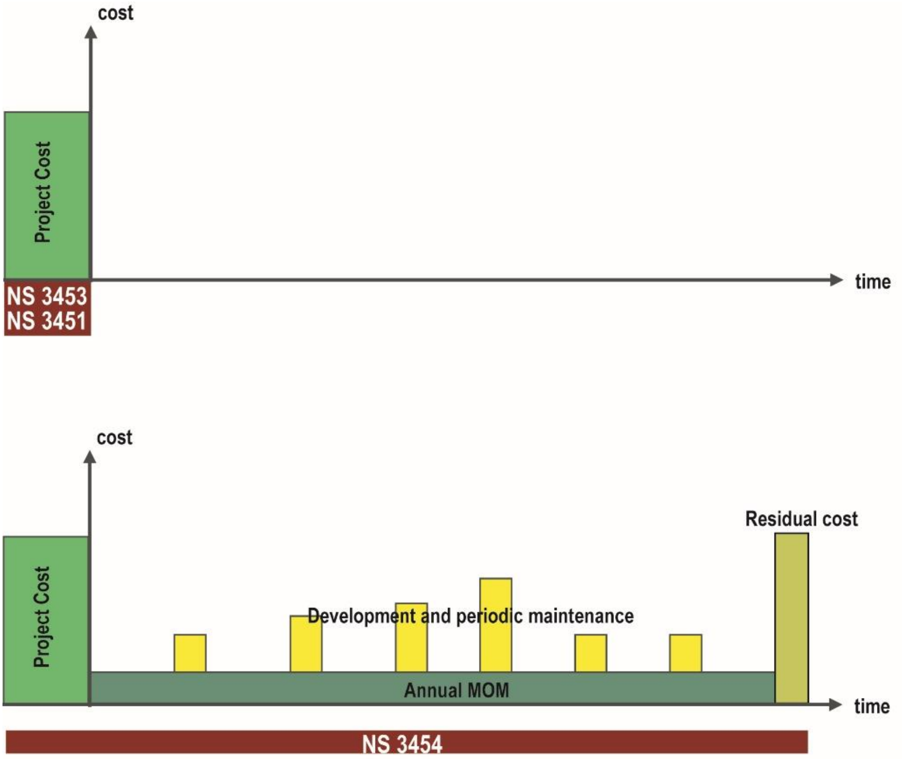

Figure 7.3 Relation between some of the standards. Adapted from NS 3454.

The standard NS 3451:2006 formed the basis for classification of all objects or construction elements for building and other civil engineering works. It provided a structured list of all physical parts of a building and its associated exterior. This served as the basis for how to design the construction stage in the LCA model.

The standard NS 3453:1987 Specification of Building Costs specified the project costs for those elements specified in the Table of Building Elements. The standard NS 3454:2000 incorporated the initial capital costs, the demolition costs and the entire annual costs of managing, operation, maintenance and development (MOMD).

The information in the graphs above was organised in a chart of accounts, as presented in Figure 7.4.

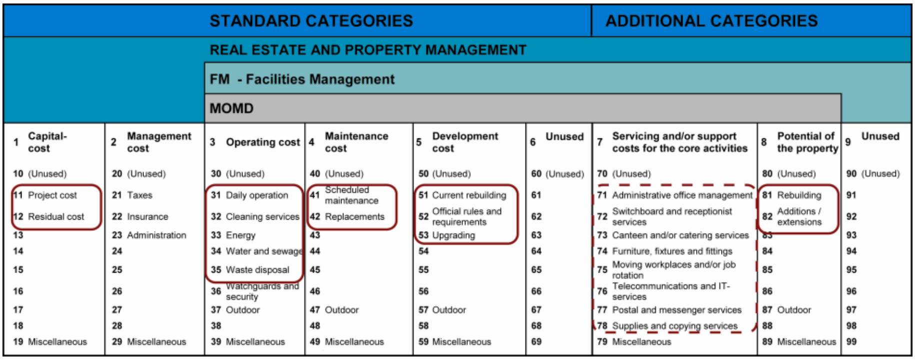

Figure 7.4 Elements included in the Jomar model from the Norwegian chart of accounts for LCC

The red boxes in Figure 7.4, which represent the life cycle phases construction, use, maintenance and end-of-life, correspond to the red boxes below the dotted line in Figure 7.1. Category 11 'Project costs' was subdivided according to NS 3453:1987 Specification of building costs and NS 3451:2006 Table of Building Elements. The Table of Building Elements is divided into three levels. However, it would be useful if a 'four-digit detail level' was defined that could identify what construction products to be included in a given building element, such as an outer wall, see for example Table 7.2.

1-digit level	2-digit level	3-digit level	4-digit level
2 Building			
	22 Primary building part		
		225 Outer walls	
			2251 Mortar
			2252 Concrete
			2253 Reinforcing
			2254 Insulation
			225x Wind barrier

Table 7.2 Example from NS 3451:2006 Table of Building Elements

In order to identify the different building materials, energy use, maintenance, etc. for defining the scenarios in Figure 7.1, the Jomar model used the scenarios given in the LCC model. When a developer performed an LCC assessment, the costs from historical projects formed the basis. Likewise, the existing LCC web tools were based on experience and historical data in order to give the output as monetary values. In the Jomar model and LCA, environmental loads were the desired outputs, and in order to estimate these, information on the physical quantities involved in the building were needed. Our experience was that contractors and owners focus mainly on economic factors and did not relate to, nor did they have information on, the exact amount of materials required for a building. Therefore, a shift in the method of capturing input data was necessary for this project. One could either base the input on a combination of assumptions and parameters from existing buildings, as turned out to be the case in this project, or - as would be recommendable for the future - start documenting the mass values of materials during the construction of buildings in order to form a material database that could serve as historical data for further use of the model. In that way, the use of the model could steadily improve.

No final decisions were made about which elements in the red boxes should be included in the model as it was considered to depend on the context of the assessment.

Figure 7.5 shows the terms used in the model along the timeline. The output (environmental load) will be given for each of the phases *Building construction, Operation, Maintenance, Development and End of Life* during the lifespan of a building construction. This is parallel to LCA methodology.

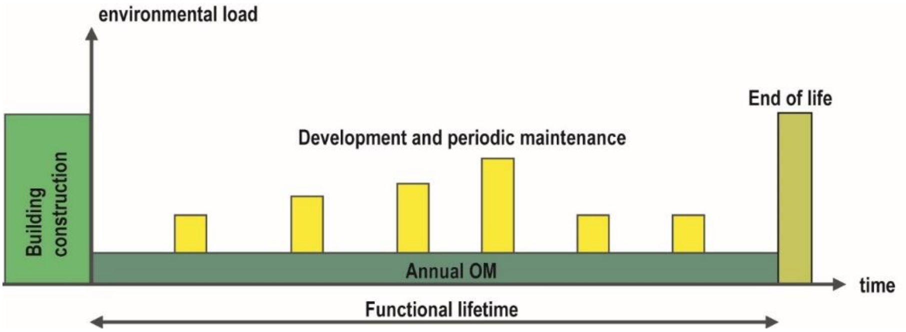

Figure 7.5 Terms used in the model along the functional timeline

This model was later applied in practice, see 8, but first tested in phase 2 of this project and phase III the ‘Konsensus project’ (Holte et al., 2011, Rønning et al. 2011). Phase II will be described in the following sub-chapter.

7.3 APPLICATION TO A CASE OF SCHOOL BUILDINGS

A departure point was the notion that attention to the environmental impacts of buildings focused on the construction products and not on the whole building during its lifetime. A holistic approach will, as mentioned earlier, not only focus on the individual construction product or material. Combinations of materials and products will also be an important factor. However, many other factors determine the criteria for a construction and which will indirectly affect the building's overall environmental profile. Geographical and climatic conditions with respect to the localisation of buildings, how they are designed, how they are situated and fit in with the terrain and how they are used were identified as significant factors in influencing the environmental profile of buildings. The Jomar model aimed, in principle, to include these perspectives. The Jomar model was tested in a comparison of three cases by simulating three fictional buildings with identical structure, but different construction materials and products:

- *Case 1: Timber based construction:* with timber framework on the majority of outer walls, inner walls and floors, and concrete slab on the ground floor, concrete foundation and load-carrying walls.
- *Case 2: Heavy construction:* with outer walls of concrete, insulated on the outside with an insulated wooden framework. Concrete foundation and slab floors and inner walls of light concrete.
- *Case 3: Flexible, heavy construction:* with foundation, outer walls and floors as in Case 2, and inner walls of timber framework.

The building of Dokka High School in Oppland was used as the volume and area reference for the three cases. The reason for using fictitious cases was primarily because there was little or no information about amounts of material in existing buildings available and secondly to facilitate comparison between three different material compositions without the area and volume influencing the assessment.

The overall composition of the building and the totality of separate building elements were divided into two factors and then their relative influence on the phases assessed in the cases was predicted (i.e. end-of-life was omitted due to lack of data), see Figure 7.6. The term composition meant choosing and designing a wide range of elements, such as the situation, the structure, the shape, the predominant materials and the details of the materials. In this project, only the predominant materials were varied.

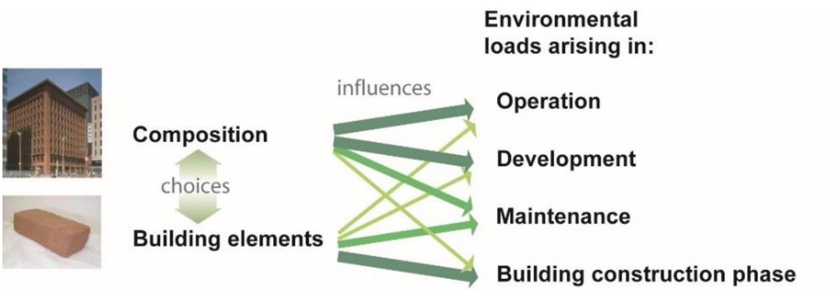

Figure 7.6 Relative influences on the environmental loads in the different phases of the overall composition and the building elements respectively (Note: The arrows do not indicate the order of magnitude), Rønning et al. (2007)

The results presented will focus on the experiences of applying the model and not the LCA results per se. It was of particular interest to test how easy it was to design scenarios using the model. This implied that there was little interest in giving precise descriptions of all activities in the use phase. For further details on the description of the cases and the results of the LCA, see Rønning et al. (2007).

The Table of Building Elements was used to structure the type of construction elements and the respective construction products used, but the amount of difference between construction products was estimated.

Figure 7.7 shows the energy use throughout the life span for one of the theoretical school buildings, the heavy building structure (Case 2), per m^2 gross floor area. The figure demonstrates how the energy use related to the different phases of construction and the user phases of operation, maintenance and development was distributed by using the model. As seen, the *operation* of the heavy structure was found to be the dominating activity during a life span of 100 years.

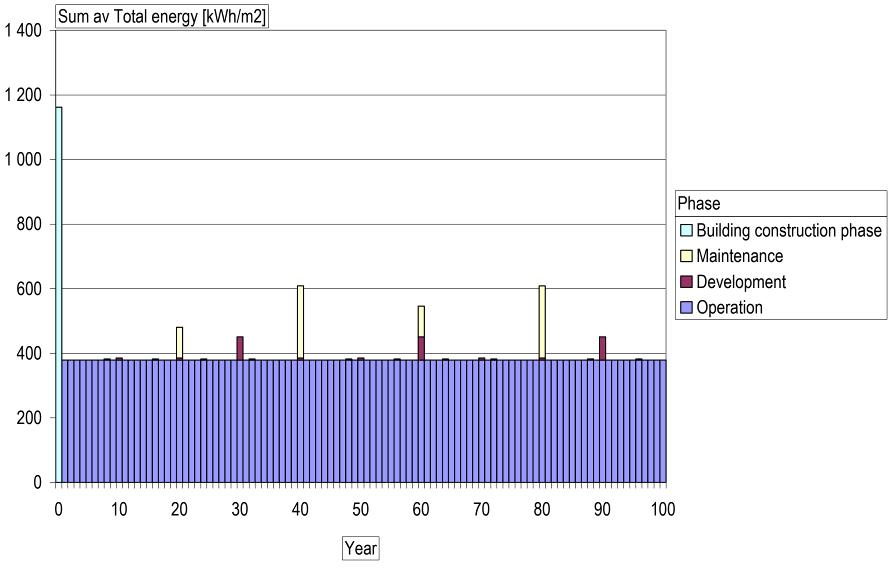

Figure 7.7 Energy consumption related to the different phases per m^2 gross floor area during the life span (100 years) for the heavy construction, Rønning et al. (2007)

The energy use was estimated by the simulating tool called *SCIAQ (Simulation of Climate and Indoor Air Quality*, programbyggerne.no, 2007).

The composition and choices of the different predominating building materials could be expected to result in some difference in *operation* loads, but this was not significantly shown in the assessments. It should be noted that, due to the scope of this project phase of merely testing a model, as well as the decisions made during the process, the input data turned out to be less than ideal for demonstrating differences in the *operation phase*. Buildings constructed of concrete and masonry have an energy-saving potential because of their inherent thermal mass, Dodoo (2012). Thermal mass is a property that enables construction materials to absorb, store, and later release significant amounts of heat. If included in the calculations, the results would probably show differences between energy use for the three alternatives. However, the importance of constructing buildings that involve low energy use was evident for all cases.

It was further concluded that relevant aspects from the upcoming standard NS 3031:2007 Calculation of Energy Performance of Buildings - Method and Data should be taken into consideration.

The way in which maintenance and development were included in the model was by adding the amount of e.g. material or paint and their respective environmental loads in the year of the activity. Data for *maintenance* and *development* were estimated for all three cases. Technical life times for building components given in Data Sheet 620.015 *Intervals for Maintenance* (Byggforsk, 1997) served as a basis for the choice of maintenance frequencies, as well as assumptions about heavy wear of the linoleum flooring in a school building. Most of the maintenance was assumed to be the same for all three cases, except for painting. It was assumed that timber walls needed paint on the inside, as well as the indoor wooden walls. For all three cases, when the *exterior finish in wood* was replaced, it was assumed that the insulation was also replaced.

The amount of *maintenance* and hence the difference in environmental loads should depend on both the choice of predominant material and its implications (*composition)*, and on the choice of one building material over another similar alternative. In the case assessments, the ambition was to investigate only the first aspect. Since it was decided to leave the concrete walls exposed on the inside in order to utilise the thermal mass for cooling, the exteriors of all three buildings were the same and hence had the same maintenance need and environmental load. This is an example of the trade-offs between choices and the complexity of their implications that were recommended to be implemented when assessing at construction works level.

Daily activities like cleaning as well as energy use and transport of cleaning and other auxiliary staff were not included. The load would be higher if they were included. How much it would increase depends on the type of building and how often and intensively it is used. This was an example of the importance of knowledge of the intended use of different kind of buildings, when describing the user stage scenarios.

As indicated in describing the model, development consists of actions with the intention to refurbish due to need or desire for change, as opposed to due to wear. An example was the need for changes due to the introduction of new regulations or that the school building had to be rebuilt because of new education plans requiring e.g. a greater or smaller number of classrooms or a swimming pool.

In this project, the assumptions made for the stage of *development* reflected the three types of school building and it was assumed that the degree of adaptability differed significantly. An example of such an assumption was that with regard to the flexible inner walls of half timbering in Cases 1 and 3, it was assumed that it was *the same 30% of the walls* that was removed or moved during remodelling every 10 years; hence the remaining 70% was not moved. Half of the 30% were assumed to be system walls and to be reused until replacement due to wear (i.e. maintenance). In addition, it was assumed that 5% of the linoleum floors were affected by the rebuilding and had to be replaced at the same intervals.

As the third school building was a heavy construction, a high frequency development, as for the other two buildings, would not apply. It was assumed that when the need for change arrived, one would either ignore it or continue the activity in the building. It was also assumed that after 30 years the need for change would be relevant and that all of the Leca block walls would then be replaced. The inner surfaces of concrete and blocks were assumed to be maintenance-free. Compared to the other two buildings, the change in environmental impact would be zero but the functionality for the users would not be optimal.

As shown in Figure 7.6, the *development phase* of a building would also be highly dependent on the composition of the building through the degree of adaptability (flexibility, generality and elasticity), and incorporated in the design (Rønning et al., 2006, Valen and Bjørberg, 2006). The case assessments demonstrated this; the building with heavy inner walls had a greater development load. When applying the Jomar model valuation/assessment, the flexibility, generality and elasticity of the building design should be included as they determine how to define scenarios. As different building types will have different adaptability demands, it was concluded that guidelines or rules should be developed according to building types; the need for changes would for example be different for a cinema and a hospital.

All these assumptions made for defining scenarios are examples of experience-based knowledge. One finding was that these kinds of assumptions could not in general be translated to other building projects, as they are contextual.

When developing the Jomar model, several other aspects were identified which had not been included but were recommended to be evaluated when applying the Jomar model in other studies. In Figure 7.8 those aspects are given.

