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An Integrated Multi-level Framework for Life Cycle Sustainability Assessment. Case study: Social and Environmental Life Cycle Assessment for the Production of High-grade Concrete from Construction and Demolition Waste in the Netherlands

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PhD Thesis

An Integrated Multi-level Framework for Life Cycle Sustainability Assessment

Case study: *Social and Environmental Life Cycle Assessment for the Production of High-grade Concrete from Construction and Demolition Waste in the Netherlands*

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April, 2016

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Preface

This PhD thesis presents the work conducted in the PhD project *Social and Environmental Life Cycle Assessment for the Production of High-grade Concrete from Construction and Demolition Waste*, implemented at the Division of Quantitative Sustainability Assessment, DTU Management Engineering under the supervision of associate professor Stig Irving Olsen and professor Michael Zwicky Hauschild. The PhD project was implemented within the framework of the EU FP7 Collaborative project *Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste* (C2CA), Grant Agreement No 265189.

The work in the thesis is based on 7 publications, out of which 6 scientific articles, 1 peer-reviewed conference proceeding and deliverables to the C2CA project. One of the scientific articles and the peer-reviewed scientific proceeding have been published, 1 article are under review, and 4 are manuscripts to be submitted in the coming months. The scientific articles and the peer-reviewed proceeding, listed below, are included as annexes to the thesis.

Acknowledgements

When I first saw the announcement for the PhD project on *Environmental and Social Life Cycle Assessment for the Production of High-grade concrete from Construction and Demolition Waste*, I felt as if someone has read my thoughts about what could be my dream PhD research project and announced it. I would like to thank my supervisors Stig Irving Olsen and Michael Zwichky Hauschild for creating the PhD project and giving me the opportunity to implement it. I would like to thank my main supervisor – Stig Olsen - for his kindness, enormous patience, unconditional support, earthiness and practicality, which make him a unique supervisor. I would like to thank my second supervisor - Michael Hauschild - for inspiring me to work in the field of life cycle assessment.

I would like to thank the Division of QSA for the wonderful learning, research and social environment it created, for the constant aspiration for even higher scientific achievement of my colleagues, which creates a very motivating environment. I would like also to thank for all the opportunities I had at QSA to challenge and, thus, develop myself. Last, but not least, I would like to thank for the opportunity to contribute to the really exciting field of life cycle assessment.

I would like to thank my coauthors, the C2CA project partners and the SLCA group at QSA for the fruitful cooperation.

I would like to thank my family for being there for me when I needed it.

Summary

This thesis presents the work of a PhD project *Social and Environmental Life Cycle Assessment for the Production of High-grade Concrete from Construction and Demolition Waste*. The research is based on application of life cycle sustainability assessment on a case study of concrete recycling in the Netherlands.

The case study, using two different technological sets for dismantling and demolition and end-of-life concrete recycling, encompasses three levels of assessment: project, sector and economy. Implementing life cycle sustainability assessment at different levels and integrating the results requires multiple methods and tools, which are implemented following a model within a framework. Therefore, an integrated multi-level framework for life cycle sustainability assessment was created, within which a model for life cycle sustainability assessment was made.

Life cycle sustainability assessment consists of environmental, economic and social life cycle assessment (SLCA). Since environmental life cycle assessment is a well-developed method and life cycle costing, although new, has a lower degree of complexity, efforts were directed into methodological development of SLCA. There are two main approaches for SLCA – an indicator-aggregation approach and a causality-based approach. A contribution is made to the indicator-aggregation approach by creating a quantitative social performance model. In addition, a contribution is made to SLCA methodological development by reviewing relevant social theories and drawing implications for a new framework for SLCA based on practice theories. The new framework has implications for the SLCA inventory and impact assessment phase.

The results from the life cycle sustainability assessment study show that the technological innovation is performing relatively better than the reference technology on more mid-point impact categories and in all end-point categories, when the impact assessment is performed with ReCiPe. The LCC shows that the technological innovation is also performing better in economic terms. The SLCA results at project level show that the reference technology performs relatively better than the innovative one on most indicators. Upscaling of the environmental results shows that the technological innovation performs better than the technology in the regime.

The fact that the innovative technology does not perform better on all environmental impact categories and does not perform worse on all social impact categories, although it performs better on the economic assessment, requires that a multi-criteria analysis is made, in order to decide on the most preferred option.

Resumé

Denne afhandling præsenterer resultatet af Ph.d.-projektet *Social- og miljømæssig livcyklusvurdering for produktionen af højkvalitetsbeton fra bygge- og nedrivningsaffald*. Forskningen er baseret på anvendelsen af livscyklus bæredygtighedsvurdering på et casestudie af beton-genanvendelse i Holland.

Casestudiet omfatter vurderinger i tre niveauer: projekt, sektor og økonomi. Der vurderes to forskellige sæt teknologier til afmontering, nedrivning og "end-of-life" beton-genanvendelse. Adskillige metoder og værktøjer er nødvendige for implementeringen af livscyklus bæredygtighedsvurdering på de forskellige niveauer og for integrering af resultater. Disse metoder og værktøjer bør implementeres vha. en model indeholdt i et rammeværk. Derfor blev et integreret rammeværk med forskellige niveauer skabt, indeholdende en model for livscyklus bæredygtighedsvurdering.

Livscyklus bæredygtighedsvurdering består af miljømæssig (LCA), økonomisk (LCC) og social livscyklusvurdering (SLCA). Da LCA er en veludviklet metode og LCC, selvom den er ny, er mindre kompleks, blev der valgt at fokusere på metodeudvikling af SLCA. Der er to hovedtilgange til SLCA – én baseret på aggregering af indikatorer og én baseret på kausalitet. Tilgangen med aggregering af indikatorer blev videreudviklet ved udviklingen af en kvantitativ social "performance" model. Desuden blev SLCA metodeudvikling forbedre gennem evaluering af relevante sociale teorier og deres implikationer for et nyt SLCA rammeværk baseret på praksisteori. Det nye rammeværk har implikationer for "inventory"- og "impact assessment"-faserne i SLCA.

Resultaterne af livscyklus bæredygtighedsvurderingen på case studiet viser at den teknologiske innovation performer bedre end referenceteknologien for de fleste "mid-point" påvirkningskategorier og for alle "end-point" kategorierne indeholdt i ReCiPe metodikken. Ifølge LCC'en performer den teknologiske innovation også økonomisk bedst. SLCA resultaterne på projekt-niveau viser at referenceteknologien performer bedre end den teknologiske innovation for de fleste indikatorer. Opskalering af LCA resultaterne viser at den teknologiske innovation performer bedre end reference-teknologien.

Det at den innovative teknologi ikke performer bedst for alle LCA påvirkningskategorier eller værst for alle sociale

påvirkningskategorier betyder at en multikriterieanalyse er nødvendig for at identificere den optimale løsning.

Contents

1. Introduction

The purpose of the thesis is to present an integrated multi-level assessment framework for life cycle sustainability assessment applied to the case study on the production of high-grade concrete from construction and demolition waste made in the framework of the FP7 Collaborative Project *Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste* (C2CA), Grant Agreement No 265189.

Part 2 of the thesis presents the research structure, part 3 the contextual and theoretical background, part 4 conceptual and theoretical model for an integrated multi-level life cycle sustainability assessment, part 5 presents the symbolic model, part 6 gives results from the application of the methods to the case study and part 7 presents a framework for SLCA based on the implications from practice theory, part 8 presents conclusions and part 9 presents outlook and future work. In addition, there are 7 annexes with publications:

Annex 1: Kossara P. Bozhilova-Kisheva, Mingming Hu, Eric van Roekel, Stig I. Olsen. An Integrated Life Cycle Inventory for Demolition Processes in the Context of Life Cycle Sustainability Assessment. *LCA&Construction Peer-reviewed Conference Proceedings*. 2012.

Annex 2: Mingming Hu & René Kleijn & Kossara P. Bozhilova-Kisheva and Francesco Di Maio. An Approach to LCSA: the Case of Concrete Recycling. *International Journal of Life Cycle Assessment* (2013) 18:1793‑1803.

Annex 3: Kossara Bozhilova-Kisheva, Stig Irving Olsen. Towards Elaboration of a Comprehensive Social Performance Model within the Framework of Social Life Cycle Assessment. Manuscript submitted to the International Journal of Life Cycle Assessment.

Annex 4: Kossara Bozhilova-Kisheva, Alexandra Bonou, Arne Wangel, Stig Irving Olsen. Revisiting SLCA's Principles and Toolbox: A Call to Social Science. Draft Manuscript.

Annex 5: Kossara Bozhilova-Kisheva, Bettina Hauge, Stig Irving Olsen, Kirsten Jørgensen. Implications of Social Theory for Assessing Social Impacts from Products and Technologies in a Life Cycle Perspective. Draft Manuscript.

Annex 6: Life Cycle Sustainability Assessment for the Production of High-grade Concrete from Construction and Demolition Waste. Draft Manuscript

Annex 7: An Integrated Framework for Multi-Level Sustainability Assessment of Innovations in Large Technological Systems: The Case of Concrete Recycling in the Netherlands. Draft Manuscript.

Table 1 provides an overview of the contribution of the articles to different aspects of sustainability, levels of assessment and research approach.

Table 1. Distribution of publications over topics

Topics	**Environmental**	**Economic**	**Social**	**Integrated**
Process-level	1,2	2	2,3	1,7
Meso-level	1,7	1,7	1,7	1,7
Macro-level	1	1	1	1
Application (C2CA project)	1, 6, 7	1,6	1,2,3,5,6	1,6,7
Theoretical development	7	7	5,7	1,7
Research field review			3,4,5	7

2. Research Structure

2.1. Research Framework and Context

The PhD project is implemented within the research framework of life cycle sustainability assessment (LCSA) (Fig. 1). According to Heijungs et al. (2010) LCSA encompasses life cycle assessment (ELCA, LCA), life cycle costing (LCC) and social (socio-economic) life cycle assessment (SLCA, S-LCA) (Heijungs et al., 2010). Furthermore, according to the authors the three separate assessments are given equal weight in the following equation: LCSA = LCA + LCC + SLCA. Fig. 1 shows the focus of the PhD study within the theoretical framework of life cycle sustainability assessment (with full arrows). The research focus of the PhD project within LCSA covers application of LCA to the case study of production of high-grade concrete from construction and demolition waste and the combination of LCA and S-LCA and LCC. The research focus on S-LCA covers both application and methodology development. The application refers to using the UNEP-SETAC Guidelines for Social Life Cycle Assessment of Products (hereafter referred to as *the Guidelines*) and the methodology development refers to developing a social performance model for SLCA and a new approach for assessment of social impacts in a life cycle perspective based on practice theory, health and safety at work, multiple capital model and capability theory.

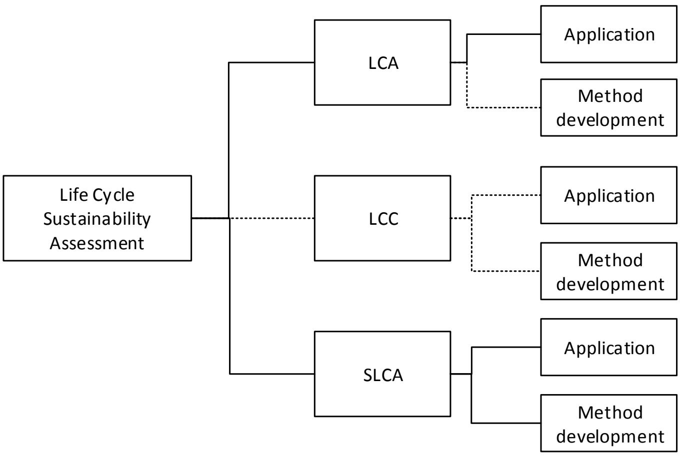


Fig. 1. Research focus in the field of life cycle sustainability assessment (dotted lines are not in focus)

The contextual research focus is based on the case study on extracting of recycled aggregates from end-of-life (EoL) concrete by a combination of different technologies for dismantling and demolition and concrete recycling. These technologies are applied in a chain perspective as the construction and demolition company implementing the dismantling and demolition technologies is providing the input for recycling to the EoL concrete recycling company, which then is providing recycled aggregates (RA) for the production of high-grade concrete and the separated cement paste, which is delivered to the cement producing company. The purpose of the project is to produce high-grade concrete from construction and demolition waste (CDW) by applying innovative technologies for separation of the CDW into fractions, which can then be re-used in the production of new concrete instead of virgin raw materials (e.g. aggregates and limestone).

By making the sustainability assessment of the technologies for concrete recycling, which provide materials for building construction, the PhD project makes a small contribution to the field of sustainable buildings, as much as materials begin to play an important role in building sustainability in addition to energy efficiency.