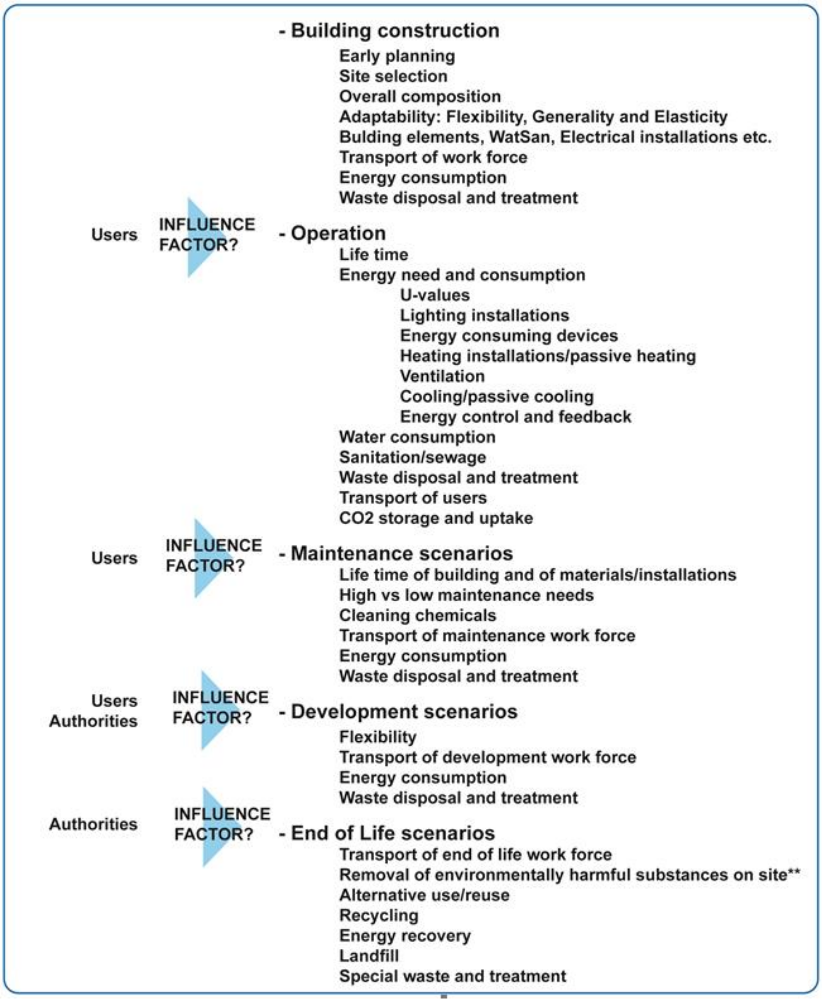

Figure 7.8 Keywords for developing scenarios based on the Jomar model (Rønning et al., 2007)

7.4 DISCUSSION

The development and testing of the Jomar model was a knowledge development project based on theoretical models involving LCA, LCC and other methods and standards already implemented by actors in the construction process.

Thus far, the conclusion was that it had been a success to build the Jomar LCA model on the basis of the principles of the various standards in 7.2. It was also found that chart of accounts of the LCC model provided input for how scenarios can be constructed. However, it was acknowledged that detailed knowledge of what actually happens to a building during its lifetime was not available to the project participants. Here it was more important to have facility management expertise available. Regarding the need for reconstruction and the amount of this as a consequence of the building's adaptability, there appeared to be little knowledge or experience-based data available.

One finding from phase 1 was that LCAs were mostly used to document the consequences of already established choices and decisions for completed construction projects, and was less used as a planning tool for simulation of the consequences of different choices in various phases of the construction process or though the lifetime of a building. Thus, the project questioned 'who needs what kind of environmental information to support which kind of decision in which stage of the construction process?'

Based on that question, the project recommended linking the Jomar model to the construction process. It may be stated somewhat schematically that decisions taken in the phases of programme, preliminary project, detailed design and actual construction lead to environmental impacts and associated expenses arising in the construction phase, the use phase and disposal phase (end-of-life), as illustrated in Figure 7.9.

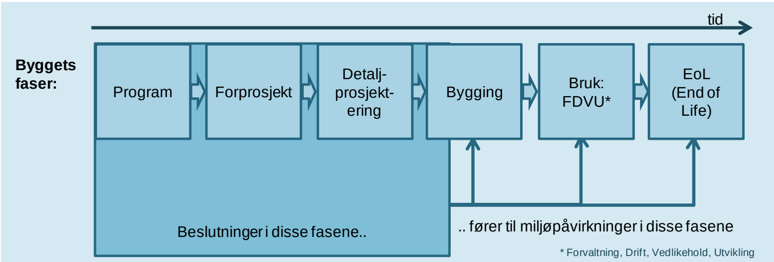

Figure 7.9 The association between decisions, phases of construction and the effects of decisions as environmental impacts

It was concluded that if improved and extended, the Jomar model could serve as basis for a design tool in addition to being a comprehensive LCA method. Then it was concluded that the usability of the tool should be addressed in order to develop something different from environmental accountancy of existing buildings. Thus, it should be questioned how such a tool can be adapted to the way the different planning actors work, cooperate and make decisions? Or maybe one could put it the other way around: Could the tool facilitate the cooperation during the planning phase between actors such as architects, engineers and owners?

Summing up, the phase 2 of the project was not as extensive as desired, either in terms of content or participation. The potential of the project was therefore not realised as intended. Seen in retrospect, it is clear that the project was premature, as nearly 10 years later there was an attempt by Standards Norway to deal with many of the same issues in their work to develop a method for calculation of greenhouse gas emissions for buildings (NS 3720, under development). It should be noted that the Jomar model do not recommended only one impact category bur rather tried to expand the number of categories.

The intention was that the results from phase 2, model development and testing, should serve as a starting point for phase 3, where the model would be further developed, tested for different building types and phases in the construction process (early planning, construction phase and as built). In phase 3, different actors from different parts of the building industry would be invited to participate, like suppliers of competing construction products and solutions, architects, entrepreneurs and building owners. In addition to testing the Jomar model, the idea highlighted was to establish a consensus on *how* to calculate e.g. the interplay between the aspects given in Figure 7.8 , as it would be a complicated chain of inputs and outputs, to enable the use of EPD and other environmental information in building information modelling (BIM).

However, it was clear that an ambitious follow-up project was premature. Ambitions were therefore lowered for phase 3 and three years after completion of Phase 2, the Consensus Project was born. The purpose was to determine how different LCA actors dealt with LCA and for which factors/data it was crucial to establish a consensus, and furthermore to establish a consensus on how to aggregate from building material and products to a combination of products applied in different type of exterior walls (Holthe et al. 2011, Rønning et al. 2011).

As mentioned, it took three years to establish phase 3. Meanwhile, the Jomar model was applied to a practical case. This case study will be presented in the next chapter.

8 LCA IN PRACTICE

8.1 INTRODUCTION

In 2008, the managers of the Norwegian Bank 'SpareBank 1 SMN' decided to relocate their headquarters to Trondheim. The existing building was built in the early 1970s and was found to be increasingly inadequate for the provision of present and future bank services. The challenge was to decide whether they should refurbish the existing building or demolish it and construct a new one. Thus, the objectives of the project were firstly, to document the GHG emissions from the two alternative solutions, and secondly, to gain experience from using LCA methodology as a basis for decision-making in the feasibility and planning phase as a more proactive tool. The second objective was especially interesting from a research point of view, since most building environmental assessment tools focus on the end of the design process to evaluate the environmental results by assessing 'as built', Happio and Viitaniemi (2008a). In addition, environmental considerations should be an integral part of decisions made in the process.

This chapter deals with the application of the Jomar model in practice in a project where there was a specific issue of either constructing a new building or renovating the existing one. This project was not directly connected to the 'wood and concrete war', but was primarily intended to show how the Jomar model could be applied in practice, since it was 'material-neutral'. Those involved had no preferences for materials or construction products, but focused on the use of life-cycle thinking, in terms of both economy and the environment, as the basis for their decisions. The project was organised as a collaborative process, with participation of actors from different disciplines.

This chapter is based on the following conference papers and project report:

Rønning, A., Vold, M. (2008): Miljøvurdering av nytt hovedkontor for SpareBank 1 SMN. Sammenligning av to alternative løsninger (Environmental assessment of the new headquarters for SpareBank 1 SMN. Comparison of two alternatives), Ostfold Research, OR.10.08, Fredrikstad.

Rønning, A., Vold, M. (2009), *Refurbishment or Replacement of Buildings - What is Best for the Climate?*, SB11 Helsinki World Sustainable Building Conference, October 18-21, Aalborg.

8.2 DESCRIPTION OF THE CASE

8.2.1 THE TWO ALTERNATIVE BUILDING STRATEGIES

The existing building was approximately 30 years old. The building was found to have poor adaptability, flexibility and space efficiency. To meet the energy efficiency and quality requirements expected from future tenants, a rather extensive refurbishment of the existing building was needed. The actors involved had already by that time found that environmentally conscious tenants were established in the market and assumed that the number would increase in the future. There was also an expectation that the bank's functions would change from the current way of organising and running its activities, as had been seen during the past 20 years. Therefore, the actors presumed that the building needed to be constructed to cope with extensive modifications for several decades.

This had to be taken into consideration when assessing the environmental loads involved in renovating the existing building. Thus, the parameter 'adaptability' was a criterion for defining the two alternative strategies; these were defined as follows:

New building:

- Existing building demolished and new building constructed.
- New building has good adaptability.

Refurbished building:

- Demolishment of all interiors excluding primary building components and building envelope, and reconstruction of the interior.
- Due to technological constraints of the existing design, no more than medium adaptability was possible to achieve through refurbishment.

The total energy demand for the existing building was relatively high at 524 kWh/m^2. As the existing construction was considered to have low adaptability and area effectiveness, even an extensive refurbishment would not reduce the energy use after refurbishment to a satisfactory level compared to what would be possible to achieve for a new construction. The energy use was predicted to be as high as 300 kWh/m^2 after refurbishment. The goal for the new construction was a net energy demand of 85 kWh/m^2.

8.2.2 SYSTEM MODELLING, DATA AND SCENARIOS

To conduct LCAs of buildings requires methodological considerations on three dimensions. The first one relates to the question of which emissions should be included, i.e. the activity of boundary setting to decide which emissions belong to the building being studied. The second dimension is related to definition of the scenarios for operation, repair, maintenance, replacement and end of life. The third dimension is related to the actual data collection and which figures should be used for emissions from basic technologies such as electricity generation and various infrastructures. These dimensions are of course interconnected: the first dimension will determine the data to be collected, the second dimension is part of the boundary setting itself and the third dimension will decide whether the actual data to comply with the system boundaries are at all available. All these three dimensions formed the basis for designing the analysis.

In this study, the developer only wanted to include CO_2 emissions on the grounds that this was the focus of the government, pointing out that the political discussion revolved around the carbon footprint of different building materials, see Chapter 1.3. But this developer already had experience of thinking beyond the construction process by using LCC as an approach for calculating the economic basis for building projects. It was thus natural to acknowledge that considering building materials in isolation and not in a lifetime perspective would be too narrow a knowledge base for comprehensive decisions.

An important aspect of this project was the development of scenarios. The Jomar model had established a knowledge base based on scenarios for buildings where other non-LCA-based standards were linked up, such as LCC, Service Life Planning and the Table of Building Elements. This project enabled clarification of how data related to defined scenarios are developed in cooperation with actors concerned with experience from practice, such as architects, contractors and builders. In this chapter, I will highlight some examples of such data and processes that lead to new knowledge of modelling and assessment at building level.

The Jomar model used NS 3451:2006 Table of Building Elements to define and separate out which construction products would be used, see Chapter 7.2.2. A challenge in this project was that in the feasibility phase no information or calculations regarding the amount of materials to be used were available, neither was there information on quantities of construction products used in previous projects. All information was in monetary terms. There were two approaches to solve this. One could either use figures from previous projects to estimate quantities based on price and estimated weight, or use the budget estimates and attempt to link environmental impacts to these. The latter approach was chosen and will be elaborated further.

Estimates for use of construction materials and products were available in monetary terms. Thus, the budget estimates for the project were used as input data. In Table 8.1, the distribution of different construction products and materials used and labour cost are given as percentages. Due to confidentiality, the exact cost figures are not presented.

Table 8.1 Estimates for materials and work cost for the feasibility project

Building elements (Refers to Table of Buidling elements NS 3451:2006)		Working cost [%]	Material cost [%]	Material costs distributed as percentage of total material cost [%]				
				Wood based products	Heavy materials (concrete, masonry etc.)	Metals	Electrical and mechanical products	Paint and chemical products
1	Overhead costs							
11	Overhead cost rigging and operation	100						
13	Contract administration	100						
18	Supplementary work, technical disciplines	100						
2	Construction							
21	Groundwork and foundation	28,5	71,5		64	7,5		
22	Primary constructions	25,5	74,5	15	52	7,5		
23	Secundary external constructions	37	63		48	15		
24	Secundary internal constructions	45	55	15	40			
25	Surfaces	47,5	52,5	15				37,5
26	Complemental building components	37	63		40	15	8	
27	Fixed furniture	36	64	4		12	48	
3	HVAC installations							
31	Sanitary installations	60	40			10	30	
32	Heating	60	40			30	10	
33	Fire extinguishing	80	20			20		
35	Process cooling	65	35			20	15	
36	Central air treatment	20	80			70	10	
36	Air distribution and ducts	70	30			30		
37	Comfort cooling	40	60			45	15	
4	Electric power							
40	Electric power	80	20				20	
41	Core installations for electric power, ger	50	50			25	25	
42	Low voltage supply	30	70			35	35	
43	Lighting	30	70				70	
44	Electric heating	60	40				40	
45	Backup power	30	70			50	20	
5	Teleprocessing and automation							
50	Teleprocessing and automation, general	70	30				5	25
51	Base installations for tele og automatic	60	40			10	30	
52	Integreted communication	70	30				25	5
53	Telefon and pager	60	40				35	5
54	Alarm and signal systems	60	40				35	5
55	Sound and display systems	30	70			10	55	5
56	Automation	50	50				45	5
6	Other installations							
62	Transport of persons and goods	52	48		5	10	33	
65	Waste and vacuum cleaning	55	45			10	35	

As discussed in 3, calculating life cycle emissions can be approached methodologically from two different perspectives: bottom-up, based on process life cycle assessment (PLCA) or top-down, based on input-output life cycle assessment (IOLCA), (Wiedmann and Minx 2007; Pettersen 2008). In the building sector, PLCAs had been the most usual approach. This approach was used to calculate emissions from inputs by mass, which presents certain challenges as in this case, due to the lack of information on the mass of products and the fact that LCA data were not available for all building materials and components.

The combination of PLCA and IOLCA, the hybrid LCA that linked process information collected in physical life cycle inventories with monetary flows in economic models, had been found to be a valuable, complementary tool to traditional inventory methods in LCA (Guggemos and Horwath, 2005; Sharrad et al., 2008). Thus, a hybrid LCA was chosen to overcome the lack of data in this project.

Then, emissions related to the economic value of the different products or services were needed. Here the emission intensity per sector as emissions per NOK gross product in the different sectors (NAMEA statistics - National Account Matrix including Environmental Accounts) was used based on the figures given by Statistics Norway. Table 8.2 shows emission factors used for some products and services based on this approach.

Table 8.2 GHG emissions for different products and services, Statistics Norway

Sectors	Tonne GHG emissions/MNOK
Construction and building work activities	13,7
Consultancy work	1,1
Wood based products	24,5
Electrical and mechanical products	3,6

The hybrid LCA approach, which combined the budget estimates, the Table of Building Elements and the emission intensity per sector, served as the basis for making the scenario for the construction stage in this project, in addition to EPDs for those products where information of mass estimates were available.

The scenarios for MOMD had to take into consideration a relatively extensive refurbishment including upgrading of the existing building. Those assumptions influenced the results significantly. In Table 8.3 assumptions regarding MOMD are given.

Developing scenarios at the building assessment level was and still is challenging, as considerations of future use have to be estimated. Thus, scenarios for operation, repair, maintenance, replacement and end of life had to be defined in this project.

Table 8.3 Assumptions regarding Management, Operation, Maintenance and Development – MOMD

		Units	New construction	Refurbished construction
General assumptions	Gross area	m^2	12 740	12 069
	Number of work places		600	500
	Service life	years	60	60
Demolishing/constuction	Share demolished/rebuilt		Whole construction	All interior excl. building envelop and primer building elements
Energy use	Net energy demand	kWh/m^2	100	300
	Purchased electicity[1]	kWh/m^2	85	174
	District heating2	kWh/m^2		126
Inspection technical equipments	Building condition		Good condition and good routines	Medium condition and routines
	Cost	NOK/m^2 per yrs	60	90
Cleaning	Building condition		Good condition and good routines	Good condition and good routines
	Cost	NOK/m^2 per yrs	70	70
Maintenance and development	Building condition		Good adaptability	Medium adaptability
	Cost	NOK/m^2 per yrs	1 500	4 500
	Cycle	years	every 7th	every 7th

[1] Nord-el mix (Nordic el production, loss included)

[2] FREVAR: Emissions per kWh produced + 10% loss

Here, I will not go into all the scenarios in detail, but refer to the main report (Rønning and Vold, 2008) for further details. Nevertheless, two scenarios are of specific interest, as one represented a construction service and the other resolved how to predict future development or rebuilding. As the Table of Building Elements and estimated cost were available, one could easily identify the activities besides material cost assumed to have high future costs. One of these was the cost of cleaning, which was considered a daily operation in the building, but seldom included in LCAs. Design and choice of materials strongly affect the need for and type of cleaning. In this case, both buildings were considered to provide easy access to the cleaning area to enable good cleaning routines, resulting in no differences in emissions between the two alternatives. If the design of the buildings were different, differences in emissions from cleaning could be significant.

The other scenario of interest was the basis for determining when there is a need for rebuilding an office building. The average rental period for office buildings in Norway is 7 years. Every seventh year, buildings are extensively rebuilt due to new tenants' needs and requirements (Rønning et al., 2008). How extensive the rebuilding processes will be will depend on the degree of adaptability of the building. Some building managers claim that with good adaptability, one needs to invest approximately one year's rental income in the cost of rebuilding. As the two buildings were considered to have different adaptability, good and medium respectively, rebuilding based on the scenario described above gave quite different results, as the one with medium adaptability needed greater efforts and more construction products to achieve the goal for rebuilding, see Figure 8.3 'maintenance and development'.

8.2.3 FUNCTIONAL UNIT

The basis for the comparison of the two alternative strategies was that the buildings would use the same plot of land and have roughly the same volume and height. In that case, it could make sense to compare two buildings. Thus, the functional unit was defined as operation and good maintenance of the building for 60 years. The comparison was based on calculations of greenhouse gases related to the stages of the construction process including cradle-to-gate data for building materials, products and services, operation, maintenance and development during the lifespan of 60 years of the two alternatives. Demolition - or end-of-life - was not included in the comparison due to lack of data.

Energy efficiency or environmental load of buildings was typically expressed in terms of technical parameters such as kWh or CO_2-eq. per m^2. In this project, the new building design had a greater area of use than the existing building. Thus, comparing the two buildings directly could not capture how an increased area of use would affect the results. In general, I would argue that reference to area alone is insufficient, since aspects such as the function of the building in relation to user needs, its adaptability, etc. have to be taken into consideration.