2.2. Research Objective

The research objective of the PhD study is to make a contribution to the field of LCSA and SLCA, to analyze the feasibility of different methods and combination thereof for sustainability assessment for different levels of analysis and different objects, scopes and purposes analysis. Levels of analysis refer to micro (process, project), meso (sector) and macro (economy, country, region). Objects of analysis refer to products and technologies.

In addition, the project aims to contribute to the elaboration of SLCA and its integration with ELCA by conducting theoretical and practical research (a case study) and providing recommendations for an integrated social-economic and environment life cycle assessment. The social and environmental LCA is conducted together with a life cycle costing assessment, which is performed by C2CA project partners.

2.3. Research Questions

2.3.1. Main Research Question

In what way can environmental and social LCAs complement each other in life cycle sustainability assessment and what methodological development is needed in S-LCA for a potential integration?[1]

2.3.2. Sub-research Questions

The following methodology-related sub-research questions are answered by the PhD project:

- What is the baseline (starting point) for sustainability assessment for decision-making by using environmental, social and economic life cycle assessment and what are the similarities and differences with other methods?
- In what way can the compatibility of E-LCA and S-LCA be increased with respect to boundaries?
- In what way can experience from other assessment tools and theories be used to strengthen SLCA methodology?
- What else can be included in the SLCA methodological sheets for stakeholders in the construction sector in order to improve them?
- What other methodologies can be used to support the LCA in the case study?
- What are the strengths, weaknesses, opportunities and threats of performing an integrated social, economic and environmental LCA in comparison to a non-integrated LCA[2]?

The following case study-related sub-research questions are answered by the PhD project:

- What environmental and social-economic inventory indicators and impacts are applicable to the sector?
- What are the environmental and socio-economic impacts of the substitution of raw with recycled materials?

[1] A more focused version of the previous main research question: "In what way can sustainability life cycle assessment (especially the social and environmental component) be improved on the basis of the conducted case study?"

[2] Generally the term *integrated assessment* can be used in terms of horizontal integration (joint use of different types or categories of impacts), vertical integration (joint use of results from different levels or scales) and integration of assessments in decision-making (Lee 2002 in Sala et al., 2013).

2.4. Research Methodology

2.4.1. Research Stages

The research methodology and process for the PhD study is based on approach for problem-solving in research (Fig. 2), which has four research stages: reality, conceptual model, symbolic model, ideal optimal solution.

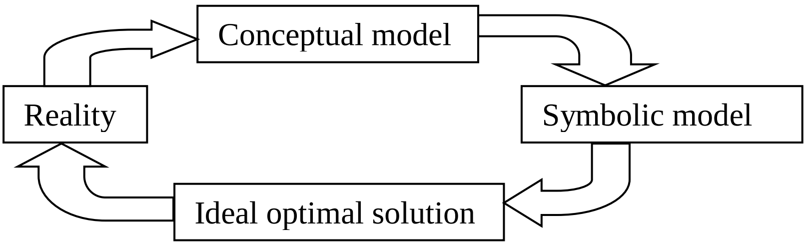


Fig. 2. Problem Solving Stages

Stage 1: Reality (Case Study, LCSA)

The reality is the context – theoretical and case study – in which the research is being conducted. The PhD project is application-oriented, which means that it starts by looking in the C2CA case study context (providing data for all assessments), and the theoretical background of life cycle sustainability assessment, in general, and social life cycle assessment, in particular.

Step 2: Conceptual Model (Framework)

On the basis of the reality a conceptual model for an integrated life cycle sustainability assessment is made, which is based on the identified needs from researching the background in LCSA and the state-of-the art in SLCA and the case-study. A general conceptual framework is provided by Klöpffer (2008), and complemented by the life cycle sustainability analysis framework, provided in Guinee et al. (2011) and Heijungs et al. (2010), but needs to be tailored to the specific application case of the C2CA project, therefore it starts at the conceptual model and continues to the stage of symbolic model elaboration. The suggested integrated conceptual model includes a social performance model, a multi-criteria decision-making model for LCSA and a conceptual framework for SLCA based on practice theory. The conceptual model for SLCA in the beginning of the research process was taken from *the Guidelines* and the research continues in the modelling stage. Nevertheless, since the existing methodology for SLCA requires improvement, a part of the research is focused on a conceptual model or a new framework for SLCA methodology development.

Step 3: Symbolic Model (Mathematical Model)

According to the approach for problem-solving in research, the conceptual model is translated into a symbolic model. In this PhD project, the conceptual model for LCSA (including social performance) was translated into a symbolic model). The conceptual model for SLCA based on social theory was not translated into a symbolic model, but it is recommended that it is further elaborated.

Step 4: Ideal Optimal Solution (Assessment Methods Application)

The symbolic model was then applied to the C2CA case study to calculate environmental and social life cycle assessment results and to conclude which technology performs relatively better than the other based also on the LCC results, generated by the project partners. If an ideal optimal solution can be found on the basis of the results, then the research can stop, if an ideal optimal solution cannot be found on the basis of these results, the research needs to continue in a specific field by going back to previous stages.

2.4.2. Research Type and Process

The PhD project is both educational (applied research), the output of which is a case study assessment and methodological (elaboration of an integrated multi-level framework for sustainability assessment). The ELCA applied to the case study is analytical (it analyzes relationships between different variables) and predictive (it makes it possible to predict the outcome from changing certain variables) (Collins & Hussey, 2009).

In relation to the case study, it is possible to analyze different scenarios and to extrapolate the results of the case study (at a sector level) to higher levels (state level or even EU level). The SLCA has both a descriptive and analytical nature. It is descriptive because it first aims to establish a baseline, describing the characteristics of a particular situation in particular location (on the basis of the social-economic indicators from the SLCA Guidelines). These indicators can be quantitative, qualitative or semi-quantitative. It is analytical because it aims to provide an analytical framework and a calculation model.

Another characteristic of the research project is that it abductive because it has moved back and forth between theory and reality (Fig. 3), “relying on the best set of explanations for understanding one’s results)” (Johnson & Onwuegbuzie, 2004). Most the research has started from reality (the C2CA project), thus providing the context of the case study by discovering the existing patterns in the construction sector in the Netherlands and in the ELCA and SLCA. Since the research project is on application of LCA, it is very important to know the context to which the LCA will be applied. After the patterns are discovered, the deductive approach will be applied by starting from the theories and applying them to reality.

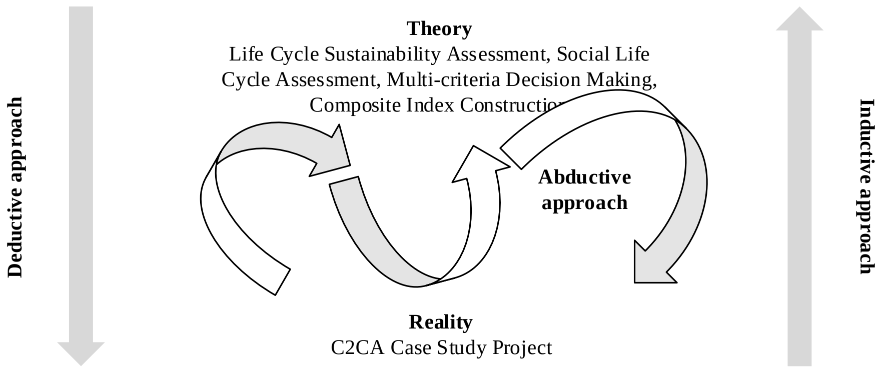


Fig. 3. Research Approach

The research for the PhD study started with researching the context of the C2CA project and the available publications in life cycle sustainability assessment. On this basis an attempt was made to make an integrated inventory for LCSA for the traditional and innovative demolition processes in the C2CA project (Annex 1). The integrated LCI for the demolition processes went through the conceptual and symbolic model stages, but at the stage of the optimal solution we found that with the available data (social and economic), it was not possible to make such an inventory for the whole technological system. Therefore, a second iteration was made and an operational approach for life cycle sustainability assessment of concrete recycling in the Netherlands (Annex 2) was elaborated on the basis of separate inventories for the three assessments. However, when elaborating both the integrated and separate inventories, we could only confirm the finding of other researchers that not all indicators in S-LCA can be expressed for the functional unit of a LCA study. Therefore, the primary focus of the research became collecting, processing and interpreting data for the social life cycle assessment and elaborating a quantitative model for social life cycle assessment (Annex 3), which can handle different types of data, different objects of assessment, different number of companies, different life cycle stages and stakeholders, and express the results for the functional unit for the case study. Although, this model is capable of calculating social performance of a supply chain of companies, it supports the compliance type of social life cycle assessment, or otherwise called "CSR" SLCA (Falque et al., 2013). Since this model was not based on social theory and there were researchers raising voices in favor of turning to social science to support S-LCA (Feschet et al., 2010; Annex 5) and a review (Annex 4) showed that most of the researchers in the field of SLCA are not coming from social sciences, a research was done on which scientific paradigm is compatible with SLCA and on application of practice theoretical approaches to SLCA for improvement of the existing methodology (Annex 5).

The research project uses the mixed methods research approach, considered to be the third research paradigm in educational research. The mixed methods research is defined "as the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study" (Johnson & Onwuegbuzie, 2004). This paradigm is chosen over the positivist or phenomenologist (interpretivist) one because the assessments need support from both quantitative and qualitative research methods since both environmental and social-economic assessment of the technology for production of concrete will be implemented. The two main reasons for using the mixed methods research are achieving complementarity and expansion. Complementarity can be reached by using the results from one method to explain the results from another method and by using different methods for different inquiry components an expansion can be achieved (Johnson & Onwuegbuzie, 2004).

The mixed methods research can follow two types of design: the mixed-model design and the mixed-method design. The mixed-model design means that different methods (qualitative and quantitative) are used at the different research stages (research objective, data collection, data analysis and interpretation) (Johnson & Onwuegbuzie, 2004). The mixed-method design is "based on crossing of paradigm emphasis and time ordering of quantitative and qualitative phases" (Johnson & Onwuegbuzie, 2004). The research project applies mixed-method design rather than mixed-model design, since the research is not going to be based only on quantitative methods in one stage and only on qualitative methods in another stage, rather the mixing will be in one, mostly two, stages. The following research methods are used for the case-study: interviews, structured and non-structured surveys and quantitative assessment. The research is conducted on a case study.

3. Theoretical and Contextual Background

3.1. Brief Theoretical Background of LCSA

Sala et al. (2013) analyze the state-of-the art of sustainability science (SS) – "an emerging discipline, applicative and solution-oriented whose aim is to handle environmental, social and economic issues in light of cultural, historic and institutional perspectives". The authors recognize that the "challenges of the discipline are not only related to better identifying the problems affecting sustainability but to the actual transition towards solutions adopting an integrated, comprehensive and participatory approach" (Sala et al., 2013). Life cycle thinking (including life cycle-based methodologies and LCSA) is suggested by the authors as a systemic approach for "integrating sustainability into design, innovation and evaluation of products and services" (Sala et al., 2013).

Klöpffer recognizes that there can be several approaches for conducting LCSA based on the *triple bottom line* and life cycle thinking, but outlines two such approaches:

1) Three separate life cycle assessments:

$$LCSA = LCA + LCC + SLCA$$

based on the following requirements:

- the assessments have consistent boundaries, which can ideally be identical;
- the physical life cycle is used to model the LCC inventory;
- no weighting and compensation between the three pillars;
- high transparency and meaningfulness.

2) One life cycle assessment:

$$LCSA = 'LCAnew'$$

where 'LCAnew' is life cycle assessment including LCC and SLCA as additional impact categories in life cycle impact assessment

based on the following requirements:

- the life cycle inventory (LCI) for the three components (environmental, economic and social) is identical (only one LCI model is defined);

- the identical LCI is followed by three impact assessments and the same areas of protection.

The approach for quantification of sustainability, suggested by Klöpffer (2008) refers to quantification of sustainability of products (goods and services), but does not discuss sustainability related to production sites, companies or large systems.

The scope of LCSA was broadened further by Heijungs et al. (2011) and Guinee et al. (2011), who made a transdisciplinary integration framework for life cycle sustainability analysis (LCSA). According to Sala et al. (2013), although the transdisciplinary approach is more suitable for sustainability assessment than ´the multi-disciplinary one, it has not been applied in many studies. The framework suggested by Guinee et al. (2011) includes the three pillars of sustainability and the micro (product-oriented), meso and macro (economy-wide) level. The authors suggest suitable tools for impact assessment at the three levels for the three pillars. Zamagni et al. (2013) also address the issue of the appropriate scale for implementing LCSA – products, enterprises, communities, or nations. Sala et al. (2013) refer to the levels as local, national, regional, and global.