As stated, adaptability was a criterion for defining both the scenarios as well as the functional unit. The discussion of the latter had its origin in a previous project where the definition of a sustainable building was formulated, Rønning et al. (2007). Here, sustainable buildings were defined as buildings that *function* optimally for their purpose over time, while using the optimal amount of resources. A sustainable building should:

- function optimally to meet users' needs effectively
- be suitable for its use
- be flexible to adapt to changing needs and user requirements over time
- have optimal resource use, i.e. low material and energy consumption, low carbon emissions, etc.

Rønning et al. (2007) introduced a distinction between so-called energy efficiency and energy effectiveness. The former concept refers to the capability of technical installations to deliver services with a given energy use. If technological changes are made to provide a greater effect with a lower consumption of energy, energy efficiency increases. A change from electric panel heaters to a heat pump would be an example of such an improvement in energy efficiency. On the other hand, energy effectiveness means that energy use fulfils the functions required by the users of a building. To measure energy effectiveness, user requirements must be included in the calculation in order to determine whether the energy product delivered is suitable or could be more effective.

The purpose of a storage building may be to store products in a dry atmosphere, with an optimal temperature, etc. For storage, the height of the building will be utilised. In this perspective, measuring energy use per square metre does not make sense; volume has to be included in some way.

I will illustrate this by referring to a study where energy use in 39 different office buildings was assessed (Rønning, 2011), see Figure 8.1. The ranking of the buildings is presented using two different indicators; first as specific energy use (kWh/m^2) and then as energy use per employee and hours the offices are in use.

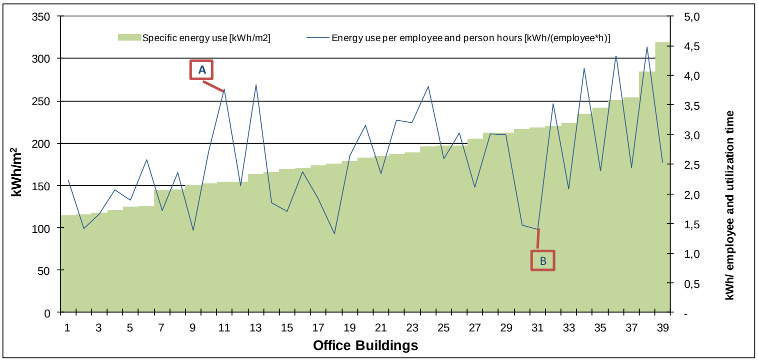

Figure 8.1 Ranking of energy efficiency (kWh/m²) versus energy effectiveness (specific energy consumption per person/time utilization) for office buildings

As shown, the ranking between the different buildings changes as a consequence of choice of indicators. Office building A was ranked as No. 11 in a comparison based on energy efficiency per m^2 but as No. 34 when the number of employees and the time the building is in use are included. The opposite was the case for office building B; it was ranked as No. 31 in terms of traditional specific energy use, but was the third best or third most eco-efficient building among the 39, as it was used more effectively.

This issue should be reflected in measurement indicators. In other words, indicators for energy use should incorporate energy *effectiveness* rather than energy *efficiency*, mirroring the function of the building and satisfying a set of requirements by the user. Different building types have different functions, and therefore Rønning et al. (2007) do not propose one common building indicator, but define a set of elements as listed above, that should be considered for an indicator.

As described in 3, the European standardisation (EN 15978:2011) has later introduced the term 'functional equivalent', which involves a similar approach to the one we suggested in the Jomar project and tested in the Sparebank project. In relation to defining the functional equivalent, the pattern of use is highlighted (EN 15978:2011). In this project, the building was supposed to operate as a bank and the amount of work space was therefore of vital importance to include when comparing the two strategies for the future bank location. In the design of the new building, it was assumed that because of its better adaptability, there could be up to 100 more work spaces. This will later be illustrated.

8.3 RESULTS

I will not go into detail about the sensitivity of the results to all assumptions made and the quality of the data in general, but focus on those issues that underpin my research questions. The results were of course sensitive to the estimates performed, especially the combination of data for investment planning and material flow data, and the scenarios for maintenance and development in addition to traditional uncertainties with respect to LCA. On the other hand, the estimates were in the same order of magnitude for the two different cases.

From an environmental point of view, it was concluded that the most favourable strategy was to replace the existing building and construct a new building. The results are illustrated in Figure 8.2.

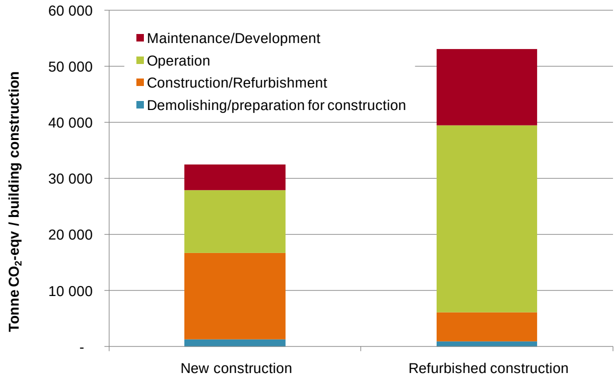

Figure 8.2 Total emissions of greenhouse gases given in CO_2 equivalents for new and refurbished buildings during 60 years.

Figure 8.2 shows that emissions related to producing the materials and constructing the new building were more than twice as great as for the refurbished construction. On the other hand, emissions related to operation, maintenance and development of the refurbished construction were three times the size of emissions related to the new building. This was mainly explained by the low adaptability and flexibility of the refurbished building.

Figure 8.3 shows consequences of the chosen scenarios in more detail. Emissions from the construction process, including upstream emissions, are given for year zero.

Emissions related to operational energy, periodical maintenance, cleaning and rebuilding are given for the year after the construction stage or after year zero.

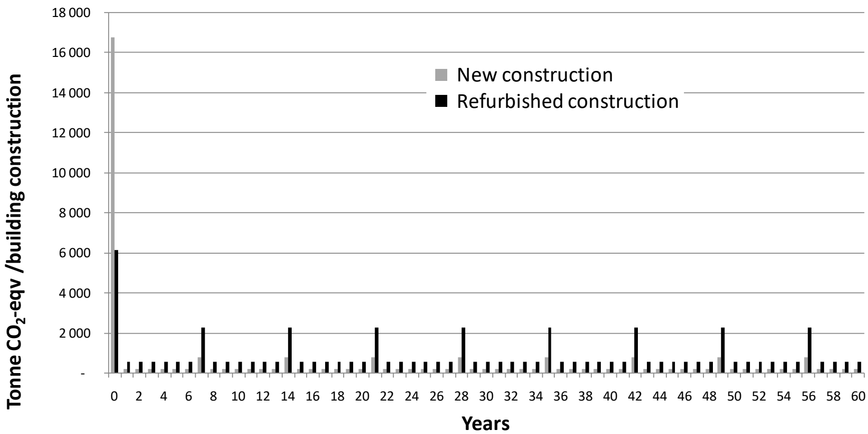

Figure 8.3 GHG emissions given as tonnes of CO_2 equivalents distributed per year of operation during a 60-years lifespan for the new and refurbished building

This figure clearly shows the assumption that buildings must undergo extensive reconstruction every seven years both because of the needs of new tenants, or, as here, because of the presumed future use of the bank. One can also see the difference between a building with low or medium adaptability and one with good adaptability, where reconstruction requires much less work.

This conclusion was further strengthened when comparing emissions per square metre or per employee since the new building was more area-efficient and increased the number of work spaces from 500 to 600.

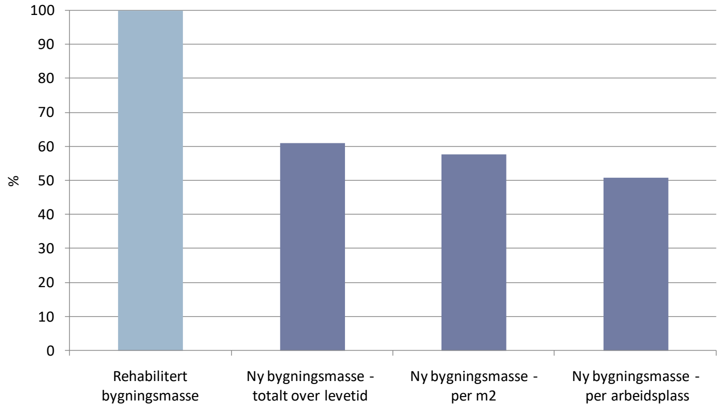

Figure 8.4 Differences in CO_2 emissions in percentages for different functional units for the new building (total per building, per m^2 and per work space), compared to the refurbished building

The results confirm the findings in previous studies that one can accept a heavier environmental load in the construction phase, if the way the building materials and solutions affect each other increases the adaptability of the building and therefore reduces emissions during its lifetime.

The results were sensitive to the estimates made, especially the combination of data for investment planning and material flow data, and the scenarios for maintenance and development. On the other hand, the estimates were in the same order of magnitude for the two different cases.

The results from the simulation of the two alternatives were considered to be suitable to support the decision made by SpareBank 1 SMN in the feasibility phase. In 2010, SpareBank 1 SMN decided to replace the existing building. It was documented that 99% of the materials were delivered for either recycling or reuse (Nordby, 2010).

Figure 8.5 Sparebank 1 buildings: the old and new buildings

8.4 DISCUSSION

This project was designed in a way that required new knowledge, new actors and new links to other knowledge bases. What was particularly important about this project was that it was concerned with a specific building process, which made the context of the building the most significant factor. Therefore, it was necessary to have a comprehensive perspective on the building in the analysis to be performed. The project was therefore organised as a collaborative effort involving actors from a number of disciplines.

What new knowledge are we referring to here? It was realised at an early stage of the project that there was a lack of data to calculate the amounts of the various construction products and technical installations used in the buildings and the environmental data for all these input factors. The first point was familiar in the Jomar model and an attempt was made to solve this by linking it to the investment budget. The division in the investment budget was based on NS 3453:1987 and the Table of Building Elements, which was also recommended in the Jomar model.

In terms of overcoming the lack of data, the approach of IOLCA and hybrid LCA had been applied successfully in the analysis of construction projects (Guggemos and Horwath 2005; Sharrad et al. 2008). In addition, this approach captured embodied emissions related to products and services. When PLCA is applied, total embodied energy or emissions are not included. IOLCA for typical US industries indicated that up to 75% of total emissions were overlooked when only the industries' direct emissions were considered, without including services, etc. (Matthews et al., 2008). Thus, a hybrid LCA was chosen as a new approach to overcome lack of data, as a complementary tool to traditional inventory methods in PLCA.

The budgeting also revealed the labour costs associated with service functions. It was therefore decided to try to include GHG emissions that were not only linked to construction materials and installations, but also to construction services. The challenge here was the lack of readily available LCA data for this, in addition to few EPDs and only for a limited range of construction materials; these factors supported the decision to use a hybrid LCA approach.

It was a relatively easy task to obtain the data described in 8.2.2. As this was a study in the early planning phase, using such aggregated and general data could be justified. However, if the study were to be used later in the construction process, in the modelling of the contribution of different suppliers, product- and supplier-specific data should be used. In this study, cleaning services were included. Traditionally, there existed no LCA data on this in the literature or databases. This meant that it would probably not be included in the analysis and the use phase would then have a lower overall environmental impact relative to other phases of the life cycle.

As mentioned, the ‘wood and concrete war’ was all about ‘the most environmentally friendly building material’ and to the extent that materials were assessed in a general building context that included the use phase, it was mainly energy use for heating (and perhaps cooling) which was included. As advocated, one of the main advantages of LCA is to avoid problem shift by including many environmental aspects related to the system under study. Despite this, greenhouse gas emissions or global warming potential was the only environmental impact assessed. On the other hand, the project made an effort to include the user MOMD phases, which until then were less commonly included, except for operational energy use. As stated above, there was an attempt to include other operational parameters such as cleaning and periodic inspections of technical facilities (e.g. change of filters, fluorescent tubes or disposables), in addition to maintenance and development of the building.

In order to develop good scenarios for the two alternatives analysed, it soon became clear that the function and adaptability of the building were key elements in the design of the scenarios. In designing the scenario for the existing building, it was assumed that even after refurbishment factors such as daily cleaning and inspection of technical equipment would be more extensive than in a new building. Reconstruction work during the next 60 years would also need to be more comprehensive for the existing building due to its poor adaptability. These examples show that modelling a good LCA for these buildings required a completely different kind of knowledge.

The actors involved included architects, representatives from various disciplines such as plumbers, electricians, MOM (management, operation and maintenance) and contractors/builders, which meant a different range of actors from earlier projects, as there were now participants who were linked to later stages in the life cycle than previously. Manufacturers of construction materials now had a minor and indirect role, since it was only environmental information documented in EPDs that was used, without the involvement of manufacturers.

Since this development project was organised as a collaborative effort, the LCA results were found to constitute a communication platform. Through discussions with many different actors, the knowledge these results represented became available for the project and it was then possible to calculate and simulate the environmental impact of the solutions chosen by the various disciplines. This knowledge proved necessary for the development of good scenarios. In retrospect, one may wonder whether the collaborative model was a prerequisite for making the necessary knowledge available.

One reflection after this project was that LCA expertise must also eventually become specialised in relation to the factors mentioned above. On the one hand, the LCA method is of general applicability in the sense that an LCA expert should be able to perform LCAs for ‘all’ products and services. However, as it now appears necessary to have new, comprehensive understanding of the systems to be analysed, contextual knowledge of a given system is a prerequisite for designing more realistic and applicable LCAs. This will involve the addition of both new fields of knowledge and new actors who possess this knowledge.

With reference to the ‘wood and concrete war’, which in its early phase was characterized by a limited non-contextual analysis, we see that the knowledge and the actors who were vital to this project were not represented there.

9 INTEGRATION IN POLICY

9.1 INTRODUCTION

In 2010 the Norwegian Ministry of Local Government and Regional Development (KRD) started to prepare Parliamentary Report No. 28 (2011-2012) 'Good buildings for a better society'. The report was intended to outline the issues and challenges faced by the Norwegian building sector in the years ahead, and consider suitable measures for the Government to implement to reach certain defined social objectives. In this context, the Ministry needed a basis for describing the climate and environmental impact of various construction materials. The Parliamentary Report was scheduled to be published in November 2011.

The Ministry of Local Government and Regional Development therefore requested a literature review of studies comparing greenhouse gas emissions in relation to different construction products. In addition, a brief assessment of other possible environmental impacts should be included. The study should summarise relevant research and show what factors influence climate and environmental impacts.

The call for tender by the Ministry explicitly pointed out that *'A literature study is requested that compares the climate impact of different construction materials. Greenhouse gas emissions from buildings are mostly linked to energy consumption during its operation period. Through increasingly stringent energy requirements and other changes, energy use for the operation is likely to decrease over time. If so, this means that the energy consumed during production, transportation and construction of a building can be relatively more important in a life cycle assessment'*.

The Norwegian Ministry of Local Government and Regional Development commissioned Ostfold Research to conduct the literature study. The object of the project was defined as follows:

- To provide an overview and assessment of existing literature that describes the global warming potential of various building materials and how this translates into a life cycle perspective (LCA), and to describe the knowledge platform these assessments were based on.
- To provide a description of the factors that affect the climate and environmental impacts, including the parts of the life cycle that are important in this context.

Further, on the basis of the literature review, Ostfold Research conducted an assessment which focused on explaining the methodological platforms the different studies were based on, and thus explained why the results varied and/or may not be comparable. Here, we also mapped the climate impact of different building materials as requested. To illustrate these issues, the assessment was based on two statements that were prominent in the public debate about the environmental impacts of construction materials and buildings throughout their lifetime:

1. Climate impacts of today's buildings are linked to the operational phase.
2. For low energy buildings, the production phase becomes as important as the operational phase or more so.

The literature search was limited to studies based on LCA as the method to calculate climate impacts associated with buildings and building materials. Altogether, 41 studies were referenced. Some of these were literature reviews that again referenced several other studies.

This chapter is based on the project report *'Knowledge platform for calculation of climate impacts for buildings and building materials. Literature study*' (In Norwegian), Rønning et al. (2011) and the book chapter *State of the Art Study – How is Environmental Performance Measured for Buildings/Constructions?* (Rønning and Lyng, 2011) in Finkbeiner (Ed.) *Towards Life Cycle Sustainability Management*. The project report is more extensive than the book chapter, especially regarding the climate impact of different construction materials, and also in addressing the need for the expanded use of EPDs.

9.2 STATE OF THE ART

State of the Art Study - How is Environmental Performance Measured for Buildings/ Constructions?

Anne Rønning and Kari-Anne Lyng

Abstract Several studies have used life cycle assessments to measure the impacts of energy consumption in different building stocks in a quantitative way. The use of LCA as the assessing tool has become commonly used in this respect. Today, greenhouse gas emissions from buildings are mostly linked to energy consumption during its operation period. Through increasingly stringent energy requirements and other changes, energy use for the operation is likely to decrease over time. On the basis of a literature reviews, an assessment is carried out with the focus on explaining the methodological platforms the different studies are based on, and thereby explaining why the results vary and / or may not be comparable.

1 Introduction

For more than a decade life cycle assessment (LCA) has been developed as a tool for assessing environmental aspects of different building products and constructions during its lifetime. However, we see a lot of LCA and environmental product declarations (EPDs) of building materials which to a great extent have been limited to the environmental impacts associated with the building materials or products – cradle to gate. On the other hand as the energy for operation decreases as passive or low energy houses are built, the relative contribution to the total emissions in an LCA-perspective from building materials will increase.

Today, greenhouse gas emissions from buildings are mostly linked to energy consumption during its operation period. Through increasingly stringent energy requirements and other changes, energy use for the operation is likely to decrease over time. If so, this means that the energy consumed during production, transportation and construction of the building to a larger extent can be relatively more important in a life cycle assessment.

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The Norwegian Ministry of Local Government and Regional Development has in this connection commissioned Ostfold Research to conduct a literature study, which will provide an overview and assessment of existing literature / research reports that describe various building materials' global warming potential and how this translates into a life cycle perspective (LCA – life cycle assessment), and thereby describe the knowledge platform these assessments are based on. Moreover, it entails a description of the factors which affect the climate and environmental impacts, including the parts of the life cycle that are important.

2 The review study

The literature study was carried out through searches in scientific databases (Springer Link, Science Direct, Google Scholar, EPD Norway's database of environmental product declarations). The literature search is limited to studies that are based on LCA as a methodology for calculating the climate impacts associated with buildings and building materials.
Further, on the basis of the literature reviews, it is carried out an assessment with the focus on explaining the methodological platforms the different studies are based on, and thereby explaining why the results vary and / or may not be comparable. To illustrate this, this assessment is based on two statements that are strong in the public debate about the environmental impacts of building materials and buildings throughout their lifetimes; 1) Climate impacts of today's buildings are linked to the operational phase and 2) In low energy buildings the production phase becomes as important as the operational phase.
The methodological foundations that are used in the different studies are further applied in relation to the two statements.

3 Results

There are several LCA-studies that compare building materials, such as wood against concrete or steel. Many of the studies exclude phases or activities throughout the life cycle of the building [1]. The argumentation of the exclusion is not always clear, however some argue that "energy for heating is equal for both building systems" [2, 3]. This is clearly a weakness when comparing building systems based on different building materials.

Although numerous studies conclude that "the LCA shows that energy use during use phase is most important", it is simultaneously concluded that a building based on one particular building material is better than the other, without discussing if there are significant differences between the systems.
The different approaches of performing LCAs and of excluding certain life cycle phases or activities, affect the results in two main directions; a) what life cycle phases that has the largest impact and b) the influence of material choice on the results.
Haapio and Viitaniemi [4] have performed a literature review on different calculation tools for environmental evaluations based on LCA of entire buildings. The study shows that LCA results are dependent on the tool used, and that a comparison between results from different tools is impossible.

3.1 Are climate impacts of today's buildings linked to the operational phase?

One important result from the LCA analyses is that energy use for operation contributes to 70-90% of the total during the lifespan. This is a general conclusion and assertion that is verified whether analysing heavy or light constructions [1, 5, 11].
Several factors are influencing the relative importance between production of building materials and operation phase. They can be divided in three categories - LCA methodology, localisation and building technical aspects.
Geographical and climate conditions with respect to the localisation of the buildings, how they are designed, fitting in the terrain and how they are used will influence the total energy use and embodied energy. On the other hand these factors are not highlighted in the literature; it is mainly LCA methodological aspects that are focused.

3.1.1 Data

The selection of data is of vital importance for the results. First of all, an LCA can be approached methodologically from two different perspectives: bottom-up, based on process life cycle assessment (PLCA) or top-down, based on input-output life cycle assessment (IO-LCA) analysis. A combination is hybrid approaches, which link process information collected in physical life-cycle inventories with monetary flows in economic models.

In the building sector PLCAs have been the most usual approach. This approach is calculating emissions from the inputs by its masses, which represents challenges for several reasons. Firstly, the construction sector does not have a tradition to evaluate their projects on mass basis, only in economic terms. Thus, one does not have key figures or experienced based calculations to lean on. Secondly, in a feasibility phase one doesn't know which materials will be chosen. And last but not least, there are not environmental data available for all building materials and components.

The combination of LCA and input-output models has shown value as a complementary tool to traditional inventory methods in LCA. The reason is bipartial. Firstly, the total embodied energy is not included when using PLCA. Input-Output life cycle assessments for typical US industries indicate that on average up to 75% of total emissions were overlooked when only looking upon the industries direct emissions and not include services etc. [12].

Secondly, in a feasibility phase one does not know which materials will be chosen and the construction sector does not have a tradition to evaluate their projects on mass basis, only in economic terms. Especially in US one see the approach of IOLCA and Hybrid LCA utilised when analysing a construction project to overcome the lack of data and to include embodied emissions [3, 13-15].

3.1.2 Electricity model

When considering greenhouse gas emissions, the choice of energy model is essential, including the assumption of what energy carriers are generating the electricity consumed in the building. The assumption considerably affects the relative difference in impact from each life cycle phase. Reviews of variation in greenhouse gas emissions for different electricity models used in Norwegian calculations differ from 0 - 1.400kg CO_2e/kWh [16].

This implies that the choice of electricity model may overturn the conclusion that the use phase is the most important phase when it comes to greenhouse gas emissions, as for cumulative energy demand. This proves the importance of considering more environmental indicators than greenhouse gas emissions to obtain a holistic information basis.

3.1.3 Definition of user phase or operation

The perception and understanding of the term operation is not unambiguous. Figure 1 shows a typical environmental profile as a result of an LCA [9]. The phases and terms are in accordance with the MOMD-term – management, operation, maintenance and development and in addition end of life is included.

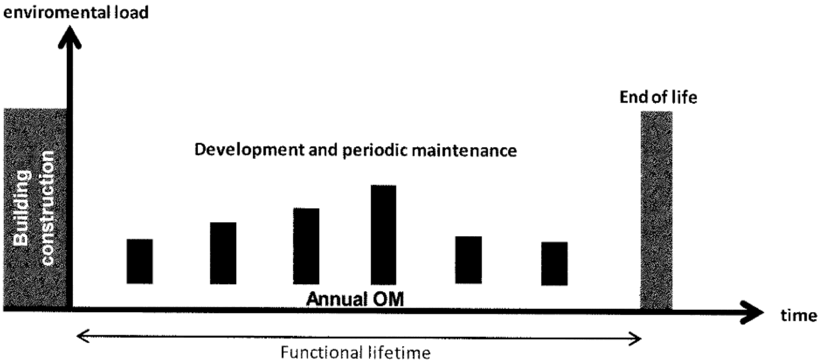

Fig. 1: Life cycle phases of a building [9]

Some studies are defining operation as use of energy for heating and cooling [17]. Other includes lighting, use of technical equipment and appliances in addition [18]. In the first case one can question whether lighting and use of technical equipment are explicitly included since it is hard to address the total energy used to different purposes. Other operation related activities like e.g. cleaning and inspection technical equipment are a part of daily operation of the building, but seldom included in LCAs. At the same time will design and choice of materials and equipment affect the need for and type of e.g. cleaning [15].

It is a challenge for the credibility of LCA results that the phases maintenance, replacement and development are excluded from the analysis. With that the total environmental performance through the life span of the building is under estimated. And the results from those studies are not presenting in real terms what life cycle phases are important and for what conditions they are important [7, 17]. Thus, design focused upon adaptability and use pattern is of more important than the building materials and products itself [15, 19-22].

The average rental period for office buildings in Norway is 7 years. Every seventh year the building is undertaken an extensive rebuilding due to new renters needs and requirements [15]. How extensive the rebuilding processes will be, is depending on the building's degree of adaptability.

This review study found no LCAs simulating consequences different use patterns have on the total energy use or other environmental aspects. This is interesting due to the fact that use pattern affect the energy use vitally. Comparison of five two-person households living in exactly equal houses in the same area shows that the variation between lowest and highest energy use for heating was 4.000-14.600 kWh/yr [23].

3.1.4 Factor of time

Estimated time, for which the LCA is undertaken, is of vital importance for the results due to a relatively long service life [19, 24, 25]. The choice of service life period (SLP) influence the climate impact vitally and the range in SLP is found to be 20-100 years in the literature. SLP is defines as the period where no changes of the building occur.

With the exception of service life predictions the factor of time has not been dealt with in LCA until now [25]. Changes over time, being changes in the building and changes in technology, are not mentioned. If SLP will last during the whole life of the building, then there is no need for high adaptability, e.g. an opera building. But, in those cases where SLP is short e.g. hospitals or private houses were changes occur due to new technology or changes in household and use pattern the different those aspects should be included in an LCA. So far mainly static factors such as energy for operation and maintenance are taken into account in LCAs [25]. Aspects related to adaptability; re-design, changes in use pattern and functionality are often neglected in LCAs. Adaptable buildings give lower refurbishments cost and then total low life cycle costs [25].

On the other hand LCAs are often based on technical service life for products given by producers. Then this will again be basis for defining scenarios for maintenance, repair, replacement etc. to be included in the LCA. This often leads to prediction of use phase activities which not reflect real life. Studies of SLP in practice, shows that the real SLP differ considerably from the SLP given by producers [27, 28]. The building product itself can satisfy the given requirements, but it may be other factors that define how and when changes occur, e.g. design and colour trends influence the need for paining and not necessarily the need for maintenance the set the frequency for panting.

3.1.5 Transport

Several studies conclude when doing LCA of buildings for planning purposes, especially regional planning, one should include transport activities related to use of the building. Transport may contribute to as high as 50 per cent of the total energy use [29, 33]. Transport of construction workers are not insignificant and are excluded in most studies [34]. On the other hand, LCA standards do not require transport of users (or workers) as a consequence of localisation to be included in LCAs.

3.2 Will the production phase become as important as the operational phase for low energy building?

A building material's impact on an entire buildings total energy use throughout the use phase has large influence on the results, as shown in earlier chapters. As the buildings become more and more energy efficient, the importance of the emissions from the production of the building materials increases [35-41]. Hubermann and Pearlmutter [41] give an example where upstream energy use is responsible for 60% of the total energy use. Dependent on type of building, location and type of model applied for the calculations of CO_2 factor for electricity, the balance between the impacts from each life cycle phase may shift even more. Simultaneously, awareness should be raised with regard to interaction between the life cycle phases. A narrow focus on the importance of each individual life cycle stage must not lead to ignorance of the significance of choices done when designing the building, such as choice of building materials, as these choices has large impact life cycle of a building [17].
Sartori and Hestnes have performed a literature review where the objective was to clarify the relative importance of energy use during operation opposed to energy use in upstream processes, including energy use to extraction of raw materials, production of building materials and on site construction and transport to site - especially related to low energy buildings [39]. Most of the 60 cases studied concluded that energy use during operation represent the largest contribution, and that low energy buildings are more energy efficient than conventional buildings although energy use for production of (upstream) materials increases.

4 Discussion

To ensure greater use of life cycle considerations, focus should be on the challenges along two axes: on the one hand, to strengthen the credibility of the underlying data and calculation methods of LCAs and on the other hand facilitate the use of results in actual construction processes, companies' product development and overall priorities at the state and municipal levels. There are a number of measures that could increase the use of lifetime considerations along the two axes. Examples of such measures could be:

Methodology – strengthen the credibility of calculations:

- Ensure equal calculation methodologies for LCAs of building materials, though the development of product category rules (PCR) for building materials and composite building elements such as external wall solutions, roof structures and floors
- Develop and make data available; establish key values or databases with realistic lifetimes for maintenance and development phases and investigate the relationship between user patterns and energy consumption
- Clarify the relationship between the building's adaptability and consequences on maintenance and replacements.
- Establish consensus on how the environmental data for different building materials can be calculated on the entire building's lifecycle; i.e. how to connect the material properties and technical properties different materials have, singularly or in combination with other materials

Encourage increased use of LCA in decision making processes and policy formulation:

- Clarify what environmental information decision-makers need in the various phases of the construction process
- Increase knowledge in the industry about the relationship between choices in the construction process and environmental performance through, for example, training courses, education and other outreach
- Integrate LCA results in existing tools that are traditionally used in the construction process (e.g. BIM)
- Encourage the private sector to increase their focus and knowledge of their own products by requiring the use of LCAs in the tender processes, in relation to new construction processes, rehabilitation and maintenance
- Encourage increased use of interaction processes in public development projects, where LCA can be used as a communication forum though simulation of the environmental consequences of choice
- Require LCA documentation with future scenarios for buildings of a given size in building permit procedures

5 Conclusion

Based on the reviewed LCA literature, we highlight the following main findings;

- The environmental impacts and energy consumption associated with the operation, maintenance and development phases (OMD) are of great and greater importance than the production of various materials.
- For low energy buildings, the relative importance of the production of building materials will increase.
- There is no basis to claim that one kind of building material should be prioritised over another with regard to environmental impacts.
- Through the inclusion of the overarching choices of solutions, which means that more phases and activities will be incorporated in the LCA, the total environmental loads through the building's life span will increase. The importance and scope of the various phases will depend on the purpose of the analysis, the type of construction, user patterns and more.
- LCA as a method makes it possible to assess the environmental consequences of different choices during the early planning stages, the design phase and the MOMD stage.
- Because it within the LCA modelling is given opportunities to make large variations in terms of calculation methods, it will be possible to get different results with regard to environmental impacts. The variations are explained in relation to the purpose of the study, the available data used and the quality of the data used as well as how the system boundaries are determined (which phases to include / exclude).
- Excising models and methods for calculating the LCA presents results in a form that is not necessarily adapted to the specific actors in the construction industry's need for environmental information. Neither are they adapted to existing tools which traditionally are used in the building process.
- LCAs are mostly used for documenting the consequences of already established choices and decisions or completed construction projects, and are to a lesser extent used as a planning tool for simulation of consequences of different choices in various phases of the construction process or though the lifetime of a building.

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9.3 DISCUSSION

The request from the Ministry of Local Government and Regional Development specified the status regarding how to compare the climate impact of different construction materials and how this is translated into a life cycle perspective (LCA). It also specified a description of the knowledge platform these assessments were based on.

Here I will highlight some of the main findings from the literature review and then link these to the official Norwegian environmental and building policy as described in Chapter 1.3, and show how these findings were included in Parliamentary Report No. 28 (2011-2012) 'Good buildings for a better society'.

An overarching conclusion from the review was that there was no basis to claim that one building material should be given priority over another with regard to environmental impacts when using an LCA approach where all life cycle stages were taken into consideration. It was striking that all life cycle stages were often *not included* in the LCA studies examined. Several LCA studies that compared wood-based construction products with other construction materials were identified and what most of them had in common was that they were commissioned by actors with a vested interest in the wood industry. These studies were conducted as cradle-to-gate LCAs and did not include energy use or other scenarios for the use phase and end-of-life. These assessments showed that wood-based products had lower emissions of greenhouse gases than other construction products based on other materials (Petersen and Solberg, 2002; Petersen and Solberg, 2005; Werner and Richter, 2007; Sathre and O'Connor, 2010).

Studies of concrete and metal products in buildings paid greater attention to a building's energy consumption in the use phase, and showed that the main environmental impact occurred in the use phase, related to energy consumption for operating the building (Gerilla et al., 2007; Zhang et al., 2007; Guggemos and Horvath, 2005). Common to these materials was a powerful environmental impact in the production stage, which meant that it was important and in the interest of these industries to communicate the qualities of the products at the building level by including the use phase.

In studies of insulation materials, the use phase also showed the greatest environmental impact, since the function of the material is directly related to energy use in the building (Schmidt et al., 2004; Papadopoulos and Giama, 2007). The results of comparisons of various insulation materials were therefore largely dependent on the functional unit; this could for example merely reflect the amount of insulation material or also include insulation performance over a defined lifetime (Schmidt et al., 2003).

As stated in Chapter 9.2, the general conclusion and assertion verified by the literature review was that energy use for operation contributes 70-90 percent of the total during the lifespan (Rønning et al., 2001; Vold et al., 2006; Fernandez, 2007; Barrett and Wiedmann, 2007; Sartori and Hestnes, 2007; Rønning et al., 2007; Dimoudi and Tompa, 2008; Bribián et al., 2009; Ortiz et al., 2009).

Studies of new buildings show that if they are energy-efficient, the raw materials and production can have an equally great environmental impact as the use phase (Hubermann and Pearlmutter, 2008). This was confirmed by Sartori and Hestnes (2007), who performed a literature review where one main conclusion was that low energy buildings are more energy-efficient than conventional buildings, although the energy use for production of the materials increases. On the basis of these findings, energy consumed during production, transportation and construction of a building was verified to be relatively more important in an LCA.

It is also important to point out that it was discovered that the use phase was often only related to heating a building and that a conclusion involving a change of emphasis whereby the production phase was equally or more important needed to be reconsidered. Several of these studies made no mention of indirect energy use associated with e.g. MOMD. Indirect energy use is defined as the use of energy that goes into producing materials and energy to perform e.g. the maintenance and development of a building ('embodied energy'). Thus, in the trend towards low-energy buildings, the environmental impacts and energy consumption associated with the maintenance, replacement and development phases were considered to be of greater importance than the future operation of the building. Such activities will again increase emissions and resource use from e.g. the production of new building materials and products.

The environmental performance of buildings depends on many factors, such as how they are designed, what they are made of, where they are located and how they are used. Adaptability and patterns of use were found to be of more importance as design factors than the building materials and products themselves, as the latter are a consequence of those factors (Erlandsson and Borg, 2003; Davison et al., 2006; Gibb et al., 2007; Manewa et al., 2009). Further, high replacement rates of materials with high embodied energy as a consequence of low adaptability or changes of the function of the building will have a greater impact on life cycle performance.

In a study by Danish Building Research Institute, a comparison of five two-person households living in exactly equal houses in the same area showed that the variation between lowest and highest energy use for heating was 4.000-14.600 kWh/yr, Gram-Hanssen (2010). This illustrates the importance of defining the function of a building including user behaviour. The review study found no LCAs simulating consequences different use patterns will have on the total energy use or other environmental aspects.

This is interesting due to the fact that use pattern affects the energy use for operation vitally.

The literature study made it clear that because LCA modelling allows for large variations in calculation methods, different results may be obtained with regard to environmental impacts. The variations are explained by the purpose of the study, the available data and the quality of the data used as well as how the system boundaries are determined (which phases to include/exclude). Thus, it was concluded that the performance of an LCA should be contextualised and reflect the actual purpose of the study.

As the literature review revealed limited use of LCAs in the building sector, diverse interpretations of how to conduct an LCA and to a certain degree even misuse of results, input was provided on how to proceed to ensure greater use of life cycle considerations. The focus should be on challenges along two axes: on the one hand, to strengthen the credibility of the underlying data and calculation methods of LCAs, and on the other hand, to facilitate the use of results in actual construction processes, product development in companies and overall priorities at state and municipal levels.

As mentioned in the beginning of this chapter, the project report was a contribution to the political processes related to the issues launched in the "wood and concrete war." Here the project was based on knowledge linked to the emphasis of the previous projects (7 and 8) on product neutrality in analytical models. The order from KRD, however, still included the well-known problems associated with comparisons of building materials, but now allowed for a more comprehensive perspective (for example, a focus on energy consumption in the use phase), which enabled a discussion on the basis of the knowledge established through the Jomar project.