Guinee et al. (2011) acknowledge that in order to make "the LCSA framework operational for today's LCA practitioners, substantial research is needed". Heijungs et al. (2012) develop further the approach of life cycle sustainability analysis by suggesting a matrix-based computation approach for LCC. With respect to S-LCA the authors recognize that there is no computational form for S-LCA, but "conjecture, however, that it has, like environmental aspects, primarily a process-related character", which would make possible the use of a social satellite matrix. Zamagni et al. (2013) also find out the applications of LCSA are limited and are mostly focused on environmental and economic aspects, as the social aspects are not addressed as much and the difficulties occur not only at practical level (data and indicators), but also at conceptual level (valid for both SLCA and LCSA).

Klöpffer (2008) outlines the main problems in SLCA, among which are: "How to relate quantitatively the existing indicators to the functional unit of the system? How to decide between many indicators (most of them qualitative) or a few ones that can be quantified?)". The author also acknowledges that the quantification of the SLCA impacts is the most difficult one of them.

Zamagni (2012) outline a range of sustainability-related topics, which need contributions from practitioners and method developers, for example:

- "How can the LCSA framework be consistently applied considering also the different degree of maturity of the three methods? Which difficulties have been encountered in applying the framework?"
- "What role does scenario modelling play in the LCSA framework?"
- "How can LCSA move from three separate assessments carried out under consistency requirements, to what Klopffer (2008) defined as LCSA = "LCA new", which would consist of one Life Cycle Inventory to be followed by up to three impact assessments, possibly leading to the same set of areas of protection? What other approaches to LCSA can be proposed?"
- "What approaches exist for including mechanisms in the analysis? …And what kind of methods and tools can be used, combined and/or integrated?"
- "What do we need to further develop LCSA? […] How can future changing structures of the economy be accounted for? What research strategies and lines are considered relevant?" (Zamagni, 2012)

Sala et al. (2013) present a hierarchy of framework, methodologies, methods (models, tools and indicators). "The framework is the key level for setting the rationale and the structure for the further integration of single methodologies, methods, models, tools and indicators" (Sala et al., 2013). The authors acknowledge that system-wide and holistic approaches for sustainability are still lacking and that a sustainability assessment needs to be based on an integrated assessment (horizontal and vertical) (Sala et al., 2013). It can be concluded that frameworks for LCSA and life cycle sustainability analysis, outlining assessment methods have been suggested, but model development, especially such for horizontal and vertical integration is still necessary.

3.2. Project's Context

The C2CA project provides the contextual background for the model for all assessments in the project: environmental, social and economic.

The C2CA project aims to develop three innovative technologies: smart dismantling and demolition, advanced dry recovery (ADR) separation for recycling of end-of-life concrete (EoL) aggregates, which can be used in buildings and not, as traditionally, in roads; and a censor for quality control. The traditional dismantling technology is not that much different from the smart dismantling technology, but the smart dismantling technique removes more materials from the building before it is demolished. The top down demolition is the innovative technology, which in combination with the short-reach demolition, produces higher quality EoL aggregates from building demolition than the existing technology (high-reach demolition in combination with short-reach demolition).

The project is motivated by the fact that 97 % of the EoL aggregates in the Netherlands are downcycled by use in road construction, and only 3 % are used in buildings. It is expected that by the year 2025, there will be even higher quantity of EoL concrete, which cannot be absorbed in roads, therefore it is necessary to find another application of the EoL concrete by improving the existing concrete recycling technology. If the innovative ADR technology is fully realized it is expected that recycled aggregates can be used instead of natural aggregates in buildings, and calcium-rich ADR fines will be utilized in cement production, as replacement of limestone.

The decision-context in the C2CA case study is based on the results from the three assessments: LCA, LCC and SLCA. The analysis of the results should be able to show, which technology performs relatively better with respect to environment, economy and society. In addition, the assessment considered not only the project level, but also sector and economy-wide level in the Netherlands.

4. Conceptual Model for LCSA

The conceptual model elaborated in this PhD project is the Integrated Multi-level Framework for LCSA (Fig. 4) based on different levels of the system assessed, definition of sustainability at the three different levels, the existing practice and the methods and tools for life cycle sustainability assessment at different levels. The starting point for elaboration of this framework is the work of Klöpffer (2008) and Guinee et al. (2011). The framework considers the three life cycle assessment methods (LCA, LCC and SLCA) in LCSA providing methodology and guidelines for assessing the three pillars of sustainability (environmental, economic and social), as suggested by Klöpffer (2008). The framework considers the three levels of analysis suggested by Guinee et al. (2011) in broadening the object of analysis from product (at micro level), meso level and economy-wide (macro) level and relates them to the levels of analysis in the multi-level perspective (MLP) theory: niche, regime and landscape (in Rip & Kemp (1998), (Smith et al., 2005) and Geels & Schot (2007)).

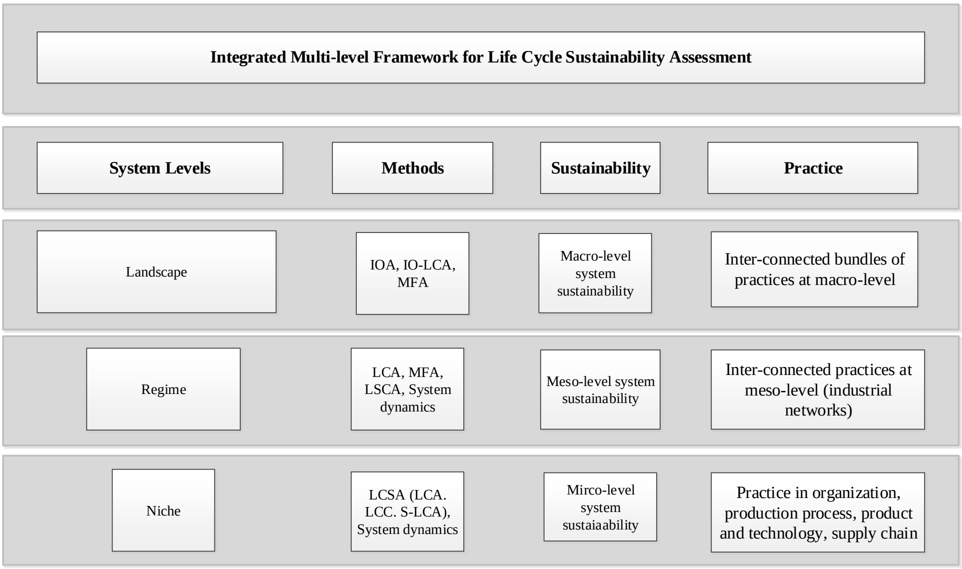


Fig. 4. An Integrated Multi-Level Framework for LCSA

The framework is further elaborated on the basis of the context analysis in Hu et al. (2013) and the multi-level perspective (MLP) and practice theory (Annex 7). The approach presented by Hu et al. (2013) is a practical (operational) approach for sustainability assessment of innovations in large technological systems at three levels: project-level, sector-level and economy-wide (NL) level. The present study frames the suggested approach into an integrated framework for assessment of technological innovations on the basis of two theoretical approaches – MLP and practice-theoretical approaches. According to Rip & Kemp (1998), (Smith et al., 2005) and Geels & Schot (2007), the MLP can support a study on sustainability of technological innovations, which requires "[linking] broader analytical frameworks to successively larger problem framings", because of its ability to describe the pathway of an innovative technology from developments in the niche to consolidation at regime level and its influences on the landscape (Geels, 2002). The MLP conceptualizes the dynamic patterns in socio-technical transitions (Geels, 2011) and "organizes analysis into a sociotechnical system that consists of niches, regimes and landscapes as a nested hierarchy of structuring processes" (Geels & Schot, 2007). This framework has mostly been used for historical transitions and descriptive analysis of innovations. The contribution of this study is to suggest that sustainability assessment of innovations in large technological systems can benefit from a combination of the understanding of qualitative description of large socio-technical system with MLP and quantitative assessment of sustainability performance of technological innovations, which allow for projection of impacts in the future. Such quantitative methods are (dynamic) material flow analysis (MFA), life cycle assessment (LCA), input-output analysis (IOA). The qualitative and quantitative evaluation of the system can then be the basis of a system dynamics model.

The dynamic MLP for technological innovation with the three levels (niche, regime and landscape) and the pathway of a technological innovation are presented in Fig. 1 in Annex 7. The different levels are actually "analytical and heuristic concepts to understand the complex dynamics of sociotechnical change" (Geels, 2002). These levels are perceived as a nested hierarchical structure (Fig. 2, Annex 7), in which niches are located within socio-technical regimes, which are located within a landscape, which is the overall context of various factors (social, physical, etc.) that structure the system (Smith et al. 2010). The higher hierarchical levels are more stable than the lower level "in terms of number of actors and degree of alignment between elements" (Geels, 2011).

The landscape level represents economy-wide, macro developments at country level. The regime level includes the existing technological practice in the sectors of construction and demolition, construction and demolition waste recycling and construction materials (concrete) manufacturing, which consists of the current technique for dismantling and demolition of end-of-life building, concrete recycling into new aggregates, cement and concrete production and building construction. The niche represents the technological innovation, performed by small networks of actors (the C2CA projects and the industrial partners). In order for a technological innovation to be successful it is necessary for the innovation to become the new practice at the sector.

An interesting observation of the thesis is based on the results from the assessment at micro, meso and macro level and the implication for the decision-making process at each level. In the C2CA project these levels are illustrated by decision-making at project level and decision-making at national level.

As a starting point of the study a Conceptual Model for an Assessment Framework for LCSA was made. The purpose of the framework was to include, as much as possible, the different analytical aspects of LCSA and to serve as a basis for a multi-objective LCSA-assessment tool. The conceptual model is based on the sequence of LCA phases, as outlined in the ISO standard for LCA, and has 5 modules (each base on different LCA phase) (Fig. 5):

Module 1: Goal definition with respect to sustainability assessment

The purpose of this module is:

- to establish the type of decision-maker – a single private or public decision-maker (e.g. a company or a municipality) or several decision-makers (e.g. supply chain, industrial network).
- to outline the nature of the sustainability problem, which needs to be solved, as defined by the decision-maker.
- to state the object of the assessment: a product (good or service), technology, policy, etc.
- to outline the life cycle stages included in the assessment: raw materials extraction, manufacturing, use and maintenance, end-of-life (EoL).
- to state the purpose of the assessment as defined by the decision-maker.

- to define the decision situation: according to the ILCD *Handbook.*

Module 2: Scope

The scope of a sustainability study can be defined in two directions: "horizontal" and "vertical". The "horizontal" dimension includes all the aspects, usually considered in a sustainability assessment – environmental, social and economic sustainability, and for which there is a methodology or guidelines for assessment. In addition, sometimes other aspects are considered, such as culture, governance, technical aspects, therefore they are also included in the conceptual model, although, they are not included into LCSA. The determination of the relevant sustainability aspects to be included in an assessment depends, among others, on the sustainability problem and the decision-maker. The "vertical" dimension of the scope is the consideration of each aspect in depth.

Module 3: Life Cycle Inventory

The characteristics of the life cycle inventory in the LCSA model follows from the goal and scope of the assessment. Two types of inventories for LCSA are included, based on Klöpffer (2008), separate inventories for the different life cycle assessments and an integrated inventory for LCSA.

Module 4: Life Cycle Impact Assessment (LCIA)

This module relies on the existing methods for LCA and on the environmental LCC. As far as SLCA is concerned the model is based on the approach of indicators for compliance, but a theoretical development is made at conceptual level for application of practice theory to SLCA.

Module 5: Integrated Assessment and Interpretation

The purpose of the module is to provide interpretation of the results from the LCIA phase and, if possible, to integrate the results from the different assessments, which are expressed in different units. Methods considered to this purpose are aggregation, distance-to-target and multi-criteria decision-making.