As shown in Chapter 3, there was a change in the Government's approach to the environmental friendliness of construction materials in the last period of the 'war' as presented here. This was particularly prominent in Parliamentary Report No. 28 (2011-2012) 'Good buildings for a better society. A progressive building policy', which recommended increasing the use of EPDs and making them a requirement in the upcoming new building regulations. These recommendations also implied a focus on strengthening the analytical methods and ensuring their use, thus 'liberating' the strategies from the link to agriculture and forestry policy, which was one of the problems in relation to the ESA decision (Chapter 1.3.2). While wood was for many years prioritised as a building material - and the parliamentary report still highlighted wood as a very eco-friendly building material - the foundation had now been laid for a more open, contextual, approach to this question. It was now stated:

'The environmental impact from the use of materials in buildings can be improved by using construction products and methods that reduce resource use, energy consumption, the use of substances hazardous to health and the environment and the

type and quantity of waste. In addition, the environmental impact from materials will depend on how they affect the operation of the building, how often they are replaced, maintenance requirements and the lifetime of the building. A life cycle analysis of a building will provide useful information about the total environmental impact of the materials used in the building' (Parliamentary Report No. 28 (2011-2012): p.65).

EPD as an environmental tool is closely related to LCA, as an 'executive', more concise tool that is politically and administratively simpler. This shift in political focus should be seen in the context of the processes involved in the 'wood and concrete war'. These took place in the form of discussions and industrial policy initiatives, and were at various times, as we have shown above, communicated as reports and public policies.

The parliamentary report also focused on the need to increase the use of EPDs in the construction industry. Here, too, formulations from the project report were used in Parliamentary Report No. 28:

"Today there are few construction products with EPDs in Norway, and there is therefore little demand for them. Statsbygg's environmental strategy involves laying down requirements for documentation in the form of EPDs or the equivalent for the five to ten most used materials in the construction and renovation of buildings......... The Government will facilitate efforts to intensify work on EPDs and in the next revision of the building regulations will consider stricter requirements for environmental documentation" (Parliamentary Report No. 28 (2011-2012): p.66).

The conclusions of the parliamentary report regarding the demand for a broader perspective on environmental analysis and greater use of EPDs in line with the recommendations of the project report were formulated as follows:

"The Government will:

- *consider whether the next revision of the building regulations shall stipulate that the environmental impact of construction products must be documented by environmental product declarations (EPD), official environmental labels or the equivalent.*
- *facilitate efforts to intensify work on EPDs and cooperation between EPD Norway and Stiftelsen Miljømerking on common documentation requirements" (Parliamentary Report No. 28 (2011-2012): p.66).*

The parliamentary report was largely a confirmation that the approaches presented in the project report now became the basis for official policy in this field. This also meant that many of the issues that had formed the background to the 'wood and concrete war' were now downplayed, and that there was political acceptance of more complex and nuanced knowledge for the further development of environmental policies in this field.

10 ADDING SPESIFISITY TO CALCULATIONS

10.1 INTRODUCTION

As mentioned in 0, where I described my first LCA project for cement and concrete, carbonation was discussed and to some extent attempted to be included in the analysis. Already at that stage, it was obvious to the participants that CO2 uptake in the carbonation of concrete would affect the total greenhouse gas emissions associated with concrete products. But it was also clearly too complicated to include this in the analysis at that point, since there was no agreement on how to calculate it in terms of the extent of the contribution of CO2 uptake by carbonation and the relevant stage in the life cycle of concrete products. The researchers saw this uncertainty as a factor that would undermine the credibility of the calculations.

The carbonation of concrete can diminish the quality of reinforced concrete products, as the steel is oxidised and degraded, which is an undesirable effect. From the perspective of the industry, this was probably one of the main reasons why it took another 20 years until carbonation was again emphasised as part of a comprehensive basis for LCA calculations, and thus also documented in EPDs.

Quantification of CO2 uptake is also a known problem in LCAs, which include bio-based materials, such as wood-based building materials. Here, the uptake of CO2 takes place at a completely different stage from in concrete, since carbon dioxide from the air is absorbed while trees are growing. In the life of the building material, this carbon is stored in the product. When the wood is burned in an incinerator after use, the same amount of CO2 will be released. It is quite common to exclude emissions of biogenic CO2 in LCA calculations, since it is assumed that the uptake of the same amount of CO2 takes place within the system limits and an acceptable timeframe, so that net emissions equal zero. In this context, both the concrete industry and the LCA community have raised the relevance of this issue to discuss whether life cycle thinking should also be applicable to the carbon cycle of concrete.

As the numbers of EPDs required by clients increased, together with a growing need for more specific numbers for greenhouse gas emissions from the life cycle of construction products, the importance of capturing all relevant and reliable information in EPDs also increased. Therefore, in 2013 the environmental committee of the Norwegian Concrete Association initiated the project ‘CO2 binding by concrete’. Specifically, this involves a direct link to the ‘war’ in the desire to include carbonation, which reduces the greenhouse gas emissions from concrete in the calculations. This is thus a ‘response’ to issues that originated in the basis of the ‘wood and concrete war' as it was first defined. This is a parallel process to that of the timber industry, which is keen to refine methods of calculating biogenic carbon (Levasseur et al., 2013; Tellnes et al., 2012; Tellnes et al., 2104).

The project consisted of two sub-projects. The objective of the first sub-project was to estimate the total CO2 binding in the Norwegian concrete building stock during service life and in the recovery phase due to carbonation of concrete (Engelsen and Justnes, 2014). The estimates were based on the latest data and modelling tools for CO2 binding in concrete carbonation. SINTEF Byggforsk was given responsibility for this work as they represented supplementary knowledge of concrete chemistry and were not LCA experts.

The second part was led by Ostfold Research. Here the objective was to evaluate the feasibility of including CO2 uptake by carbonation in life cycle assessments (LCA) and environmental declarations (EPD), using a literature review and applying the results from the first part of the project. This was done by examining the effect of including CO2 binding by concrete carbonation in the EPDs of three construction products: inner wall, hollow core slab and roof tiles. CO2 binding was included both in the user stage and after the end of life stage. The quantification of carbonation as part of GWP was based upon the estimates for CO2 binding by concrete carbonation of Engelsen and Justnes (2014).

This chapter is based on the report 'Carbon uptake in concrete in LCA and EPD. Status and recommendations' (in Norwegian), Lyng et al. (2014). The study was presented at the International Concrete Sustainable Conference in Washington DC in May 2016.

10.2 CO_2-BINDING BY CONCRETE CARBONATION

Carbonation is a well-known ageing process in concrete. As thermodynamically stable CaCO3 is formed when air or water-borne CO2 dissolves in concrete pore water, it can be regarded as a natural process in time. Roughly described, when the carbonation layer is formed during service life, the carbonate species need to penetrate through the denser carbonated layer and thus ever deeper into the concrete, and the carbonation rate slows down with the square root of time (Engelsen and Justnes, 2014).

When concrete structures are demolished and refined to Recycled Concrete Aggregates (RCA), the surface area is greatly increased. The CO2 binding rate per unit mass of concrete and thus the total amount of CO2 binding may therefore increase in the recovery phase (after the demolishing stage), provided sufficient access to CO2.

One of the first estimates of how much CO2 could be bound in concrete due to carbonation was made by Jahren (1998). In this study, 5-25% of the CO2 released from cement production was anticipated to be bound globally in concrete during its service life because of carbonation. In a more systematic study, a CO2 binding of 11% was found, i.e. 112 kg CO2 per ton of cement clinker produced (Jacobsen and Jahren, 2001). The assumption was a service life of only 20 years and a recovery phase where 10% by mass of annual Norwegian concrete production was converted to RCAs for which the remaining depth was carbonated.

Since a number of parameters control the carbonation process, the challenge is to provide more precise estimates regarding for example a concrete strength class or an exposure scenario. This is also reflected in several studies conducted during the past 10 years (e.g. Kjellsen et al., 2005; Kikkuchi and Kuroda, 2011; Talukdar et al., 2012a-b). In short, these studies focus on carbonation speed in various climatic conditions and for different concrete qualities, the effect of the recovery phase and the carbonation degree (the amount of CaO available for carbonation).

Engelsen and Justnes (2014) further elaborate these important aspects and their model forms the basis of the calculation of CO2 binding by concrete presented in this paper. The authors conclude that the available CaO content for normal carbonation is around 72% of the total CaO. The calculated quantity of CaO is in line with previous studies (Engelsen et al, 2014; Engelsen et al., 2005; Lagerblad, 2005). Furthermore, based on the theoretical binding capacity of Portland cement, the authors calculated the normal binding capacity when applied in concrete to be 330 kg CO2/tonne cement.

10.3 TECHNICAL INFORMATION AND ASSUMPTIONS

The basis for calculations of carbonation for inner wall was an EPD for a wall element from Contiga AS (EPD Norway, 2009). For hollow core slab, the EPD for Contiga's product was used (EPD Norway, 2013). No EPD exists for roof tiles in the Norwegian EPD system. Thus, Ostfold Research's web-based EPD generator for concrete products was applied to produce LCA results for a roof tile (Vold et al. 2012). The functional units used were 1 m^2 for inner wall and hollow core, and 1 roof tile.

It was assumed that both the inner wall and the hollow core would be demolished after end of service life. In practice, 65% of concrete products are refined to RCA in Norway (Rønning et al., 2016). Even though the remaining 35% will carbonate, it was decided to use the conservative value of 65% in the study. Concrete grades M60 and CEM I were selected for inner wall and M40 for hollow core.

It was also assumed that the roof tiles were demolished after end of service life and recycled. A k value of 1 will be representative (>35 MPa) for an exposed surface (Engelsen and Justnes, 2014). This is weather dependent and subject to a variety of weather conditions; in Norway with very humid environments, carbonation speed is lower and approaches k = 0.75. Some roof tiles are coated and as coating of surfaces slows down the carbonation rate, a conservative k value of 0.7 was chosen.

The technical information is presented in Table 10.1 as a basis for calculations; it shows the functional unit, product dimensions, binding capacity, k value and carbonation depth for the three products.

Table 10.1 Functional units and product dimensions for the three products

	Inner wall	Hollow core slab	Roof tile
Functional unit	1 m^2	1 m^2	1 tile
Thickness mm	180	320	14
Length m	1	1	0.42
Width m	1	1	0.37
Volume m^3	0.18	0.32	0.0022
Binding capacity kg CO_2/m^3 concrete	99	142	149
Estimated k value mm/y^2	6	4	0.7

Two different service lifetime scenarios for inner wall and hollow core slab were defined: 60 and 100 years. For roof tile, an additional scenario of 30 years was included. In all scenarios, the exposure time for recycled concrete aggregates was 100 years. It was assumed that the wall and the hollow core slab would be fully demolished at the end of RSL.

10.4 RESULTS

In all scenarios, CO2 binding during the user stage was higher than after demolition. For hollow core slab, approximately 70% of the CO2 binding is related to the user stage, while for inner wall more than 90% relates to this life cycle stage. The calculations were based on an assumption that 65% of the demolished concrete was crushed and available for carbonation for inner wall and hollow core. The remaining 35% was not included in the model, although this part will also bind CO2.

For roof tile, it was assumed that 100% used for roof tile was crushed and available for carbonation. On the other hand, roof tile was fully carbonated after 30 years.

In contrast to Kikuchi and Kuroda (2011), who measured the uptake in real samples and obtained data for the user phase, Collins (2010) assumed that most of the CO2 was absorbed after the end of service life (based on estimates only).

When assessing CO2 binding for a reinforced concrete column during its service life, García-Segura et al. (2014) found that the CO2 binding rate was approximately the same during the user stage and after the end of service life. Engelsen and Justnes (2014) estimated that only 15% of the total CO2 binding occurred after the end of service life.

If individual products are demolished at a 100% rate with a 90% crushing rate after service life, they may carbonate in the range of 69-93% by volume depending on the concrete segment (Engelsen and Justnes, 2014).

Figure 10.1 to Figure 10.3 illustrate the effect of CO2 binding during the user stage and after demolishing for the total GWP (global warming potential), compared to a case where no CO2 binding is included.

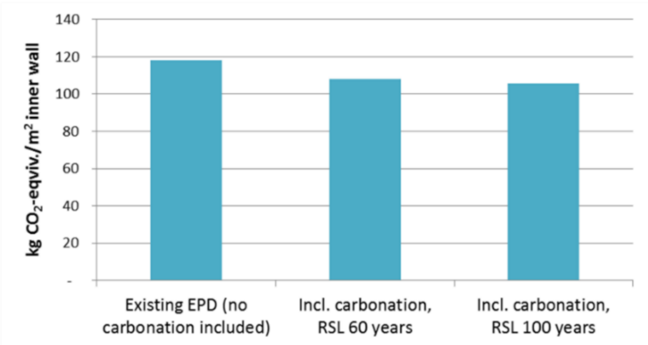

Figure 10.1 Total global warming potential for 3 LCA scenarios for 1 m^2 of concrete inner wall: no CO_2-binding included, CO_2-binding during 60 and 100 years RSL and during 100 years exposure of RCA

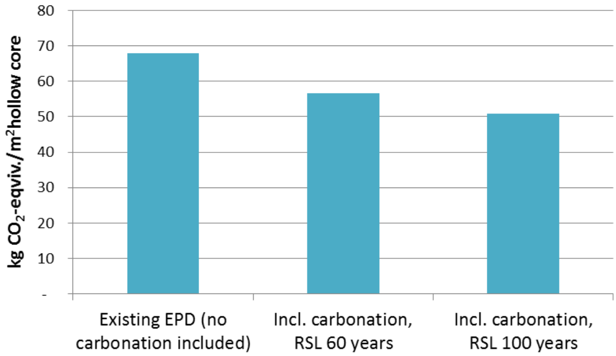

Figure 10.2 Total global warming potential for 3 LCA scenarios for 1 m^2 of hollow core slab: no CO_2-binding included, CO_2-binding during 60 and 100 years RSL and during 100 years exposure of RCA

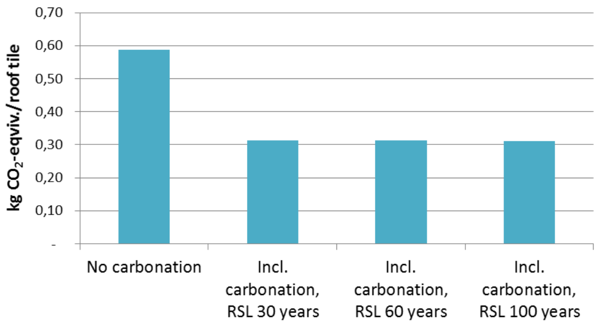

Figure 10.3 Total global warming potential for 4 LCA scenarios for 1 roof tile: no CO_2-binding included, CO_2-binding during 30, 60 and 100 years RSL and during 100 years exposure of RCA

The CO2 binding rate influences the reduction of total GWP value to different degrees. Based on the assumption made in this study, including CO2 binding will decrease the total GWP by 8-11% for inner wall and 17-25% for hollow core slab. The GWP value for roof tile will be 50% lower when CO2 binding is included. This demonstrates that CO2 binding by concrete carbonation has a significant effect on the total GWP for all three concrete products. When assessing CO2 binding for a reinforced concrete column during its service life, García-Segura et al. (2014) found that the user stage represented 22% of the total CO2 emissions. In addition, if the demolished concrete is crushed and recycled as gravel-filling material, the reduction in CO2 emissions reaches 47%. Collins (2010) concluded that CO2 emissions were overestimated for concrete by 13-48%, assuming a service life of 100 years and a recovery phase of 30 years, because binding of CO2 was not considered.

As the degree of CO2 binding in concrete products results from several factors, the study concluded that the scenarios for CO binding stated in EPDs should reflect these factors. Thus, it is necessary to develop a model for different cement types used in different concrete classes applied in different concrete products. In addition, such a model should include the intended use of the concrete products, as it is necessary to assess the degree of exposure. Figure 10.4 illustrates the potential CO2 binding rates for different products when applying such a model.

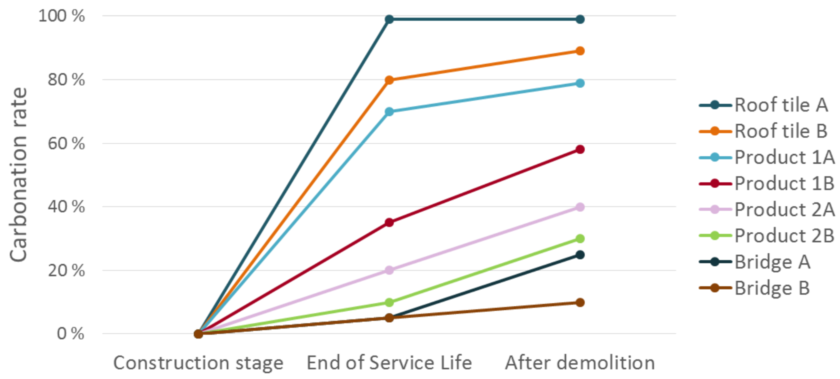

Figure 10.4 CO_2-binding throughout lifetime and after end of life for different concrete products

It is pertinent to develop flexible models that assess specific concrete products, since clients increasingly require manufacturer-specific EPDs.

10.5 DISCUSSION

The project presented here was concerned with enhancing the credibility of the analyses from a scientific perspective by including knowledge related to the chemical processes involved. There was therefore a need to recruit scientific expertise beyond specific LCA competence, and the interdisciplinary expertise underlying this case was absolutely necessary to achieve valid results.

The project also shows that the framework for discussions on eco-friendly buildings has changed since the ‘wood and concrete war’ of the 1990s and 2000s. Today, the actors who establish the basis for such discussions are primarily scientific communities linked to LCA, but now in interdisciplinary collaboration. Taken together with the corresponding discussion of CO_2 emissions related to wood, this shows that the ‘wood and concrete war’ no longer appears as a ‘trade war’, but is generally in the hands of researchers who are primarily concerned with credibility on the basis of LCA and other scientific perspectives.

As the need for specific numbers for e.g. GWP from the life cycle of construction products increases, the importance of capturing all relevant and reliable information in EPDs increases accordingly. During the past decade, knowledge of the capability to estimate CO2 binding by concrete carbonation has increased significantly. This includes better insight into carbonation mechanisms, a greater quantity of field data, and developments of models that calculate CO2 binding by concrete during service life and after end of service life. Thus, reliable models are available for calculating CO_2 binding by concrete carbonation that can be adopted by the LCA community and applied in LCAs and EPDs for concrete products.

Current standards for LCA and EPD allow for the inclusion of carbonation as long as this reflects the purpose and scope of the study and if the underlying LCA report describes how CO2 binding is calculated. Nevertheless, CO2 binding in concrete products is only to a limited extent included in LCA studies (Lyng et al., 2014), while others consider CO2 binding to be negligible (Flower and Sanjayan, 2007). The main reason is that a profound understanding of the chemical mechanisms for CO2 binding is required, and there has been a lack of research on how to perform these calculations applicable to an LCA context (Santero et al., 2011; Lyng et al., 2014).

There is ongoing European standardisation work to develop product category rules (PCR) for concrete products. This work emphasises the inclusion of carbonation when calculating GWP in EPDs for concrete products (EN 16757:2017). In addition, the International Standard ISO 21930:2017 states that carbonation can be included in EPD, but does not specify which method is to be applied.

As shown in the present case, the GWP values given in the EPD for the three concrete products assessed are reduced significantly when CO2 binding by concrete carbonation is included. To obtain reliable results in a life cycle assessment, the credibility of calculations is crucial.

EPDs for construction products are primarily intended to support assessments at construction level and such assessments are contextual. Thus, scenarios at product level given in EPDs should be flexible and allow for the use of different types of cement and concrete, generally reflecting a variety of conditions when used, as illustrated in Figure 10.4. A development of scenarios for buildings, where carbonation is included, require a broad set of knowledge from different actors. In order to form an opinion on the extent of exposure of the concrete in a given structure, there must be knowledge of how the building is managed during its lifetime and how the concrete is handled in the disposal phase. As mentioned, the carbonation after end of life will depend on how the concrete waste is used.

There is a clear political objective for the recycling of construction waste: 70% is to be recycled and is a strong driving force to develop strategies for recycling and reuse of concrete. Developing credible scenarios to document how the construction industry will address this recycling requirement are vital for estimating the potential carbonation rate.

The present case indicates how knowledge develops within the framework of a product and also illustrates how this takes place through the refining of analytical methods within the framework of broad-based LCA/EPD analyses. This reveals that the calculations in EPDs become somewhat more complex when manageability is an initial objective. This dynamic between credibility and manageability will be discussed in the following chapter.

11 DEVELOPMENT OF EPD AS INSTITUTIONAL STANDARD

11.1 INTRODUCTION

The various stakeholders, especially in Norway, involved in the building and construction sector (e.g., designers, manufacturers, users, owners, etc.) are increasingly demanding information to help them address potential effects on the environment that could result from the choices they make for the construction products used in building or infrastructure projects (Selvig et al., 2014, Table 11.2). LCA is the approach used for assessing the potential impacts of construction products and construction works on the environment. EPDs serve as a tool for the documentation of such environmental information for construction products, which can subsequently provide the information needed to support the assessment of the environmental impacts of an entire building or civil engineering works.

Within the LCA framework EPD for products and services is a ‘synthesis’ (executive summary) related to LCA of construction products as discussed (see Chapter 4.3.). Thus, EPD intends to be a *manageable* instrument by users and still with holding the scientific knowledge to make it *credible.* In this chapter I will outline the evolvement of EPD and discuss how, and to what extent, EPD has served as an institutional standard that obtain these goals. The EPD institutionalization process is part of my ‘travels with LCA’ that has become an important part of the LCA discourse. However, until recently not receiving much scientific consideration outside the EPD community.

My work with EPD began in 1997 when the NIMBUS project was established as a joint Nordic project that aimed at developing methodology and establish a system for a Nordic EPD programme, see chapter 1.1. EPD as tool for documentation was introduced in the two previously described cases (cement and Leca industry cases) in the late 90ties. Those manufacturers were front runners in developing methodology for EPD and testing the response in the market for such documentation. Later I became board member and member of technical committee of EPD Norway, developing PCR, reviewing PCR and as verifier of EPDs. In addition, I have held numerous presentations and courses for students, authorities and companies. In 2011, I was offered the position as convenor for ISO/TC59/SC17/WG3 Environmental declaration of products. The main task for this group was to revise ISO 21930:2007. This work was finalised in July 2017 and ISO 21930:2017 replaces the previous standard. My position as convenor for the working group continues and the main task for this group is to develop a standard for how to enable use of digital EPDs in building information modelling (BIM).

The evolvement of EPD as a tool for documentation can be seen as an institutionalisation process embedded by the broader LCA discourse. Following Røvik (2007) this process involves paraphrasing the "concept" as a global standard (de-contextualisation), then a translation process to make the global concept adapted to local contexts (re-contextualisation). I will return to these in the discussion at the end of the chapter. Initially, I will study the evolvement of EPD as three, empirically based, relatively distinct phases:

1. The initial design phase (1995 – 2006): Development of the EPD standard and concept. EPDs were prepared without being based on any regulatory regime; construction product manufacturers early in the value chain were drivers for developing and spreading EPDs in the market without any basis in government policy or any other requirements or formal demands.
2. The transition phase (2007 – 2013): A regulatory regime was established based upon legal requirements. The use of EPDs increases and to some extent EPDs is required in the market as a formal requirement but the content and values representing the environmental profile of the product is not used.
3. The implementation phase (2014 -): The content of the EPD is used as a basis for assessments at the construction works level and for selecting building materials in this context. The dialogue between manufacturers and clients and other actors is an active driver for improvement. Still, a number of challenges can be identified for implementing the EPD standards.

I will here outline these developments, then discuss the present status and the challenges facing EPD.

11.2 PHASE 1 – INITIAL DESIGN

Around 2000, ISO was leading the EPD standardisation process for products and services that resulted in a technical report (ISO/TS 14025:2000). Simultaneously the Nordic Nimbus project was established and Nordic LCA experts together with different industry representatives focused on method development for EPD.

The method for EPD in its early phase made a clear distinction between production of a product (cradle-to-gate) and the use of it, including end of life practices as described by Hanssen et al. (2001). According to Hanssen, this distinction was made due to lack of knowledge on how to develop use stage and end-of-life scenarios, and to provide reliable and quantifiable information regarding these phases of a product.

The motivation for developing EPDs for construction product manufacturers in addition to turn the LCA results into a manageable instrument was to enable communication and dialogue with clients and other actors that decide upon which construction product to be used in a construction works context. Thus, construction product manufacturers emphasised the importance of including information that supported purchasers in choosing the 'correct' product in a certain context and also provide guidance for how to use this product correctly - described in both my case projects for the cement and Leca manufactures, see 5 and 6. It was therefore considered essential to include in the EPD how the product will impact different aspects in the use phase of its intended application.

The ISO standardisation process for EPDs for all products and services proceeded in the initial phase, and resulted in an EPD standard in 2006 (ISO 14025:2006), the technical committee TC 59 responsible for building and civil engineering works, had in parallel developed an EPD standard for building products (ISO 21930:2007). In this manner, the improved method for EPD for building products added more specificity to how to declare environmental impacts of products in a building context.

As an outcome of the NIMBUS project, the Norwegian EPD programme – EPD Norway – was founded in 2002. Manufacturers of construction products were the first to join the EPD Programme and still have the majority of EPDs registered. As programme operator EPD Norway played an important role initially by ensuring that the EPD system was organised and formalised in a credible and trustworthy way.

The first step in designing institutional standards is to gather information from individual projects in context, see 2.5 (Røvik, 2007). During the approximately 10 years' long initial design phase a unified understanding of the methodological basis, what the EPD standard should cover and how the results could be interpreted was established among actors involved. However, the demand for EPDs was still lacking. That could be explained primarily by the fact that no policy regulatory regimes existed, neither did other means for the institutionalisation of EPD. This, however, changed in the second phase of the evolvement of EPD.

11.3 PHASE 2 – TRANSITION

In 2004, the EU Commission mandated environmental standards to be developed where EPDs had a key position (European Commission 2004). Through the standardisation work of CEN/TC350, a suite of standards to support sustainable building assessment were developed, see chapter 4.3. These standards are considered as a further development of those standards established in the initial design phase of EPD. What characterised the development of the EPD standards in the initial phase was that the process was LCA expert driven and the European Commission questioned that the ISO standard ISO21930:2007 for EPDs of construction products could lead to trade barriers and did not provide a sufficient basis for comparison. In addition, no LCA standard to support assessment at construction works level was developed. Besides, more specification was needed that also reflected EU policies, e.g. the Construction Products Regulation[8] (CPR) that lays down harmonised rules for the marketing of construction products in the EU.

The standard EN 15978 was developed to meet the mandated requirements and published in 2011. This standard serves as the calculation standard for LCA of building projects. It includes the possibility to add up LCA-based information in the supply chain (EPDs) and to enable comparisons of the potential impacts from using different products at the construction works level, see Figure 4.5. This reflects the intention of EPDs, which was clarified in this transition phase, which is primarily to support assessments at the construction works level. Looking back on the 'material war', see 1.3, the standards when focusing on 'assessment at construction works level', emphasised turning the discussion from comparison of context free materials or construction products towards whole buildings during their life time.

Based on the mandate and standards developed, requirements for EPDs can be found in the Construction Products Regulation (CPR) by the following statement: '*For the assessment of the sustainable use of resources and of the impact of construction works on the environment, Environmental Product Declarations should be used when available',* EU (305/2011). Thus, the construction product industry in Europe adopted the regulations policy, and EPD was accepted as the tool for documentation of environmental aspect of their products.

In Norway, the 2004 regulations only slowly became policy. Here, EPD was established as a political priority in 2012, as expressed in Parliamentary Report No. 28 (2011-2012) 'Good Buildings for a Better Society', see chapter 1.3. This report showed that EPDs would be required by building commissioners (particularly public agencies). Thus, the official Norwegian environmental policy facilitated for requirement of EPDs by clients and the European Construction Regulation and the European Standards form the basis for the industry to support such requirements.

In parallel to the development of the European and Norwegian policies for sustainability in the construction sectors, some proactive construction clients started first asking for, then require, EPDs. One example is Statsbygg, the Norwegian Government's key advisor in construction and property affairs, building commissioner, property manager and property developer, which aims at a climate-neutral property portfolio and zero-emission construction, thus lowering the Government's climate footprint. For Statsbygg, LCA and EPD provided vital information to support decisions to achieve these goals.

[8] CPR lays down harmonised rules for the marketing of construction products.

As early as 2008, Statsbygg published a press release stating[9]:

> *Manufacturers and suppliers who wish to be considered (for commissioning) are hereby informed that Statsbygg will require environmental documentation for solid products to be used in these buildings. .....*
>
> *......To ensure that the target will be met in this construction project, for the most commonly used construction materials we will primarily request an Environmental Product Declaration (EPD) as environmental documentation, as a basis for our choice.*

Statsbygg later on continued this strategy of requiring EPDs, which is also seen in other public projects. The municipalities of Oslo, Bærum, Asker and Drammen are partners in FutureBuilt, a ten-year programme (2010 – 2020). This programme is part of 'Cities of the Future', a partnership between the government and the 13 largest cities in Norway, which has as one of its goals to reduce greenhouse gas emissions. During this period, FutureBuilt will implement 50 exemplary projects with a 50 percent reduction in greenhouse gas emissions from transport, energy use and material use, in comparison with current practice. This will include the use of climate-friendly construction products. As a basis for the assessment of climate-friendly construction products, EPD is used for documentation of the main construction products, www.futurebuilt.no.

In addition, the Agency for Public Management and eGovernment (Difi) stated in its recommended procurement criteria for contract work in connection with public procurement that the entrepreneur has to present the EPD for the 10 most important construction products (by weight).

In parallel to the establishing of a regulatory regime, other actors in addition to the manufacturers, as Green Building Councils[10] around the world, became active in the field of 'green buildings'. One of their strategies for achieving green buildings was rating or certification systems. They are used to assess and recognise buildings which meet certain green requirements or standards. BREEAM[11] and LEED[12] are examples of such systems. These building certification schemes give credits for building projects involving a certain number of products with EPDs. The US-based LEED scheme does not use any kind of quantitative information about the life cycle

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[9] http://www.statsbygg.no/Aktuelt/Nyheter/Miljodokumentasjon-i-R6/

[10] Green Building Councils (NBG) are independent, non-profit organisations made up of businesses and organisations working in the building and construction industry

[11] BREEAM – Building Research Establishment Environmental Assessment Method

[12] LEED – Leadership in Energy and Environmental Design

environmental performance of materials and products. However, it gives credit if EPDs are available.

In Norway, the BREEAM-NOR method is used, a version adapted to the Norwegian context. BREEAM-NOR is '*a measure and mark of a building's sustainable qualities'*, NGBC (2016). The method examines scientifically based criteria covering a range of issues in sections that evaluate energy and water use, health and wellbeing, pollution, transport, materials, waste, land use, ecology and management processes. Buildings are rated and certified on a scale of 'Pass', 'Good', 'Very Good', 'Excellent' and 'Outstanding'. It is particularly in the materials category that points can be scored for EPD and LCA. The aim is to recognise and encourage the use of construction materials with a low environmental impact (including embodied carbon) over the full life cycle of the building.

In this period, manufacturers experienced an increased demand for EPDs. Some manufacturers of construction products are small enterprises that had limited resources dedicated to environmental affairs, e.g. ready mix concrete producers (less than 5 employees). Thus, disclosure of EPDs to tenders were only possible for larger manufacturers. Norwegian Ready Mixed Concrete and Precast Concrete Federations saw the need to simplify the process of developing EPDs for their members. Concrete producers typically produce different products for which the concrete composition varies from project to project. However, there are usually a limited number of ingredients that are mixed in different proportions. Thus, the Norwegian Ready Mixed Concrete and Precast Concrete Federations initiated development of a first excel based, then online tool that calculated EPD. The EPD-generator simplified the process and gave the concrete manufacturers the opportunity to develop EPDs for their products themselves. Ostfold Research was commissioned to develop this tool (Vold et al., 2016).

This has entailed an institutionalisation process whereby EPDs are increasingly being produced, both in Norway and abroad, as a formal requirement. However, the EPD results were not used initially. The EPDs was at this stage mostly a symbolic requirement in the sense that clients were at that time not concerned about the actual numbers (results) the EPD provided, but more the fact that the manufactures could provide such a document on request.

11.4 PHASE 3 – IMPLEMENTATION PHASE

In the third phase, however, different actors got actively involved and were applying the results in specific decision-making processes. The number of published and available EPDs has been increasing in recent years. A survey by Anderson (2017) in February 2017 found that over 3500 verified EPDs are compliant with the European standard EN 15804 from different programme operators in the various countries that have EPD programmes. The corresponding number was 2600 a year earlier. The number of published EPDs by programme operator are given in Figure 11.1.

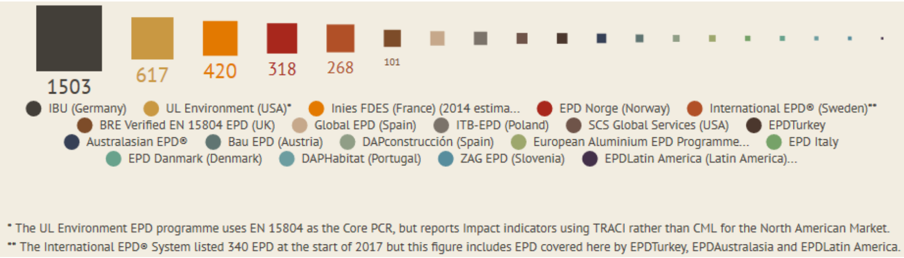

Figure 11.1 Number of EPDs published by different programme operators. Source: Anderson, 2017

Anderson found that more than 20 countries have initiated national or regional construction product EPD programmes and some countries, such as the US, have more than one programme operating. As of February 2017, Germany has more than 1500 EPDs, while EPD Norway had published more than 300.

As described in the previous chapter, verified EPD generators have been developed to allow manufacturers to adopt EPDs directly to projects that require project specific EPDs for construction products with given combinations of raw materials (Vold et al., 2016). In table x an overview of number of EPDs developed in Norway for different purposes by February 2017.

Table 11.1 Number of EPDs generated by the EPD-generator for different purposes per February 2017.

Type of EPD	**No.**
Published EPDs (EPD-Norway)	90
Project specific EPDs	450
EPDs used for internal simulation for improvements	400

Typically, a construction works commissioner require e.g. concrete product with a low carbon cement documented by EPD. The Nordic cement manufacturers have published EPDs for appr. 20 different cement qualities all together. These EPDs are again data source for EPD development for concrete products and mortar. Thus, the manufacturers can make the EPD based on the specific concrete products size, quality, composition including the specific cement type for the actual cement manufacturer, including specific transport distance and transport type to the given construction site.

In addition, the EPD generator is used for simulation of potential means for improvements. And as cement is a raw material for some products, an active dialogue is established between the concrete and cement manufacturer to improve the concrete products. This is an example of four different actors along the value chain interacting based on the information given by EPD; the commissionaire set environmental target for the project, the entrepreneur is responsible to implement the targets in the clients brief by e.g. require products with a limited GHG value, the concrete product manufacturer has to deliver product that satisfy the requirement and the cement manufacturer has to fulfil the requirements set by the concrete manufacturer.

The use of EPD in different projects has increased significantly the last few years. One of the users of the EPD generator, Norbetong, has experienced a quite significant development in demand for EPDs and project spesific EPDs. In the period 2011-2015 the number of environmental ambiosious projects that Norbetong was involved in, increased from 2 to 23. At the same time the demand for project spesific EPDs increase fom 2 to over 60 (Fredvik, 2016).