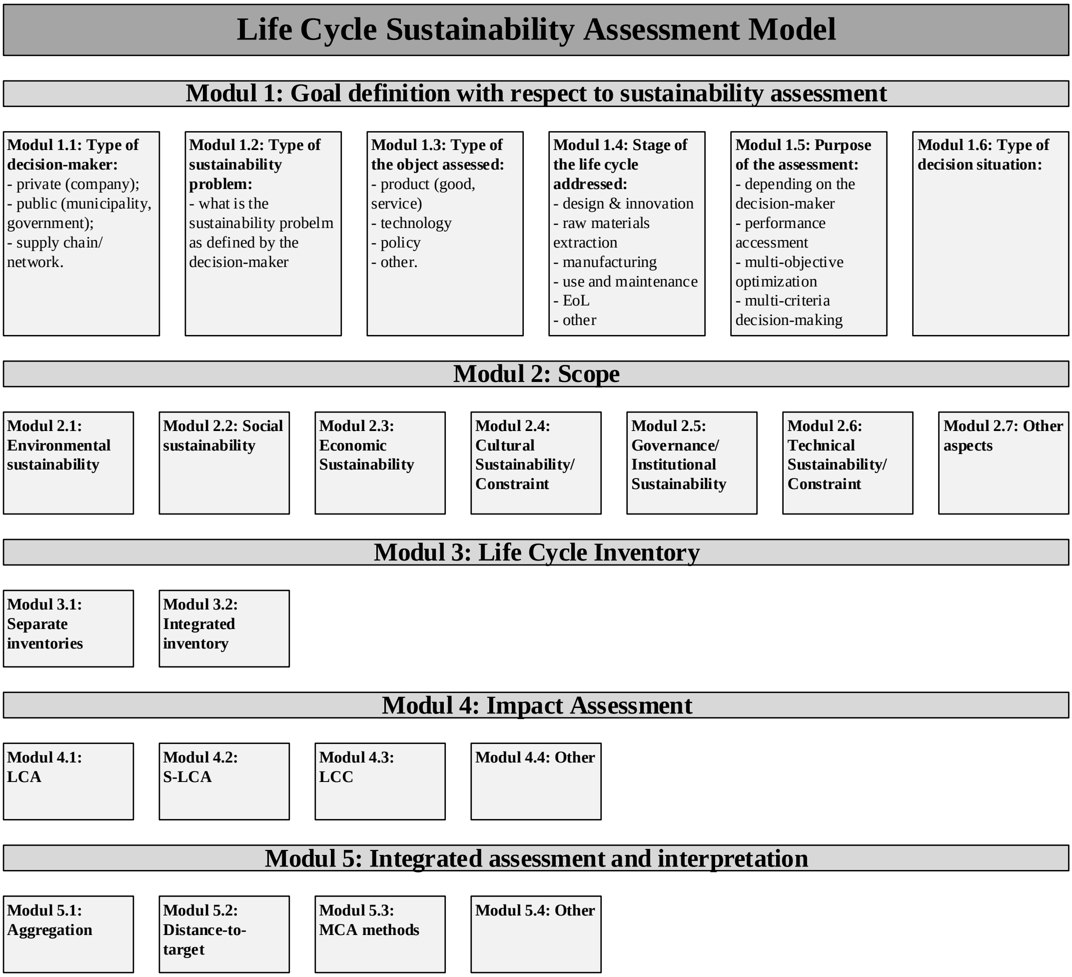


Fig. 5. A Conceptual Model for LCSA

5. Elaboration of a Symbolic Model for LCSA

The symbolic model is a calculation model for LCSA (Fig. 6) based on life cycle thinking, model elaboration, composite indicator construction and multi-criteria decision-making approaches (Annex 3 and 8). The LCSA model development is performed in 4 steps: definition, operationalization and elaboration, application and interpretation.

Step 1: Model Definition

At this step, the model is defined in such a way that it fits the requirements of the *Goal and Scope Phase* of a LCSA and lays the foundations for a separate or an integrated LCSA.

Problem Definition

The first step in making a model is to define the problem, which the model should solve. Life cycle sustainability assessment is an assessment, which involves three different assessments, based on different type of data and producing results in different units. There is a need for better visualization and easier communication of results. Hence, the objective is to develop a model, which can 1) easily fit the phases of life cycle assessment; 2) fit into a life cycle sustainability assessment, where all assessments can have both a disaggregated and aggregated (one-score) output; 3) be generic, which means to work with different indicators and life cycle impact assessment methods.; 4) be suitable to be used with different types of indicators (qualitative, quantitative and semi-quantitative); 5) provide different methods for standardization and levels of aggregation.

Since the model relates to the life cycle assessment phases, its framework and steps must fit the assessment logic needed for typical goals of LCSA. The model should be suitable for and adaptable to, but not limited to, studies with the following goals: comparative LCSA of products and technologies, design of sustainable supply chains, for hotspot sustainability analysis, for selection of a specific location for sustainable product manufacturing, for scenario simulations, etc.

In addition to fitness to the typical LCSA goals, the model aims to comply with the procedure for composite indicator construction. This procedure starts with developing of a theoretical framework for a meaningful index on the basis of a fitness-for-purpose principle

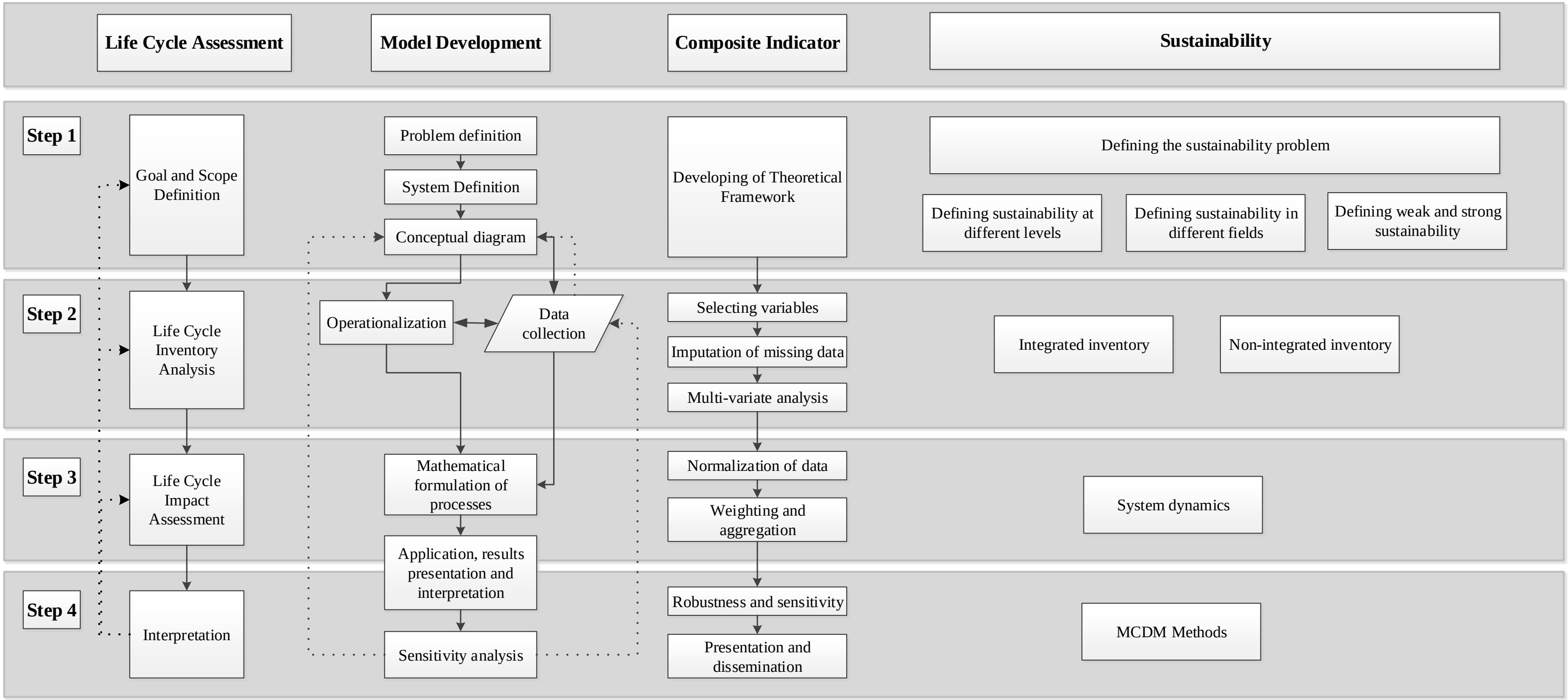


Fig. 6. Life Cycle Sustainability Assessment Model

(OECD, 2008). The theoretical framework for this particular model is given by the triple bottom line definition of sustainability as including environmental, social and economic aspects. In the case study the theoretical framework for the social aspects is based on the provisions of *the Guidelines*, but the structure of the model must fit any similar framework of indicator-based social assessment. The suitability of the model to treat different types of indicators with different units, has been exemplified with its application to social life cycle assessment (Annex 3).

System Definition

Since the model should serve sustainability assessment, it means that environmental, social and economic aspects are considered as a minimum. The social assessment is based on the approach in *the Guidelines* and in many case studies on S-LCA, that it is the companies, implementing a specific production process, which influence the social impact. In order to support a performance assessment, the system definition of the model should reflect the elements of a product/technology system, i.e. processes, companies, sustainability aspects, inventory indicators, impact sub-categories, etc. Thus, for each sustainability aspect the model system is defined by sets or sub-systems, such as: n life cycle stages. Especially for the SLCA the model includes *c* companies, implementing *p* processes or applying *t* technologies in each life cycle stage, *s* stakeholders, affected by the processes/companies in each life cycle stage and *i* indicators per impact category/stakeholder/process. The complexity of the system reflects on the complexity of the composite indicator.

Conceptual Model

In order to move from a specificity of an assessment to a generic indicator-based model in a life cycle perspective, a conceptual model is elaborated and discussed in the previous section. Since the LCA methodology is represented by many methods and models, the focus again is on developing a SLCA model. Fig. 2 (Annex 3) provides a conceptual diagram of the SLCA model in order to visualize its logic and the system it represents. The conceptual model draws on the following scientific fields: life cycle impact assessment, modelling and composite indicator construction. The model takes into account that one company can implement more than one process vice versa. The conceptual model allows the researcher to set the stage for data operationalization.

Step 2: Operationalization and Data Collection

At the operationalization step, the provisions of the conceptual model are translated in a format, appropriate for analysis. As far as the LCA is concerned the data collection is usually focused on primary data collection, since there are well-developed databases. The LCC requires data collection, since there are not well developed databases.

Both for the LCC and SLCA, data can be found mainly for the foreground system and is often confidential. Inventory calculation for the SLCA is not as straightforward as in an environmental and economic assessment. Life cycle inventory is probably the most time consuming phase in SLCA, requires thorough analysis and the result from the LCI phase in a SLCA is not necessarily a calculation. When a SLCA is performed operationalization goes in parallel to the data collection. Operationalization of indicators includes: selecting relevant inventory indicators to represent an impact category, sub-impact category or a stakeholder category; determining which state variables will be used to describe the indicators; determining in what way companies will be included in the assessment; determining, which indicators need interpretation and deciding on a suitable interpretation scheme, thus preparing the collected data for the next phase.

Data collection includes choosing a data collection method for obtaining the data necessary to assess specific social impacts. In cases of missing data when constructing an index, different approaches can be used for imputing missing values (OECD, 2008). Depending on the data source and collection method, there may be cases in which data imputation is not applicable.

After the data for the SLCA has been operationalized, there are two possibilities for the inventory phase in a LCSA (Klöpffer, 2008): to have an integrated inventory or separate inventories. An integrated inventory would require that there is environmental, economic and social data for each process in the background and foreground product system. An experimental integrated LCI based on the material flow diagram (Table 1 and 2 in Annex 1) for the traditional and innovative demolition processes in the C2CA project was created. While all the indicators from the environmental and economic assessment were process-specific, only two indicators from the SLCA inventory were process-specific and possible to be calculated for the functional unit of the study (1 m^2 gross floor area). These indicators are the hours of work created and the amount of secondary resources made available by the process to substitute virgin resources for high- or low-grade uses (or otherwise said - access to secondary materials – an indicator included in the Methodological sheets to the Guidelines).

In the process of conducting the study several methodological challenges were encountered. The first challenge relates to the data collection for an integrated ELCA, ELCC and SLCA inventory. The data collections for all three studies started in parallel, but in the course of data collection and processing it was found that it would have been easier to make the environmental inventory first, followed by the ELCC and the SLCA, since the environmental inventory (generated from comprehensive databases) was the most complete one of the three. The second challenge was calculating the SLCA inventory for the functional unit of the study. The third challenge was to identify the connection points between the inventories, i.e. to identify the inventory items for which there are data available at least for two of the assessments. The following inventory items served as connection points for the LCSA inventory:

- The materials outputs from the demolition processes and the technical demolition equipment used were the connecting inventory items between the ELCA and the ELCC inventories. The cost structure is arranged in a way that the material cost can be coupled to the amount of equipment, energy and demolished materials, using coefficients of unit prices;
- The hours of work necessary for the implementation of both demolition processes served as connection points between the ELCC and the SLCA. A trade-off between the assessments is observed: the longer working hours, which make a demolition method more costly and reflect lower unit productivity, are considered as a positive factor in the SLCA, since more employment hours are created.
- The amount of secondary resources, replacing virgin resources for high- or low-grade use, serves as a connecting point between the social and environmental inventory. Here, no trade-off is observed between the environmental and social results, since the higher the amount of the recycled EoL materials (environmental aspect), the greater the access to recycled material resources replacing virgin recourses (the social aspect).

The fourth challenge is related to the lack of easily available data for the costs and social indicators for the background processes, thus limiting the integrated LCI to the foreground demolition processes. It is possible to extend an integrated LCI to include environmental data for the background processes, but it is more difficult to do so for the ELCC and the SLCA. Both assessments require data, which is considered confidential by companies and which is very site-specific rather than generic, therefore, making it more difficult to create databases containing generic ELCC and SLCA data.