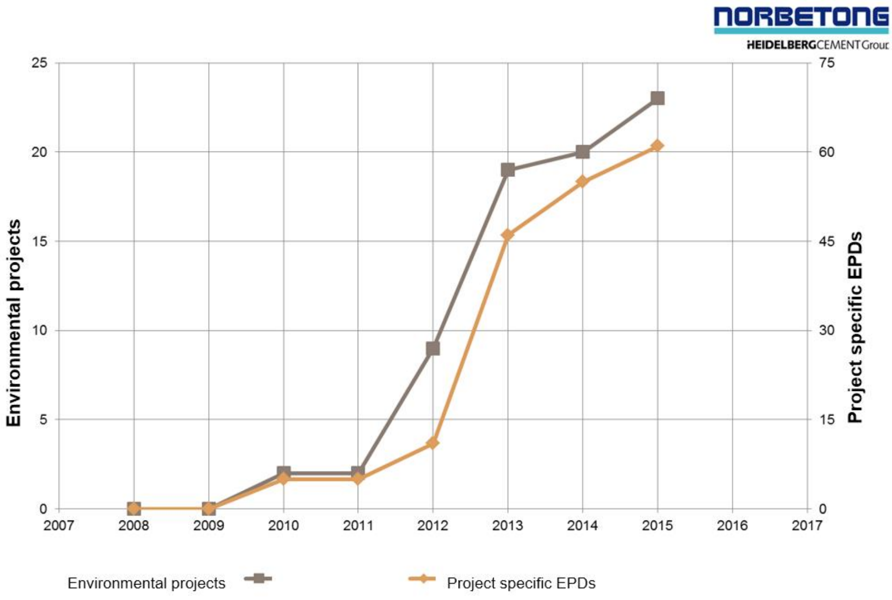

Figure 11.2 Development of request for project specific EPD and environmental projects, Source: Fredvik, 2016.

In Table 11.2 an overview of some of those actors in Norway that have environmental strategies developed and criterias that includes EPD or LCA based information. It should be noted that companies' strategies and criterias are more comprehensive than reproduced in this table.

Table 11.2 ***Actors requiring EPD. Adopted from Pettersen (2016).***

Actors	Characteristic	Environmental criteria
Statsbygg	400 000 kvm 100 ongoing larger projects	• Min 10-15 EPDs for different product groups • Product with lowest env. Load is intended to be used • For some product groups, a max limit for CO2-emission per functional unit
The Norwegian National Rail Administration	Responsible for owning, maintaining, operating and developing the Norwegian railway network	• EPD for the 10 most important construction materials (cement, concrete, mortar, steel, insulation, stone, gravel and fibre cables. • EPD shall include transport to Norway for imported products
The Norwegian Defence Estates Agency	4 100 000 kvm	EPD for min. 5 of 6 main product groups
Omsorgsbygg (property management company, Oslo)	900 000 kvm	EPD for the 20 most used construction materials
NTP 2018-2029	Nastonal action plan for transport	• In the draft NTP (2018-2029): • 40 % reduction of GHG from infrastructure projects (LCA) • EPD and products localy produced (short travel distance) will have a sentral position • To be presented in Parliamentary Report during 2017
Avinor	Responsible for 46 state-owned airports	• EPD for products and services that have significant environmental impact • Some product groups - maximum allowable CO2 emissions per functional unit • Some product groups - Requirements for recycled content

How the EPDs are used in the projects differ. Some actors require EPD for the 10-15 product groups typically e.g. cement, concrete, mortar, steel, insulation, wood based products, stone or gravel. These projects are often linked to BREEAM NOR or FutureBuilt.

In BREEAM NOR there are two level credits available: one for EPDs for building services and one for life cycle impacts of buildings. Thus, both EPDs and LCAs are given credits. Examples of achievable credits:

- One credit is given if at least 15 EPDs (developed and verified according to EN 15804, ISO 14025 or ISO 21930) have been collected for different building products from specific product groups, see Table 32 in the Technical report (NGBC, 2016). Each of the products documented must comprise at least 25% of the given product group's (listed in Table 32) area, volume or weight in order to be given credits.
- The project uses an LCA tool to measure the life cycle environmental impact of the building for at least mandatory building elements. One or two credits, depending on how comprehensive the study is.
- Greenhouse gas emissions from new materials in the building that are reduced by 20% compared to the reference building (see compliance notes) give 1 credit, while reduction by 40% gives 2 credits.

An observation is that the greenhouse gas account is viewed as a limited LCA where only one category of environmental load is analysed and it may thus seem strange that an incomplete LCA can count more than a complete LCA. On the other hand, the greenhouse gas account considers the entire building, while the LCA only contains some building elements.

The FutureBuilt projects have no requirements for an LCA of construction projects, but EPDs are required in order to assess the environmental impact of building materials. A report has been published containing rules for the calculation of greenhouse gases for use in these projects (Selvig et al., 2014). A finding is that products are not considered in a building context, but the following requirements are set: "*When emission factors from EPDs are used, it must be verified that the same definition, i.e. cradle-to-gate, is used*" (Selvig et al., 2014). This means that important aspects of LCA are negated, such as the ambition to capture all life cycle impacts and the connection to functional unit. EPDs thus become detached from a context.

However, comparisons at the sub-construction works level are possible, e.g. for assembled systems, components or services for one or more life cycle stages. In all cases of comparing construction products, the principle that the basis for comparison is the construction works level is to be maintained by ensuring that the same functional requirements are met in addition to e.g. the same functional unit, the exact same type and amount of any materials excluded, the same excluded processes and life cycle stages and the use of equivalent scenarios. The aim is that the EPDs should be information carriers to make up an LCA of the entire building.

What does it mean to ensure that the same functional requirements are met? For insulation products, this does not only apply to insulation performance, but it must be ensured that the insulation covers other functional requirements such as compressive strength and fire and sound properties. This may mean that the functional requirements must be addressed in different ways, such as choosing an insulation product that needs additional sheets of material to meet fire requirements. It is therefore not necessarily possible to make a direct comparison of EPDs for two different insulation products, especially two cradle-to-gate EPDs (A1-A3). An LCA at the building level thus requires a thorough understanding of the properties and function of a construction product in a building context.

To sum up, the experience from implementing EPDs in Norway is that despite of the standards requiring contextualised assessments and comparisons, EPD still seems to act as stand-alone document where the actual number and content (results) to a large extent is neglected or compared by cradle-to-gate data.

This conclusion is supported by Dodd (2016) in a study by the European Commission:

'*The state of the art methodology to evaluate the environmental impacts of different materials is a full LCA. Based on the findings of the study to date, however, this is not currently a common practice in the market and supposes a high level of expertise'.*

Expertise in this context can be understood as LCA expertise, but also related to design, civil engineering or facility management. This supports my findings in nearly all previous case studies, where developing scenarios for use and end-of-life stage are challenging and require other types of knowledge than LCA expertise alone, see 7 and 8.

As an indicator of the problematic or lacking use of the content of EPD, EPD Norway experienced that the results presented in EPDs were often questioned. Thus, a study of 50 EPDs were analysed to determine whether there are 'errors' that could be traced back to the (lack of) understanding requirements of EPD Norway and use of standard EN 15804 (Rønning et al., 2014).

At the time of the study, EPD Norway had published 130 EPDs. Out of these, 50 EPDs were selected as they complied with EN 15804 and the format required by EPD Norway. In addition to the format, EPD Norway made a user guideline on how to interpret the requirements. Examples of misinterpretations were:

- The declared Key Environmental Indicator (KEI) *Energy use* in Norwegian EPDs must equal the figures declared in the resource use table, given as the sum of the four resource use parameters concerning energy. For 12 of 50 EPDs, this was not the case.

- For 12 of 45 EPDs, ADP_E[13] and/or total non-renewable primary resources[14] used as energy were not calculated and/or not declared correctly. ADP_E was not declared at all or was declared higher than total non-renewable primary energy resources, which is not possible as the latter indicator also includes sulphur and uranium (which have energy content) and will always be higher than or equal to ADP_E.
- The ratio between the weight of non-renewable resources used as material and the weight of the product. For 12 of 20 EPDs for roof and waterproofing membranes, the declared amount of non-renewable resources used as material was significantly lower than the weight of the products. As these products are mainly produced from plastic (more than 99%), those results are incorrect. The amount (weight) of resources used should always be equal to or higher than the weight of the product.

This review did not cover all aspects of EPDs and compliance with the user manual. All in all, in 27 of 50 EPDs the methodological specifications given in the user manual had not been applied correctly. The review indicated that both LCA practitioners and verifiers did not follow the user guide correctly.

These errors can partly be explained by EPD practitioners' lack of expertise in LCA. However, one may also question whether these errors and deficiencies should have been identified through verification. Based on these findings, EPD Norway introduced EPD training courses for LCA experts and courses for verifiers. As an offer to users of EPD, guidelines (in Norwegian) for how to interpret EPD for some given construction products are developed[15].

[13] Abiotic depletion potential for fossil resources (ADP_{fossil}) includes all fossil resources (coal, oil, fossil gas) used as energy and material (EN15804:2012+A1:2013)

[14] Total non-renewable primary resources used as an energy carrier. $TNRPR_E$ includes sulphur and uranium (EN15804:2012+A1:2013).

[15] http://epd-norge.no/bruksanvisninger-i-hvordan-tolke-epd-er/category379.html

11.5 DISCUSSION

The institutionalisation process related to institutional standards are – in line with Røvik – generally discussed as two distinctive processes; de-contextualisation and re-contextualisation, see chapter 2.5. The three phases I have outlined above cover these processes, but the institutionalisation of EPD is not linear, but rather a complex interplay of considerations regarding the establishment of the 'standard', the legal integration of the standard in environmental policies, and the application of EPD by different actors. The phases introduced were primarily based upon empirical findings, while the dynamics of EPD institutionalisation happened back and forth between de-contextualisation (by new developments in the EPD standards), and re-contextualisation (the efforts to implement the EPD standards in practical settings; e.g. regarding commissioning). EPD at the present has a status of a global institutional standard, but in line with Røvik – continuously being subject to changes, improvements and further detailing of the scientific knowledge. The dynamics of these changes reflect some of the ambiguities and challenges EPD as a global standard face.

At the outset, EPD was introduced as an instrument to make LCA of products manageable while still retaining the scientific credibility of LCA. Throughout the outlined phases above, scientific credibility was established by continuous 'improvements' in the standard, in particular based upon ISO standardization processes. These standards are, theoretically speaking, made manageable by means of specific rules addressing development of EPDs. A challenge has been that during the initial and part of the transition phase, no method or guidelines (except LCA as such) for assessing buildings were available.

The situation changed when EPD was included in regulatory regimes in Europe and Norway, see chapter 4.3.2. Therefore, recognised and legitimate standards had to be developed in the field, as shown in 4. The following standards for LCA of buildings and products, EN 15978:2011 and EN 15804:2012, specified rules for comparability and use of EPDs in a building context. EPDs are intended to be used in projects where EPDs are transferring information from the product level to assessment of the whole building. Thus, EPDs evolved as a distinctive knowledge base from the goal of creating a more manageable, yet scientifically accurate tool within the framework of the LCA concept. The standardization processes have created uniformity and consistency in the way environmental product declarations are made for construction products and services.

In principle, the standards provide increased credibility and a level of confidence that enables the public to use such information for decision making when choosing and using construction products. This has entailed an institutionalisation process whereby EPDs are increasingly being used, both in Norway and abroad, as a requirement which have practical consequences as clients began to choose construction products based on theirs GWP values in EPDs. At this point in history of EPD development, the document has increased its status from being a piece of paper to prove that the manufacturers knew their products' environmental profile to being a 'value paper'.

Several aspects of the EPD standardization are both paradoxical and challenging:

In order to obtain scientific credibility, the standards are becoming *increasingly complex*. This complexity refers particularly to the relationship between LCA and EPD regarding 'product' and 'building' level of analysis, see chapter 4.3.2. LCA is intended to be used at building level as EPDs are intended to be used at product level, while still feeding the LCA level for several phases in the building's life cycle - see Figure 5.5. The design of an LCA for buildings must rest upon the design of the building, which depends on e.g. technical and functional requirements, climate conditions, and should in principle include all relevant aspects in the analysis as well.

EPDs as information carriers, are often general in the sense that they cover several intended uses for the product, but may declare only one use- and end-of-life scenario. Then, the challenge is that the standards add a contextual perspective and method for LCA at building level, while the EPDs are often general or free from context. This is not necessarily problematic as long as the users of EPD or LCA practitioners have the knowledge to apply the information to determine whether the scenarios stated in the EPDs are representative for the given construction works. One should bear in mind that the developer of EPD for products and LCA for the specific building projects are in general not the same actor. Thus, the implementation process of EPD is dependent upon knowledge related to how to design and perform the LCA and use EPDs in a building context.

The EPD practitioners play an important role regarding both EPD development and how to enable use of EPDs in a building context. As indicated in the evaluation of 50 EPDs performed in Norway, the scientific knowledge, which is the basis of the standard, is not being used in a correct way in many instances, from the point of view of LCA/EPD expertise. In addition, a manufacturer today will have limited basis for understanding how the content of an EPD can and should be used by architects, advisors or builders in making decisions on construction works. The EPD practitioner therefore has a responsibility to comply with the standards that apply to both the development of the EPD and the underlying LCA. At the same time, the EPD practitioner has a role in *translating* these requirements for the manufacturer to enable to obtain information about production and especially about the construction product in question as a basis for designing scenarios. The latter requires that manufactures and their EPD practitioners have extensive knowledge of scenario design at the construction works level. In order for the EPD to be used as a valuable document to create eco-friendly buildings, requirements have to be translated to ensure that the calculations are reliable and that the EPD contains information leading to use of environmental friendly materials.

PART 3 CONCLUSIONS

12 CONCLUSIONS

12.1 INTRODUCTION

In Chapter 1, some features of my ‘travels with LCA’ during appr. 25 years are outlined. One of the challenges when studying this journey is how to combine descriptions of individual projects and the critical reflection on the peculiarities of the evolvement of LCA as a ‘global institutional standard’. This evolvement has taken place at different analytical levels and with shifting foci on what might be the advantages and disadvantages of the LCA concept. My research reflects these features of the general evolution of LCA as well, since I have been involved in LCA at different phases, with different aspects of LCA as an analytical tool, and also from different theoretical angles. To grasp these matters the evolvement of LCA is framed by considering LCA as a ‘global institutional standard’, based upon Røvik (2007). This theoretical understanding implicates that LCA as a standardized concept evolves in a dynamic interaction between ‘de-contextualization’ – to make the standard global – and ‘contextualization’, to make the standard applicable to specific contexts – in my case the construction sector**.** LCA as an institutional standard is characterized by being primarily a technical one. However, one challenge, which has permeated this thesis is that in the processes of standardization, ‘technical’ issues cannot be separated from economic, social and political aspects.

Since the late 1960s, LCA has spread worldwide. This is also the case for LCA in the construction sector. Based upon its status in ISO, EU and governmental policies in a number of European countries, LCA has achieved an almost hegemonic status as an environmental analytical tool in this sector. It is now applied in international organisations, in environmental policy in many countries, and for corporate environmental work. This is why LCA is considered as an ‘institutional global standard’. LCA is, however, not a static analytical instrument developed once and for all. On the contrary, we have seen major changes in its design, methods of calculation and types of application. This has also led to disagreement and uncertainty about the status and role of LCA among scientists working on environmental issues, in political contexts, and in relation to individual results presented in specific environmental analyses of products or services. There are certainly different interests related to the application of LCA, and it cannot be considered a ‘neutral’ or ‘objective’ analytical tool, even though actors involved in the scientific evolvement of LCA might have preferred this. These processes of uncertainty, ambiguity and disagreements reflect that environmental problems are ‘wicked problems’ where final solutions are not at hand (Rittel & Webber 1973).

The research questions rest upon these features of LCA as they are represented in the construction sector. My main research question is: *What has characterised the evolution of LCA as an analytical tool in the construction sector?*

Within the frames of this main question, I presented three research questions:

1. How has LCA been subject to changes related to new knowledge during the years it has been used in the construction sector?
2. How has LCA as analytical tool been linked to other relevant analytical tools?
3. How have the dynamics between different actors involved in the construction sector developed in the studied period?

The empirical background for the answers is the description of the general evolution of LCA, but particularly how these developments have taken place in the construction sector discussed in Part 2. In this chapter, the three research questions will be discussed, then finally relate this discussion to the theoretical approach based upon analyses of 'institutional standards' and 'wicked problems' that was introduced in Part 1.

12.2 HOW LCA HAS BEEN SUBJECT TO CHANGES RELATED TO NEW KNOWLEDGE

When Røvik refers to the tendency of global institutional standards, the key concept is *standardisation*. The institutionalisation process refers to how standards are accepted as legitimate ways of understanding the concept. The evolvement of LCA has focused upon making and (as I will come back to later) re-making standards. The continuous changes in standards, and the fact that international actors (like ISO, CEN, EU, UNEP and US EPA) have formulated different standards, partly rests upon new scientific knowledge, and partly the fact that various interests at different periods of time have succeeded in influencing how standards should be presented in order to achieve legitimacy among users and environmental agencies. LCA standardisation is thus embedded in issues of knowledge and policy. Accordingly, my first research questions addressed this by asking:

> *How has LCA been subject to changes related to new knowledge during the years it has been used in the construction sector?*

The evolvement of knowledge related to LCA in the construction sector illustrates the challenges, dilemmas and ambiguities facing LCA. Rønning and Brekke, see chapter 3, argue that in order to ensure more use of life cycle considerations, focus should be on the challenges along two axes: to strengthen the *credibility* of the underlying data and calculation methods of LCAs, and to *facilitate the use of results* in actual construction processes, companies' product development and overall priorities at the state and municipal levels.

The projects discussed in Part 2 indicate different methods, which aimed to move away from a simplistic - and scientifically problematic - approach reflected in the first LCAs. What did these changes, processes and new knowledge consist of? To answer that question, we must begin with the basic idea on which LCA is intended to fulfil: *avoidance of problem shifts by capturing 'all' life cycle stages and 'all' environmental impacts related to products and services*. This was established from the outset and has been the mantra of the LCA method ever since. In relation to the research question on new knowledge, I will focus on how the LCA method has been influenced by avoiding problem shift.

The first category for avoiding problem shift by using LCA is that the method provides the opportunity to include all life cycle stages and at the same time capture the consequences of the introduction of measures at one stage for other stages. The second category for avoiding problem shift, the capturing of several environmental impacts simultaneously, that aims to minimise the risk connected with introducing a measure to reduce one impact will increase another impact. In other words, it is not obvious what the consequences of decisions made at one place in the value chain will have for the rest, when emissions that leads to one environmental impact are reduced in one place. The measures may lead to increased other emissions that in turn lead to other environmental impacts elsewhere in the value chain.

For construction products applied in buildings or civil engineering works, much of the life cycle is far into the future. This necessitates the use of scenarios and projections to determine the use and disposal phases. Defining scenarios is and has always been to some extent, a part of the design process for both buildings and civil engineering works (e.g. economical and technical life cycle planning). This knowledge formed the backdrop for how many projects attempted to solve the challenges of expanding LCAs for building materials to become LCAs with a whole life cycle and building contextualised perspective.

Both the Nordic cement project and the LIEP project (see chapters 5 and 6) included the entire life cycle of products and several questions needed answers. The questions posed in these projects illustrate these issues: How should the system boundaries be set? How to develop relevant future scenarios? What should be included in the analysis and how can one obtain representative data and information on which to base the scenarios? One specific challenge was how to set system boundaries for road paving. It was obvious that maintenance should be included, but what about emissions related to driving? What about street lighting or road marking?

Both road marking and lighting were included to gain experience in setting broad system boundaries (Häkkinen and Mäkelä, 1996). The results showed that paint for road marking adhered better to asphalt than to concrete; this meant that concrete roads required more frequent maintenance and concrete had thus higher environmental impacts. Another example was road lighting, where concrete had an advantage over asphalt, since a concrete surface is brighter, thus reducing the need for lighting. From a systems perspective, both examples showed the importance of defining system boundaries sufficiently broad to capture important aspects and activities, that can lead to system improvements. On the other hand, asking the questions above, revealed the fact that cement manufacturers often had limited knowledge of what happened to their products in the use and disposal phases of their applications. The lack of knowledge or actors that has the supporting knowledge, implicated that the early scenarios were non-contextual and that data necessary for describing and calculating scenarios were not always representative.

The experience defining scenarios and finding relevant data and information in the early LCA projects, revealed the need to involve actors that contributed with additional knowledge about construction works as the environmental performance depends on many factors, such as how they are designed, what they are made of, where they are located and how they are used. The Jomar project (7) brought new knowledge as it used the Table of Building Elements to qualitatively describe buildings, as well as standards for Specification of Building Cost and Life Cycle Cost as a basis for quantifying activities throughout the life cycle. This provided access to data describing what materials and products are used in a building and how scenarios for OMD based on facility management processes could be included. In this way, the definition of scenarios in LCA was linked to existing methods and knowledges in already ongoing processes in design and use of buildings.

When methods for future studies are integrated in LCA, the methodology not only assesses scenarios, but Ekvall et al. (2007) state that it also assists in *developing* the scenarios that are to be assessed. This complies with the experiences in the Sparebank project **(**see 8), where the project was organised as a collaborative effort, the LCA results were found to constitute a communication platform. This knowledge related to e.g. product properties, building physics, facility management provided by the interaction among different actors, proved necessary for the development of good scenarios. As discussed in 8.4, one may wonder whether the ‘collaborative model’ was a prerequisite for making the required knowledge for designing the LCA, e.g. data for scenarios and system boundaries, and that LCA practitioners would not be able to ‘find’ the data by themselves. Such data can’t be found, they are created by interaction between actors with different knowledge and experiences, often case by case. Clarke and Steward (2003) states that wicked problems require different skills, and can therefore only be solved through work across organizational boundaries.

The system boundaries activity in LCA requires that boundaries must be set not only in terms of space and the included life cycle stages. Time and functional unit (or functional equivalent for buildings) are two factors that influence the assessment when system boundaries are extended to include all life cycle stages and the focus changes from a construction product to an entire construction. The definition of service life is a part of boundary setting in LCA and a premise for defining which life cycle stages and which activities should be included in developing a scenario. This was highlighted by the Jomar project (chapter 7) and was studied more closely in the literature review (chapter 9).

In addition, the estimated service life of construction works is of great importance for the results, as service life is usually relatively long (see chapters 3 and 9). The range was found to be between 20 and 100 years in the literature review study and this will influence the LCA results significantly. In Norway, the tendency is to choose service life as 60 years independent of the specific building analysed, type of building and intended use. In chapter 3, we concluded that LCA should be contextual by focusing on 'use' and 'through the products' life cycle', and the functional unit shall reflect the 'performance' in a given context. In the review study, it was revealed that use pattern will influence the energy for operation of a building significantly; see chapter 9.

The second category of avoiding problem shift, capturing several environmental impacts simultaneously, is intended to minimise the risk that introducing a measure to reduce one impact increases another. Human activities have impacts on the environment which may not easily be quantified in an LCA. Examples of such impacts are noise, encroachment on nature during construction periods, effects on the eco systems, indoor climate. However, in the cement project (chapter 5), efforts were made to include use of land and noise as indicators. This was not found in other studies at the time, but these factors were considered important by the companies involved, because they represented a response to demands placed on manufacturers by various stakeholders in other contexts, although these demands were not directly linked to the products concerned, but rather to the production sites.

The standardisation of the impact assessment stage has mainly been undertaken by ISO/TC 207 that is responsible for the suite of LCA standards, while the standardisation processes by actors in the construction sector have focus more on construction products and construction specific issues. The European standardisation processes have evolved from 'all' environmental impact categories to a set of mandatory impact categories and resource use indicators. This can be explained by the concept of product and building level, where one EPD is information carrier to be aggregated among several other EPDs to support construction works assessment, see 4.3.2, Figure 4.5. Thus, common indicators are necessary for all commodities in the system that are analysed and that it enables to aggregate all these indicators from every single EPD to LCA of a building.

Climate change and climate mitigation were introduced on the political agenda and highly focused in both international and national environmental policies. This again reflects business' priorities; also in the construction sector where it was observed that environmental assessments of buildings and materials largely still take place in the context of capturing embodied energy and greenhouse gases. The risk of unilateral focus on one environmental challenge is that others are ignored, and problem shifts may occur. In addition, future environmental problems related to construction materials or construction technology installed, are not necessarily known or captured, and there is always a risk new like the micro-plastic entering the marine environment. Consequently, the challenges facing knowledge issues related to problem shift in the construction sector is still not 'solved'.

12.3 HOW HAS LCA BEEN LINKED TO OTHER ENVIRONMENTAL ANALYTICAL TOOLS?

My second research question is justified by the fact that from the early days of my journey I took part in LCA projects that involved relations with other environmental tools. The main reason for these couplings was the need for addressing the complexities of environmental science and policy issues. The more LCA in relation to buildings extended its scope, the more additional analytical tools were needed in order to ensure 'comprehensive' evaluation of the eco-friendliness of products and production systems.

During the time of my 'travels', the number of environmental analytical tools has increased substantially. These analytical tools share some commonalities. One characteristic feature is that they are based upon an instrumental, rationalist calculation approach. They also are tools on the same 'playing field' – environmental analytical tools. Wrisberg et al (2002) includes ten such tools for environmental decision support in their review book addressing this issue. Amongst these, seven are about 'physical' flows and three about 'monetary' flows.

As discussed by Guinee et al. (2011), the trend has been towards an expansion of the perspectives in LCA to include economic and social aspects. This has taken place, and, according to Guinee et al., should take place, by *linking LCA to other analytical tools*, such as LCC (Life Cycle Cost) and social aspects such as consumer perspectives (consumer behaviour analysis). The authors therefore propose that the more comprehensive approach involved in this linking strategy is termed 'Life Cycle Sustainability Assessment' (LCSA). This approach is more related to a lifetime perspective than a specific 'model' or a particular tool. This implies an expansion in depth by linking LCA to analyses that '*include other than just technological relations, e.g. ... economic and behavioural relations, etc.*' (Guinee et al.: 93). LCSA thus implies that LCA is connected to other important (economic/social) problems in society, which could be viewed as a strategy to maintain the complexity of the problems LCA seeks to reduce. The standardisation processes in the construction sectors, have grasped this perspective by introducing the three pillars of assessment areas that together intend to assess the sustainability performance of a building; environmental, economic and social performance, see chapter 4.3. Methods for LCA and LCC that are the fundament for the two first pillars are as discussed, developed and applied in practice. The last pillar, social performance, is now being developed.

In my thesis, other tools have variously been linked to LCA as well, and the general impression from the chapters in part 2 is that there has been a tendency to combine LCA and these other analytical tools in accordance with the findings in the Wrisberg et al's review. In the presented projects, only a limited number of these tools were coupled. In a broader perspective, one way of sorting out variations in how links works, is to separate three different types where links have been made in the projects:

Firstly, LCAs were connected to other governance and management instruments and different environmental management systems are applied (more or less) simultaneously. One example is POEMS, and related to LIEP, which is discussed in chapter 6. Here, the results from these analyses were performed for reasons of product development and marketing. The links to other governance and management instruments must be seen in connection with the need to make LCA applicable in practice. These links were made in collaboration with various actors as it spanned across the various departments of the companies involved. Environmental Performance Indicators (EPI), which are life cycle-based and contextual, represented a shift from a solely manufacturing site to value chain focus. LCA became part of a comprehensive environmental management system that connected analyses of products, materials, and contextual factors. This became part of the management system of the companies, also involving product development, sales and marketing. An example of this was the use of the 'Boston Matrix', where economic and environmental values were linked – see chapter 6.2.3.

Secondly, analytical tools were linked to LCA with the purpose of improving the LCA methodology, primarily by adding already existing tools originally designed separately, but by linking processes being integrated in LCAs. In the Jomar project (Chapter 7), LCA was linked to LCC (life cycle costs, involving a life cycle perspective in financial management), as well as *physical and monetary standards* already in use in the construction industry. This project encompassed a trade perspective, which made it concerned with how to use generic analyses. The Jomar project had the ambition to develop a methodology for this link. The challenge was how to develop good scenarios for the use and disposal phases of buildings, which would involve both the activity in the building, i.e. what actually happens with regard to use, maintenance, etc., and also data related to emissions. In other words, it was a matter of establishing real system boundaries and finding relevant data. A further challenge was to document how environmental aspects were not only related to the past and present use of a building, but also its future use. An attempt to solve this was to connect LCA to service life planning and LCC calculations in a life cycle perspective. In order to structure the data from these different sources, a link was also made to the Table of Building Elements, (see chapter 7). In this way, it was possible to structure the data sufficiently to define scenarios for entire buildings, which could then be used as a basis for decisions on e.g. a new building versus renovation of an old one, as explained in the Sparebanken case study in Chapter 8.

Thirdly, linking LCA and EPDs with separately developed tools, especially regarding certification systems for buildings. Examples are BREEAM or LEED, discussed in 11 where credits are given for both EPD and LCA. These systems consist of a broad spectrum of methods for assessing sustainability of buildings, where LCA or EPD are two of several. The certification systems are not depending of the knowledge provided by LCA or EPD to assess sustainability, but one will for sure claim the opposite; the diffusion of LCA and especially EPD have benefitted from being associated with those certification systems.

12.4 THE DYNAMICS BETWEEN DIFFERENT ACTORS INVOLVED IN THE CONSTRUCTION SECTOR

In accordance with the theories of designing and implementing – and re-designing – institutional standards, several groups of actors have been active at different stages in the institutionalization processes. A study of the participation of actors will contribute to the understanding of which knowledge, interests and power relations LCA activated. These processes are part of a general picture of how the environmental discourse is taking place. As several authors have pointed at, the actors influencing this discourse have changed significantly during the time span I have been working on environmental issues. One significant contribution is the discussion on how the environmental discourse changed during the 1990ties, and that 'industrial ecology' became a common concept describing the hegemonic approaches in the environmental discourse (Hajer, 1995, Laffety and Langhelle 1999). An overview of this development is presented in Chapter 1 (see fig. 1.1.).

The 'Wood and Concrete War' is an example of how these actor groups are related to environmental policies in the age of 'industrial ecology'. The 'war' might be understood as a scientific war, resembling others in other policy fields, e.g. health and social issues, where scientist disagree about which (scientific) knowledge will make a better answer to the issues at stake (see 2). However, the 'wood and concrete war' illustrates how governmental actors are trying to find a balance between different policy considerations; here particularly between different parts of sectors in industrial policies (agriculture/wood industry vs. concrete producers). In a long period, this 'war' tipped in the favour of 'wood' interests. However, different actions in the LCA community questioned these findings, and as outlined in chapter 1.3, their arguments become a part in the scientific groundwork for political outcomes. The ‘wood and concrete’ war illustrates that scientific knowledge is controversial, particularly when embedded in political environments characterized by economic interests.

Based upon my involvement in the ‘wood and concrete war’ as described in chapter 1, I have been interested in how LCA mobilize different actors more generally. One issue has been the motivation by many – especially among business actors - about the symbolic uses of scientific knowledge related to LCA. What has the role of LCA been in the relationships between different actors involved in the construction industry (e.g. scientists, political authorities and business interests)?

From the beginning, academics who developed and used LCA and related analytical tools were the key players. However, business actors in the early stages of the construction sector where mobilised as a response to the ‘wood and concrete war’ as it focused on construction materials. My first projects - the Nordic Cement project and LIEP - were characterized by testing of LCA both as a method in light of a ‘holistic’ analytical perspective, and how such an approach could be integrated into businesses by mobilising new actors as well.

As indicated in chapter 12.2 in relation to research question 1, I argued that it was important to strengthen the credibility of the underlying data and calculation methods of LCAs by introducing new knowledge. This resulted in new actors being involved in the development of LCA in the construction industry. Both Jomar and the Sparebank projects (chapters 7 and 8) showed that these actors were important, especially for the development of scenarios. These actors represented several disciplines - both entrepreneurs, designers and facility managers.

In Norway, the Parliamentary Report No. 28 (2011-2012) *‘Good buildings for a better society. A progressive building policy’* was a confirmation that LCA and EPD became accepted as official policy in the construction sector. Many issues that had formed the background to the ‘wood and concrete war’ were now downplayed, and there was political acceptance of a more complex and nuanced knowledge approach for the further development of environmental policies in this field. In practice, both LCA (or often only the carbon life cycle of a building) and EPD became instruments for public actors in planning and design of buildings, see chapter 12. BREEAM has played an important role as it drives different actors to be involved actively in order to gain ‘LCA and EPD’ credits.

In line with Røvik’s theories of the diffusion of institutionalised standards, the scientific environments - which have over time become international networks with a large number of representatives from research communities - create, maintain and develop the LCA method. This also includes various industry organisations, and especially in environments related to the development of standards connected to ISO and CEN. Consequently, actors from academia have been supplemented with LCA experts from the construction industry and branch organisations representing different construction materials and products.

In contrast to what was the case at the time of my first projects, the LCA discourse is now being widely shared. The actors involved in current LCA discourses represent a broad spectrum of LCA expertise and practice, while the relative role of political actors seems to have changed. It is in the interplay between environmental policy actors, business interests and environmental scientific communities that LCA and related assessment tools have evolved. Based on my data, it can be concluded that scientists and industrial actors are getting stronger, while political actors have a less explicit role as LCA has got a more specific application in the construction industry.

12.5 CONCLUSIONS – WICKED PROBLEMS AND THE EVOLVEMENT OF LCA

What has characterised the evolution of LCA as an analytical tool in the construction sector?

The evolution of LCA as an analytical tool has taken place in the dynamics between overarching principles and standards of a ‘global’ nature and local challenges in using the tool. At an overall analytical level, these characteristics of LCA may be seen in the context of the issues that it addresses. Precisely because environmental problems are inherently complex, with unclear boundaries, and involving various challenges related to the choice of analytical and action strategies, theories of ‘wicked problems’ are used as basis for discussion. Using the concept of environmental problems, uncertainty, trials and reiterations may be expected in the analytical tools used in this field. I chose to understand LCA as an institutionalised standard, drawing on Røvik’s work. Such standards are not static tools designed once and for all; on the contrary, they are subject to adjustments in dynamic interplay between local, contextual experiences with the tools and standardised analytical methods. This involves locally generated forms of analysis, de-contextualised and - through use in practice - re-contextualised. This includes processes where the standardised forms of analysis are ‘translated’ to be used in different contexts. These processes have been illustrated in the various chapters in Part 2.

A key finding in relation to research question 1 is that there have been changes in the LCA tool in a number of dimensions. The most basic dynamics of these changes is to ensure *scientific credibility* on the one hand and *practical manageability* on the other. In the journey I have undertaken, the quest for scientific credibility on the one side, and practical manageability on the other side, have been the overall themes. Sometimes, in the projects referred to in Part 2, these themes have been addressed separately, other times they have been mixed. In both instances, these issues have represented tricky challenges in the projects. These challenges reflect the underlying characteristics of LCA as an analytical tool.

The dynamics of developments in LCA related to credibility of the tool and its manageability in practical application meant that two - potentially conflicting - strategies were employed: the development of a more complex analytical tool on the one hand, and processes to simplify the tool on the other.

The journey I have reported from in this thesis, illustrates that the definition of environmental problems is not static, but continuously changing. These changes are reflected in a number of developments related to how new knowledge(s), new links to other environmental tools and new actors have been involved. In my thesis, I have emphasised the ambiguities and conflicts the making of LCA as an environmental tool has been object to. I have explained these features as expressions of the very nature of environmental problems as ‘wicked problems’. In accordance with this, the evolvement of LCA is understood as ‘taming processes’. By means of technical measures environmental problems related to the building sector have been framed, mainly by means of standardisation. I have discussed the making of these standards processes of de-contextualisation. These processes I refer to as designing ‘global institutional standards’. In accordance with theories on how such standards are constructed, applied, adjusted and re-constructed, I have scrutinized the changes taking place regarding standards for LCA and EPDs during more than two decades.

At hindsight, these processes of advancing and changing LCA/EPD standards can be seen as response to the ’wickedness” of environmental problems. When new knowledge about how to address these problems in the building sector, this has happened from a focus upon individual building products – which were supposed to be compared regarding environmental friendliness - to a broader perspective where a ‘holistic’ approach to the ‘building’ level is being focussed. By this process, LCA knowledge has responded to the need for a contextual approach, in order to grasp environmental issues in the building sector more generally.

As ‘wicked problems’, the ‘taming’ strategies I have referred to in this thesis cannot ‘solve’ the environmental challenges in the building sector (or any other sector) once and for all. On the contrary: just as the scope of analysis in LCA tools has expanded from products to buildings, there is a likeliness that an even broader perspective on ‘context’ will come. Here, a systems approach where for instance local community/social issues will become included. Most likely, this will be the next phase of applying LCA in this sector.

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