The fifth challenge is related to the importance of the different ELCC and SLCA indicators for making a definite conclusion for the results of the assessment, as well as the importance (translated to weights) of the aggregated results of each of assessment in a LCSA.

LCSA is a new approach for sustainability assessment in a life cycle perspective. Traditionally life cycle assessments are data intensive and an integrated life cycle assessment is expected to be even more data intensive. Therefore, it is necessary to come up with tools for managing an integrated LCI and to find more connecting points between the three assessments. The integrated LCI template presented in Annex 1 is applied only to one type of process which is not data intensive, but it might be interesting to be applied to more complex and data intensive processes in order to better assess its strengths and weaknesses.

The integrated LCI for this process can be considered a good tool mostly for the ELCC, for which a preliminary assessment as to which demolition method is better can be reached from inventory indicators. For the SLCA, the integrated LCI is not the best way to present the results of the assessment, since most of the results cannot be related to the functional unit of the study and the richness of the SLCA is lost. The environmental LCI usually takes into account more inventory data than the one presented in the paper, but if a full environmental LCI was presented, it would not be possible to extend the ELCC and SLCA to cover all the background processes, which are included in the ELCA. Thus, this integrated LCI inventory template can be considered a good start, but it has to be acknowledged that it needs to be developed further. Since, it was not operational at the moment of assessment, the other option – separate life cycle inventories – was chosen for the assessment.

Step 3: Model Elaboration

At this stage the underlying mathematical model for performing the LCSA and the SLCA within it (Annex 3), is elaborated. The main focus is on the indicators for SLCA and it is by application to SLCA that this step is illustrated. The mathematical model is based on selected standardization and aggregation methods, which are appropriate for the social life cycle impact assessment phase (and for an integrated assessment), when the assessment is based on indicator aggregation with the aim of producing a composite indicator, as an output. The modelling follows the logic of life cycle impact assessment: classification, characterization, normalization and weighting.

Classification

The classification step is straightforward in the model, since each indicator belongs to a specific impact sub-category and each sub-category belongs to a particular stakeholder.

The model provides for the following classifications of the inventory indicators: classification of different inventory indicators to a specific impact sub- category; classification of different inventory indicators to a specific stakeholder category; assessment- or case-specific classifications.

Characterization

The Guidelines do not provide guidelines for normalization of the characterized results, therefore it is open for researchers to contribute with their own characterization models, as long as these are transparent. Characterization in the model is performed by interpreting the collected qualitative and semi-quantitative data within a range of 0 and 1 for all inventory indicators, thus transforming them within the same scale (see Supplementary Material in Annex 3). Characterization can be directly followed by aggregation (UNEP-SETAC, 2009), but the model provides options for normalization and weighting before aggregation.

Normalization

The purpose of the normalization step in LCA is to show the magnitude of the sub-impact category results in comparison to reference values. The model considers both external and internal normalization references. An external normalization reference can be the value of an indicator (e.g. average value) for a sector, a country or a region (e.g. EU) and it is useful for comparing different supply chains. The internal normalization can show how the different nodes in the supply chain perform in comparison to each other and where some improvements may need to be made. Thus, it is useful for social design and optimization of the supply chain and for comparing different scenarios. Efforts for collection of data at national level were made and for some indicators data was available, but for others not so easily. This data was used for a qualitative SLCA analysis (Annex 6). Since data about the indicators, suggested in *the Guidelines,* is not readily available at higher reference levels (sector, country, etc.) for all indicators, the exemplification or demonstration of the model is performed with internal normalization references. After normalization the indicator results are dimensionless indexes.

Normalization is a method for data standardization, but it is not the only one. The model provides the possibility to use two standardization methods: normalization and linear scaling technique. The Z-score standardization method is also a possibility in cases, when there are no data entries equal to 0 (Salzman, 2003). Since there are many semi-quantitative indicators with values of 0, the Z-score method is not considered applicable to the model.

Normalization is a technique for data standardization, where each variable is normalized to a specific value for the same variable, called normalization reference. As already mentioned, the model allows the use of different normalization references, but the exemplification is made with a supply-chain-based normalization reference, which compares one company's performance to that of the companies in the supply (value) chain. The normalization reference is calculated for each indicator as the arithmetic mean of the performance of all companies for a specific indicator.

Linear Scaling Technique (LST)

The Linear Scaling Technique is used for standardization of variables within a certain range. For this purpose, it is necessary first to make an estimate for the minimum and maximum values of the variables. Afterwards, the data is scaled in accordance with these values. By using this standardization technique it is possible to solve the directionality problem[3] in S-LCA: in some cases the greater the value of the inventory indicator, the better the performance (e.g. worker's satisfaction); in other cases, the greater the value, the worse the performance (i.e. complaints, accidents).

[3] The increase of the value of one variable is good for the final outcome, while the increase of the value of another variable is bad.

Weighting

Weighting is an optional step in life cycle assessment and can be performed in many different ways. At the weighting step, the importance of the different impact categories is reflected. For the purposes of this assessment, a weighting factor of 1 is assumed, which shows that all impacts are considered equally important. The model provides two types of weighting: weighting of indicators after standardization and weighting for the scenario analysis after aggregation (presented later).

Weighting of indicators after standardization is performed in the following manner: all indicators explaining a specific inventory indicator are given an equal weight in accordance with the egalitarian perspective.

Aggregation of SLCA indicators

The model is set to aggregate results into the following aggregation categories:

- aggregation of weighted company scores per impact sub-category and per stakeholder;
- aggregation of weighted supply-value chain node scores per impact sub-category;
- aggregation of scenario scores per impact sub-category and per stakeholder for different scenarios.

Theoretically, there are different aggregation methods, which are possible to use depending on the purpose of the assessment. The aggregation in this case study is made by the use of the simple additive weighting method, where all the weights are equal and which provides methodological transparency (Salzman, 2003).

After the results for the SLCA have been aggregated and the scenario analysis is made, it is possible to analyze the results from the three assessments. The SLCA model is suitable for a LCSA based on both an integrated and a separate inventory. In case, separate inventories are used, it is necessary to use multi-criteria methods for decision-making in order to interpret the results from the three assessments.

6. Finding of an Ideal Optimal Solution for a LCSA

The purpose of this stage is to apply the elaborated symbolic model for LCSA to a case study – assessing the sustainability of the ´Production of High-Grade Concrete from Construction and Demolition Waste at different levels (Annex 2, 6 and 7). Based on Klöpffer (2008) and Guinee et al. (2011), an application of the LCSA framework for the case study of concrete recycling in the Netherlands was outlined in Hu et al. (2013) (Annex 2). Using as a starting point the framework, suggested by Guinee et al. (2011), Hu et al. (2013) operationalize LCSA for the C2CA project in 5 steps: broad system definition (at project, NL/EU and sector level); scenario making; defining main and sub-research questions for individual tools; application of the tools and interpreting the results in a LCSA framework. The basis for the modelling in the sustainability assessment is provided by:

- definition of two extreme scenarios: the business-as-usual (BAU) scenario and the C2CA scenario;
- posting questions for decision-making: Can the technological innovation proposed by the C2CA project improve the sustainability of EoL concrete management from a life cycle perspective?”
  - LCA: “Can the C2CA innovation lead to a reduction of the environmental impact from a life cycle perspective? In which part of the chain can this potential reduction be achieved? (Annex 6)
  - SLCA: “What is the social performance of the chain and in what way can the C2CA innovation improve/affect it?” (Annex 3)
- upscaling: “To what level can the C2CA innovation be scaled up?”
  - LCSA: “What is the sustainability performance of the future technological systems for concrete recycling in the Netherlands, with and without C2CA innovation?” (Annex 7)

6.1. Environmental Life Cycle Assessment

The characterized results from the ELCA (Fig. 7) show that the niche innovation performs relatively better but not significantly better in the following impact categories: climate change, fossil depletion,

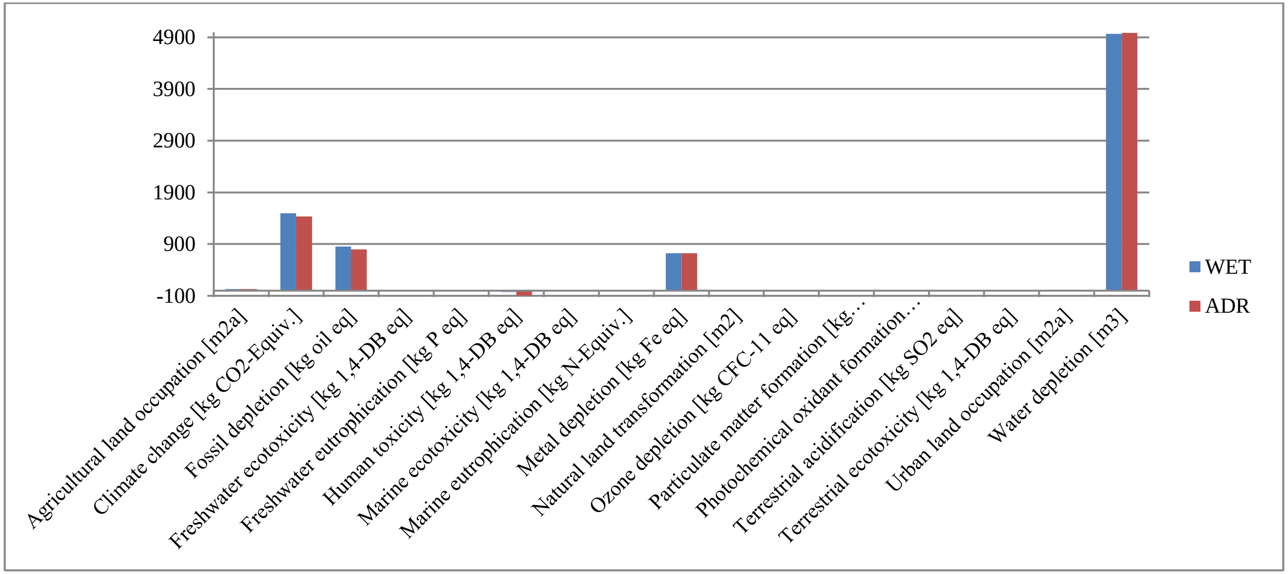


Fig. 7. **Characterized mid-point environmental impact potentials**

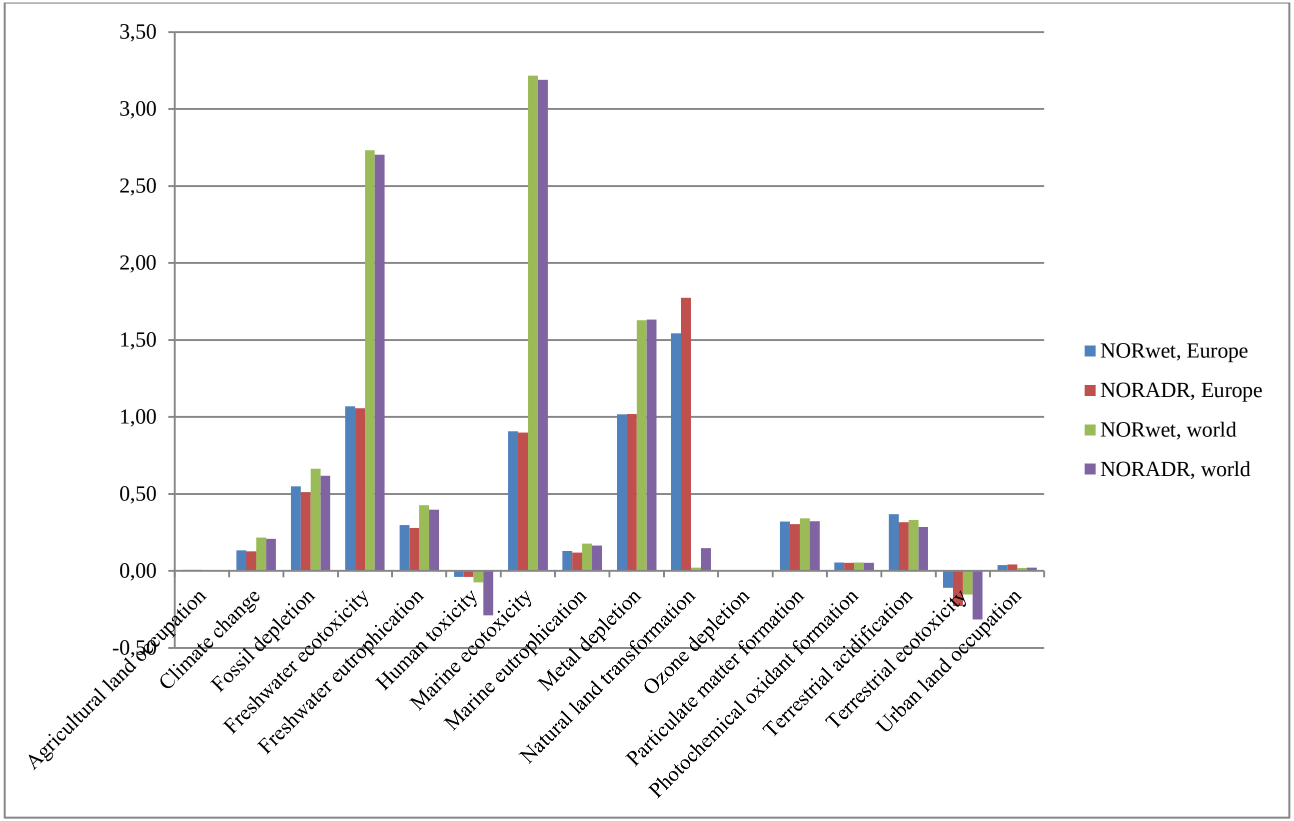


Fig. 8. **Normalized mid-point environmental impact potentials**

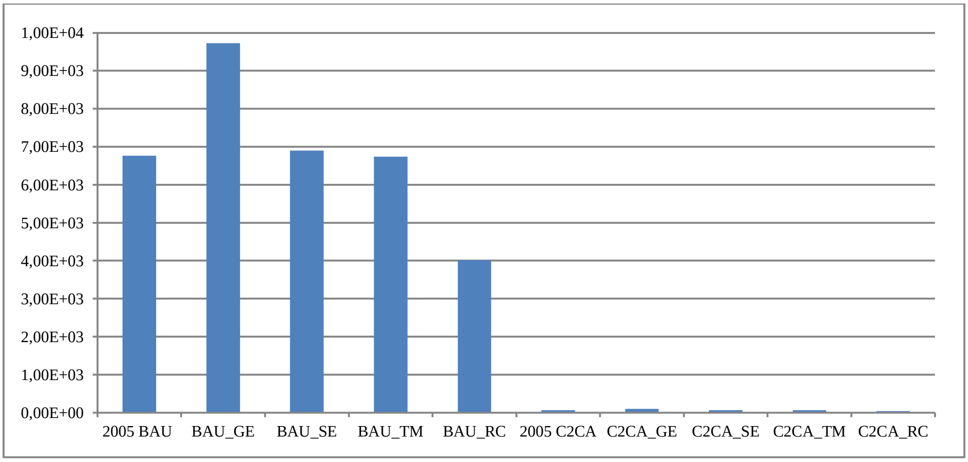


Fig. 9. Human health [DALY]

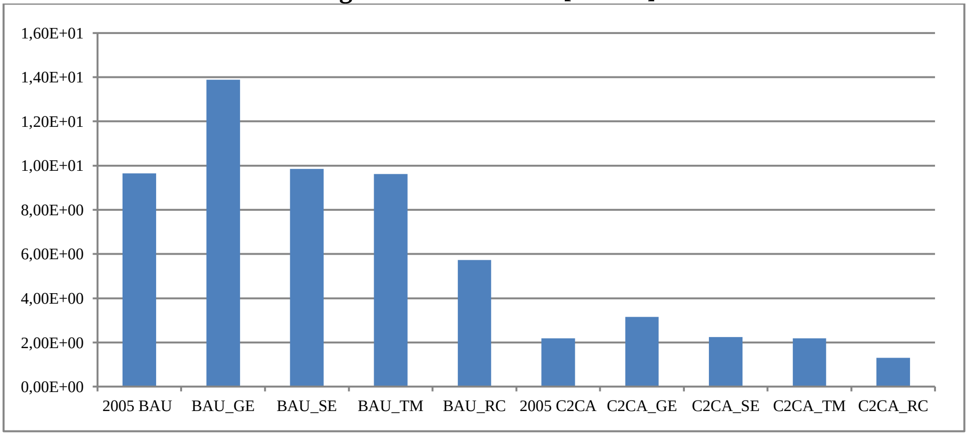


Fig. 10. Ecosystems [species.yr]

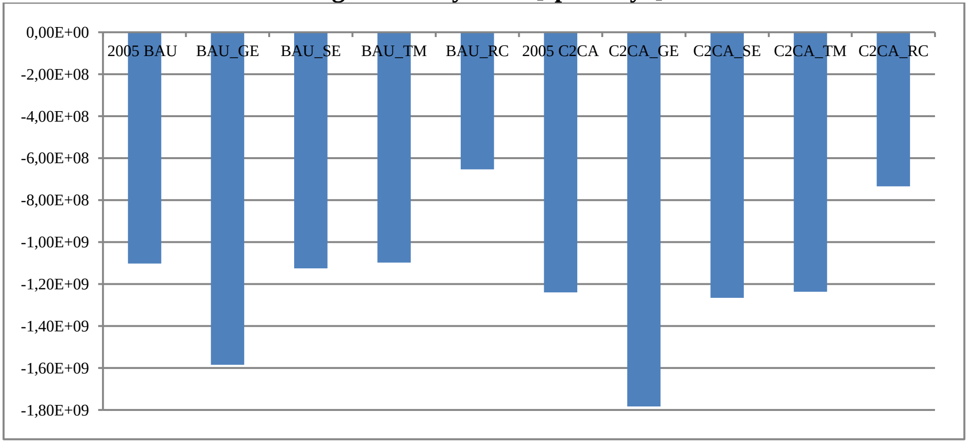


Fig. 11. Resources [$]

freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, marine eutrophication, ozone depletion, photochemical oxidant formation, particulate matter formation, terrestrial acidification, and terrestrial ecotoxicity. In the rest of the impact categories, the technology in the regime performs better that the one in the niche. The normalized results (Fig. 8) show that the niche innovation performs better than the regime technology in all impact categories, except agricultural land occupation, metal depletion, natural land transformation and urban land transformation.

The results from the upscaling (Fig. 9, 10, 11) show that the technological innovation performs relatively better in all scenarios and on all end-point categories than the technology in the regime. Contribution analysis of the different life cycle stages is presented in Annex 7.

6.2. Social Life Cycle Assessment

The SLCA results with both standardization techniques show that the company supply chain performs relatively better with the reference technology than with the innovative technology on most indicator categories at micro-level decision support. In the indicator sub-category *EoL Responsibility* and *Safe and healthy living conditions* the supply chain implementing the innovative technologies performs better than that implementing the reference technology with both standardization techniques. There is a difference in the results caused by the standardization technique used – the supply chain implementing the innovative technology performs better than the one implementing the reference technology in one more sub-category - *Technology Development*, when the results are calculated with the LST standardization technique. The standard deviations for each scenario show that the company performance values for all sub-categories and scenarios are within 1 standard deviation of the results for the respective sub-category.

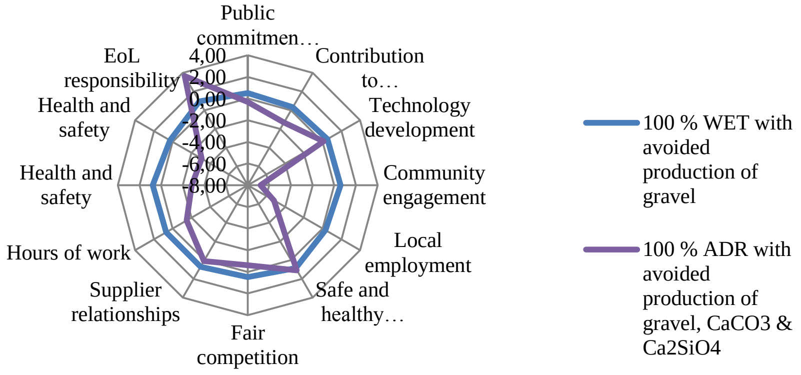
The performance of the companies at micro and meso level differ due to the consideration of the larger context in the meso-level decision-making scenario, where the social impacts of larger companies are included. In this scenario the cement production sector is included, since the maximum project performance of the ADR technology involves recycling of the cement paste substituting certain amounts of limestone. At the meso-level, it is recognized that it may not be possible to produce all aggregates by recycling and also the impacts of the aggregates-producing company are included. The company is also large and has good performance on the selected indicators.

This model for SLCA gives an opportunity for combining the results of a SLCA with results from environmental and/or economic assessments by creating unitless indexes and relating the results to the functional unit (FU). FU has been considered before in SLCA, but this study presents a different approach. Another contribution of the case study is the selection of indicators on a basis of a mixed approach: both top-down and bottom-up, which allows for certain issues to be considered and the stakeholders to participate and select relevant indicators for the specific industry and country context. Other contributions of the model are the proposed operationalization (e.g. treatment of indicators), characterization scheme and normalization approaches generating indexes, which can be further aggregated.

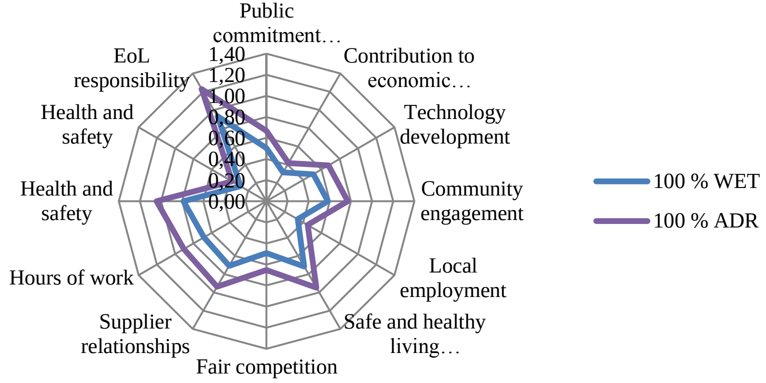
The results from the application of the model to the case study show that large companies seem to perform better than smaller companies when indicators related to complying with international agreements or with stakeholder involvement are used. Examples of such indicators are whether the company has a practice on sustainability reporting or whether the company is committed or not to international (voluntary) agreements/schemes/policies. The reason might be that such agreements are usually voluntary and require funding, which a smaller company might not be able to dedicate for such purpose. Therefore, when such indicators are used, the researchers should be careful, when interpreting the results. On the one hand, the better performance of large companies should be acknowledged, on the other, it is necessary not to discourage small companies from participating in supply chains with large companies because of fear of being judged as performing worse.

It is also possible to do a social (re-)design of the concrete recycling chain in the case study by identifying all the indicators, which need to be improved, so that the supply chain implementing the innovative technology performs better than the one implementing the reference technology on all indicators.

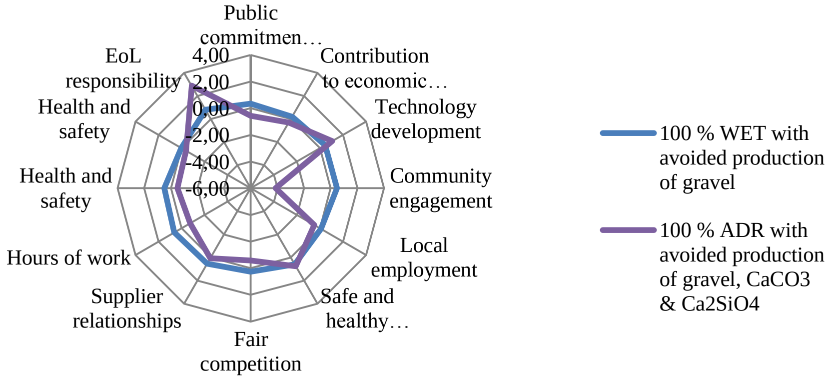
Another issue is the micro- and meso-level decision-making contexts and that the results vary depending on which decision-level is chosen. If we consider the one-score results at micro-level, then the innovative technology should be rejected on the basis of its relatively worse performance, but if we consider the results at meso-level, the



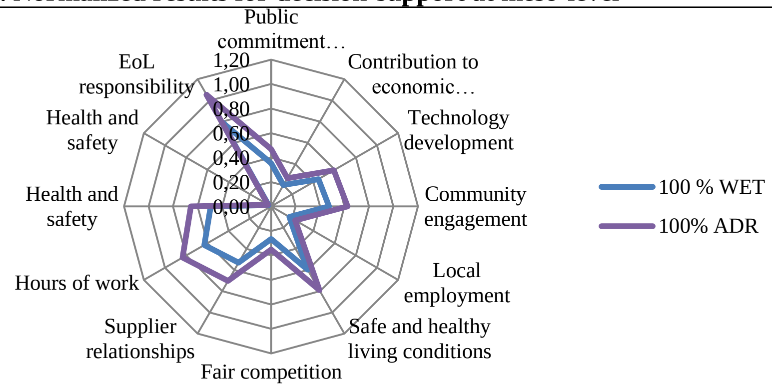
12a. Normalized results with avoided production at micro-level



12b. Normalized results for decision-support at meso-level



13a. LST standardized results with avoided production at micro-level



13b. LST standardized results for decision-support at meso-level

technology should be accepted. In this case, it will be accepted also because of the positive impacts in the supply chain of a large company. Thus, it seems that company size matters in the social performance assessment approach. It also means that if a traditional activity is performed by a large company in one scenario and an innovation of the same activity - by a small company in another scenario, then the scenario with innovative activity may not be chosen and innovation will not be supported.

There can be three implications:

- a necessity to reconsider the appropriateness of the indicators in the Guidelines for the case of a S-LCA of a supply chain of a product, produced by an innovative technology;
- the necessity to create a protected zone for companies implementing an innovative technology, if they have a relatively worse social performance, so that these companies have some space and time to improve their performance. Such a measure, requires a decision to be taken and policies to be made at government level;
- the necessity to choose the correct level for decision-support depending on whether the object of assessment is product or technology. Comparatively worse social performance at micro-level does not mean comparatively worse social performance at meso-level.

If the decision-making basis are not the most aggregated (one-point) results, but results at the level of sub-categories, then since none of the scenarios performs better than the other on all indicators, a definite conclusion would not be reached as to which technology is better than the other from SLCA perspective. Therefore, it would be necessary to introduce a subsequent step in the model for a micro-level decision-making: multi-criteria assessment.

Another aspect, which is necessary to consider is that the SLCA is based on data from the foreground system, which give opportunity to show the possibilities of the social performance model, but does not provide as complete information on the impacts from the supply chain as the LCA. Therefore, it is recommended to apply input-output analysis, in order to achieve completeness of the assessment along the supply chain and to capture sector-specific aspects.

6.3. Decision-making with Multiple Criteria

In order to take decisions, involving multiple criteria expressed in different units, it is necessary to use multiple criteria decision-making (MCDM) methods. These methods allow not only for building a decision-making tree (Fig. 14), which can support environmental, social, economic and other (technical) criteria for sustainability to be considered, but also, depending on the multi-criteria methods applied, allows for compensatory or non-compensatory approaches. The compensatory approaches would allow different valuation of the three sustainability aspects, e.g. environmental sustainability can be valued more than social sustainability. The non-compensatory approaches are based on the egalitarian principle and do not allow compensation of a bad performance on one criterion by a good performance on another criterion. Compensatory approaches can be linked to the notion of weak sustainability, while the non-compensatory approaches can be linked to strong sustainability.

If applied to the C2CA case study at project level, MCDM methods can be used to decide, which aspect of the social assessment is most important to improve to achieve a better social performance on all impact sub-categories. MCDM also allows for combining and interpreting results with different units. It is also possible in particular cases to value environmental, economic and social aspects differently, which requires the possibility to assign different weights, which is also supported by MCDM methods. Within the scope of this project, the MCDM methods were researched, a framework for application of MCDM methods was elaborated and a calculation procedure prepared in parallel to the LCA data collection. Nevertheless, the work was not completed due to the fact that the three life cycle assessments at project level were based on different system boundaries (LCA on foreground and background system, while LCC and SLCA only on the foreground one). Since it cannot be certain that the results from the LCC and SLCA will be the same, if the background system was included, the choice at the time was not to apply the MCDM.

Fig. 14. Decision-making tree at micro-level for LCSA support

6.4. Input-Output Analysis

Input-output analysis was applied on the basis of the LCC results at Annex 6. In order to calculate the economic, environmental and social effects from the existing technological regime and the innovation in the niche, a 35 sector input-output table for the Netherlands for the year 2011 (at basic prices) together with the environmental and social accounts were used. Although, the environmental impacts were calculated by the use of IOA, the results are not presented here because of the lack of comprehensive data - it is possible to calculate impacts only for a limited number of impact categories. The total economic effects from the demand on the economy created for the treatment of a 1 ton of EoL concrete with the innovative and reference technologies, at the niche and regime level respectively, were calculated and are presented in Fig. 15. The social accounts provide possibilities for calculation of social effects in terms of labor compensation, hours worked, competences of workers and accidents. The categories are again more limited in number than the indicator categories offered by *the Guidelines*. Nevertheless, IOA gives a possibility to consider limited number of indicators, but for the foreground and background system. For purposes of illustration of the possibilities of calculating social indicators with IOA, the indicators - compensation for employees, number of employees and hours worked by employees in each sector for the demand created for the FU - are presented on Fig. 16, 17 and 18.

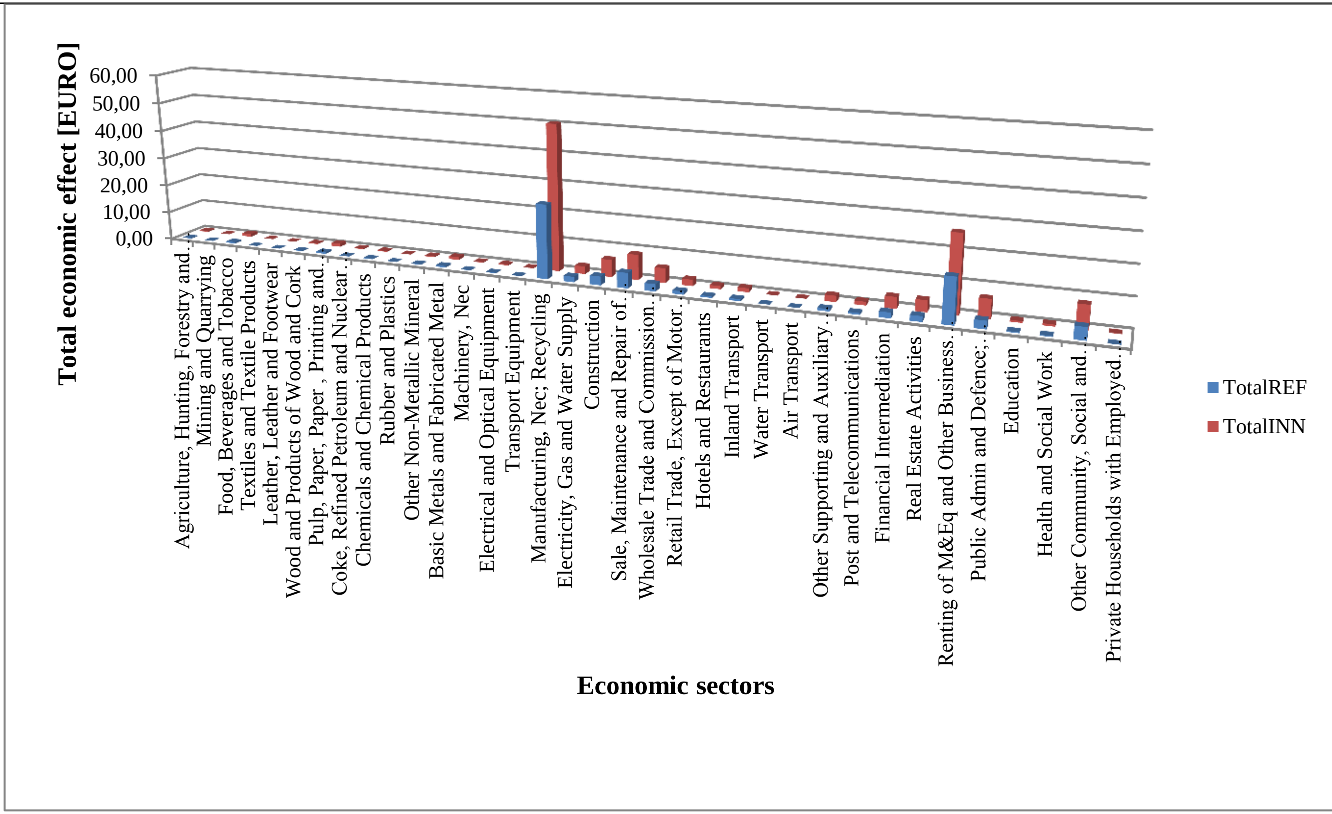


Fig. 15. Total economic effect for treatment of 1 ton of EoL concrete with innovative and reference technologies

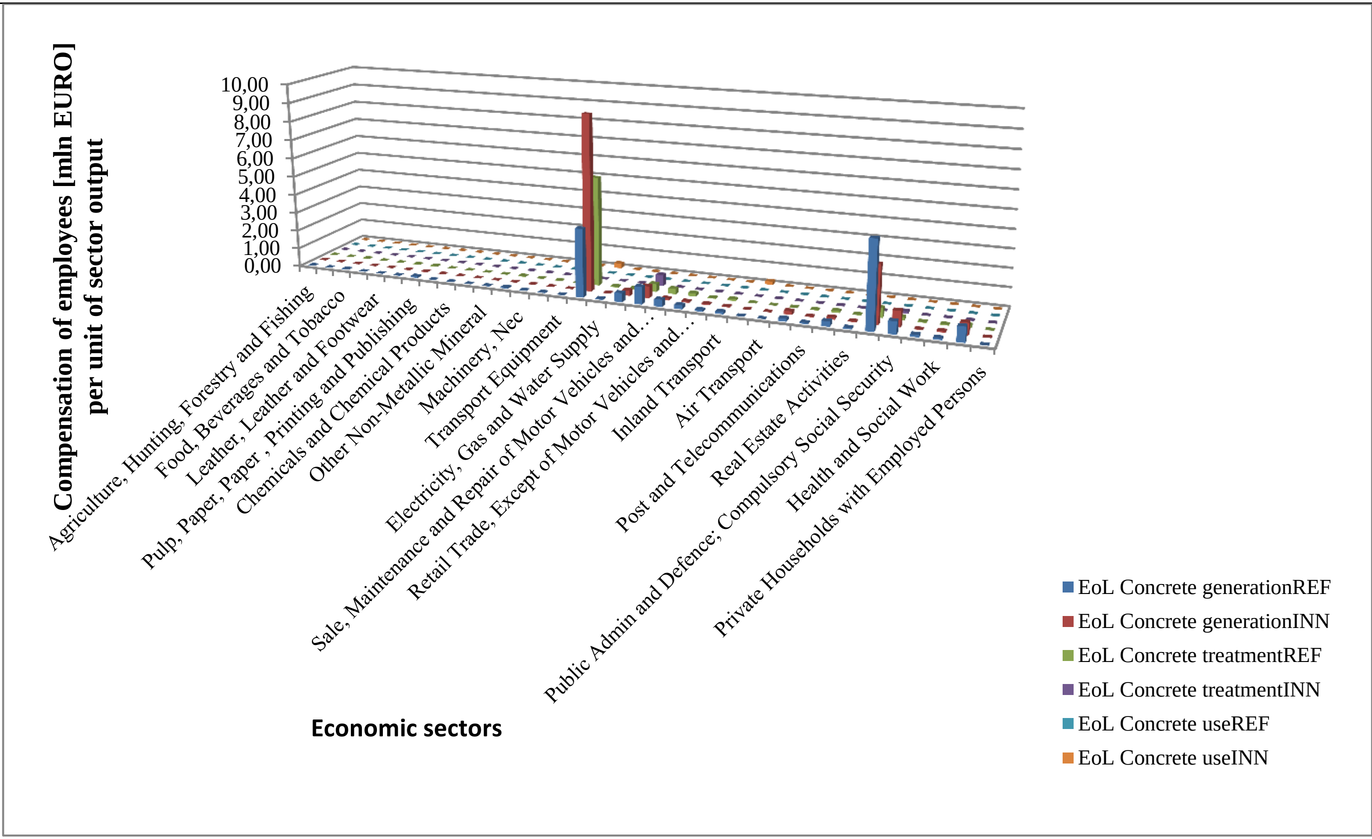


Fig. 16. Compensation of employees [mln EURO] per unit of sector output for the demand created for the FU

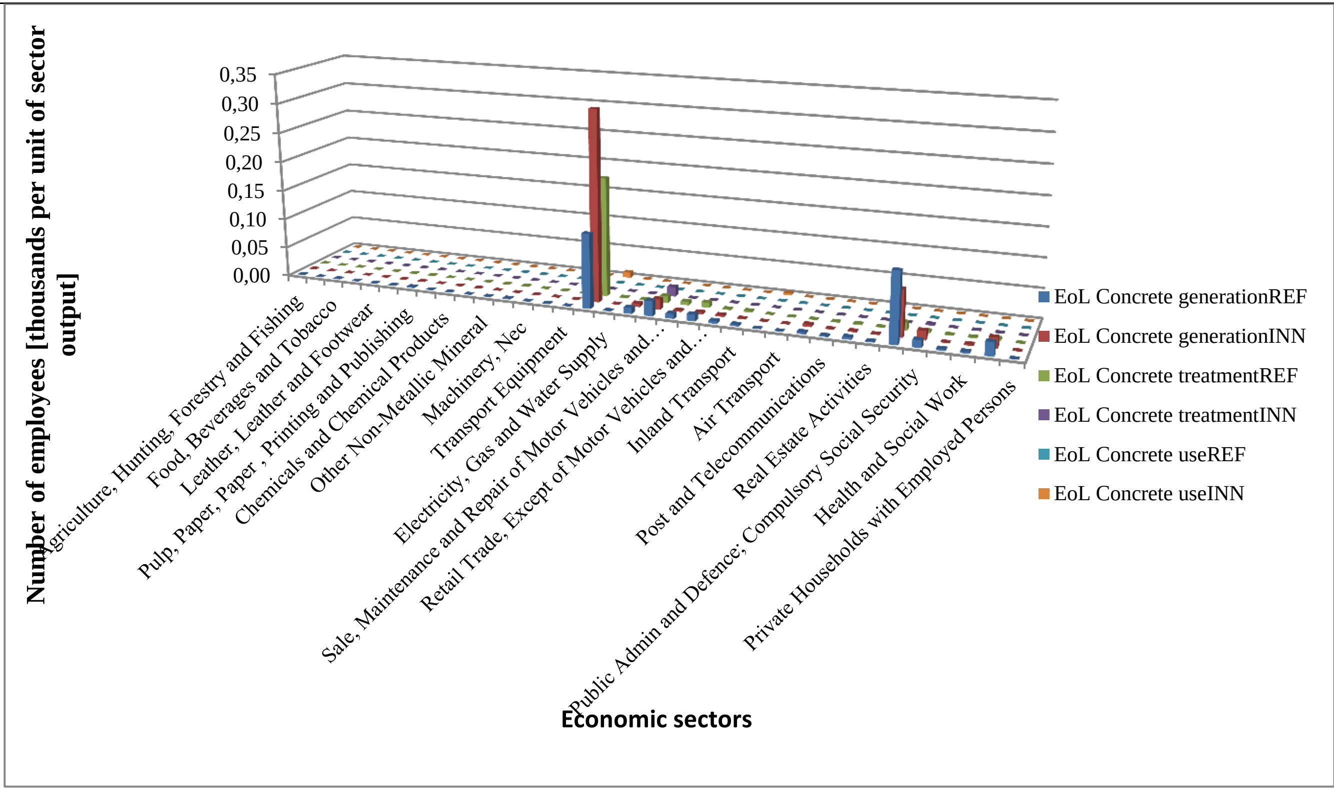


Fig. 17. Number of employees [thousands] per unit of sector output for the demand created for the FU

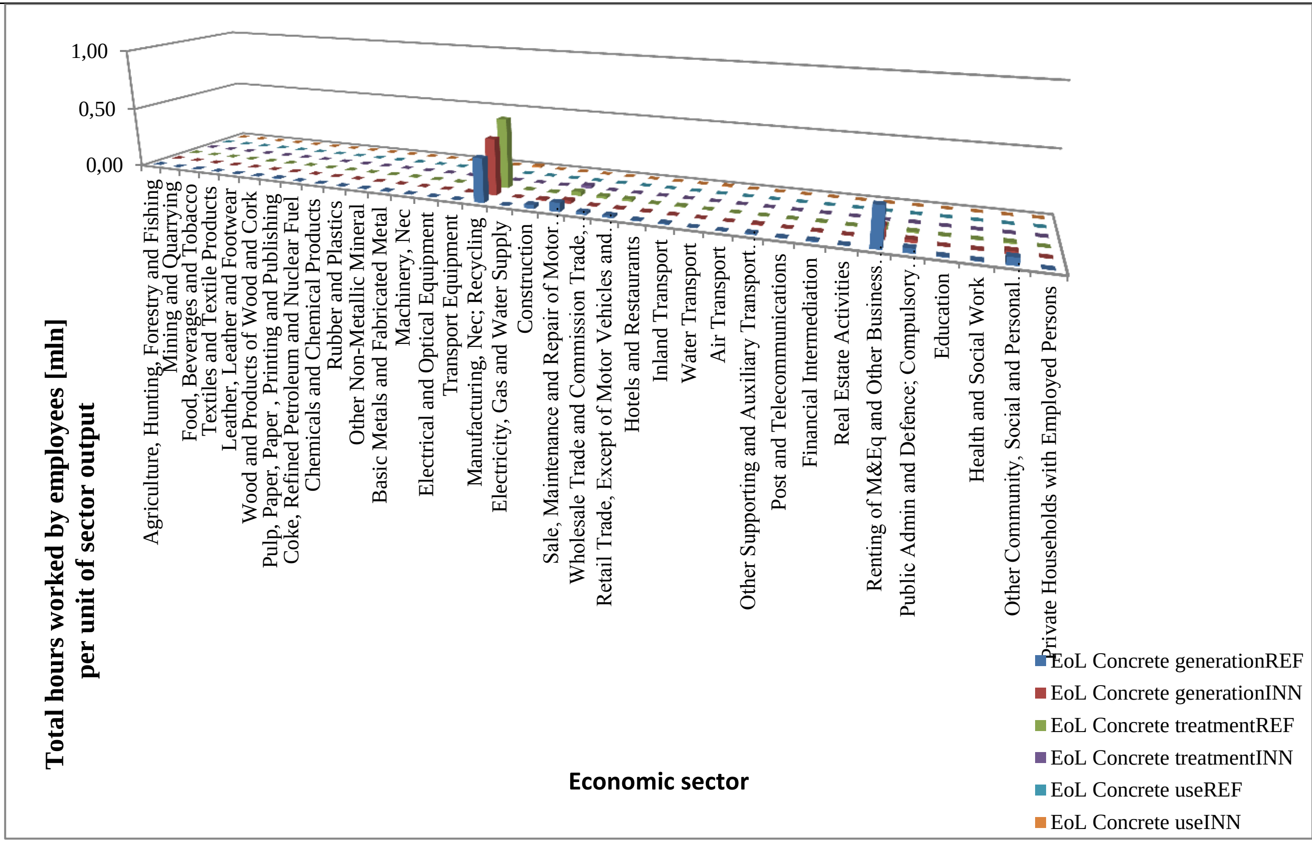


Fig. 18. Total hours worked by employees [mln] per unit of sector output for the demand created for the FU

7. Implications of Social Theory for Assessing Social Impacts from Products and Technologies in a Life Cycle Perspective

In result of the conclusions reached in Annex 3, a review study was conducted (Annex 4), which reviewed the existing literature on SLCA and concluded that it is necessary to include social scientists and knowledge from social sciences in the methodological development of SLCA, since until now it is mostly engineers, who are involved in it. More specifically, it was concluded that the research needs and unsolved issues are related to the lack of consensus on social impact modelling and the need to develop characterization models in SLCA. In addition, the existing methodological approaches were reviewed and it was concluded that *the Guidelines* and *the Handbook* are based on a similar approach, while there is third approach under development, which considers social theories, such as capability theory and multiple-capital approach (Falque et al., 2013). The conclusion is that social theories need to be considered in the methodological development of SLCA.

Therefore, a study was conducted, which tried to identify the specific gaps at each phase of SLCA (Annex 5). Some of the challenges, identified are that *the Guidelines* are neither suitable to be applied when the organizations, performing the processes are unknown, nor for assessment of technologies (Lehmann et al., 2013); that it is necessary to take into account sector-specific data (Martínez-Blanco et al., 2014); that there is no established link between product and process and social-economic indicators or an approach how to develop such metrics (Kruse et al., 2008), as well as between global value chains and site-specific sustainability assessments (Swarr, 2009). It is generally recognized that the challenges at the Social Life Cycle Impact Assessment Phase refer to characterization modeling of social impacts (Grießhammer et al., 2006; Andrews et al., 2009) and are caused by the difficulties of assigning or classifying indicators into different categories (groups). Whereas understanding of impact pathways for environmental impacts is good, Ekener-Petersen & Finnveden (2012) suggest that the understanding of social impact pathways needs to be improved. A first step is to sufficiently define the Area of Protection (AoP). Two methodological approaches for social life cycle impact assessment exist, but there is no comprehensive assessment framework (Macombe et al., 2010) and a standardized, commonly agreed methodology is lacking (Lehmann et al., 2011; Martínez-Blanco et al., 2014). In addition, the existing methods within these two approaches are inconsistent (Kruse et al., 2008), there is no theoretical (epistemological) framework developed for SLCA (Macombe et al., 2010) and the human, social and institutional dimensions are not outlined in the current SLCA framework (Feschet et al., 2010).

Practice theory provides a possibility to describe a process in an LCA inventory not only as a technical process, but as a socio-technical process by including not only the technical aspects (materials, energy), which are usually included in the environmental LCA, but also the social aspects, thus providing an opportunity to better understand and identify the factors, which cause social impacts within the process. It is also useful for identifying the sector-specific indicators and impacts because of the relationship between the sector and the production processes within the sector.

The study on the application of practice theory to SLCA (Annex 5) aims to provide an alternative for an inventory structuring in SLCA by identifying, on the basis of practice theory, which indicator categories need to be studied systematically, so that there is a higher degree of synchronization between the SLCA studies. Fig. 19 and 20 present the main elements of a socio-technical process, which need to be considered in an inventory and the bodily-mental activities of the subject in the process. The implications for SLCA would be that the inventory would be not only organization-related, but also process-related, and sector-related, which may give a possibility for benchmarking for indicators and comparison of different SLCA results.

In addition, an approach for assessment of social impacts based on a practice theory and the driver-pressure-state-impact-response (DPSIR) approach for causality modelling by linking it to assessment of health and safety impacts, the multiple-capital approach and capability theory was elaborated (Annex 5). An approach for understanding the drivers of social impacts within processes, and as a constituent part of product and technology systems, is elaborated. The approach is based on a combination of different practice theories by considering their commonalities and differences and in what way they can contribute to a methodological development of SLCA. This approach gives opportunity for understanding where in the life cycle of a product there can be social impacts by looking closely into processes and sectors in addition to organizations. It makes it possible to distinguish between the social impacts of two different products or technologies, produced and used by the same company and it includes the company and sector aspect of production in addition to the process aspect. The transformation of an object to an outcome is the technical part of the socio-technical inventory, which is taken into account in LCA, but the other elements of the process (practice) also need to be considered, so that there is synchronization among the different SLCAs and that there is not such a big difference between the number and the types of indicators used.

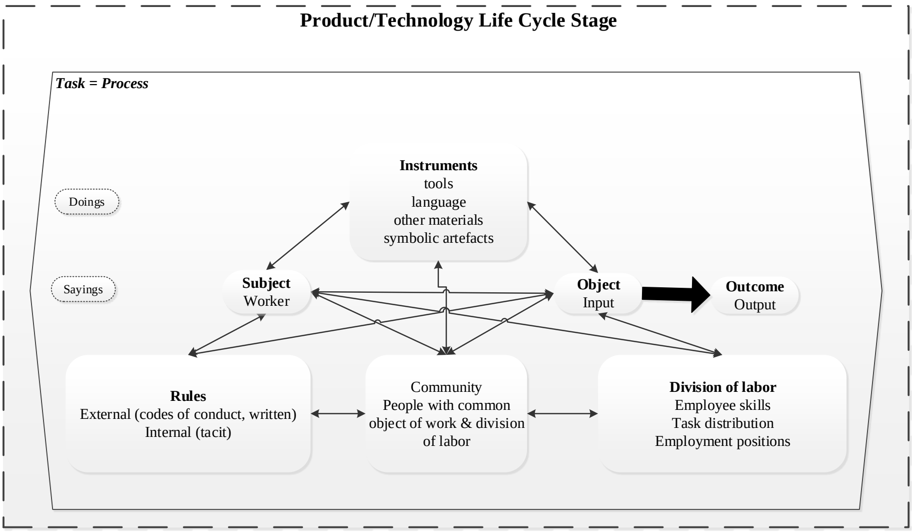


Fig. 19. In-depth view of the production process as a practice

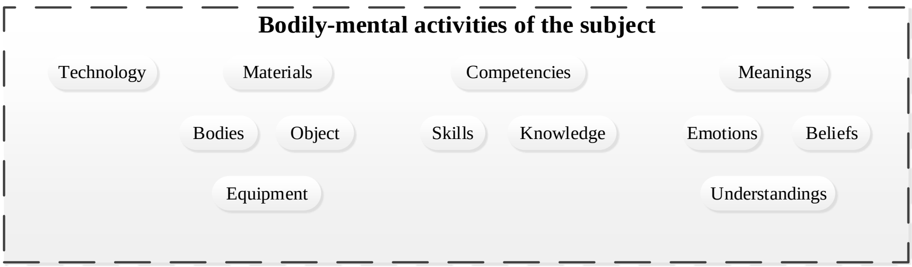


Fig. 20. Technology use and non-industrial use of product

There are different bodily-mental activities of the subject, which can be classified under 4 groups: meanings, competencies, materials and technology. The elements in the process, influence the subject by the bodily-mental activities, which the subject performs in the process and have an impact on the subject's wellbeing.

Practices are inter-related with other practices both locally and globally over space and time. Here there is a link between the product systems in life cycle assessment and global supply chains. Thus, practice theory can contribute to understanding and assessing the spatial, geographical and cultural specificity of a process.

Indicator selection has been recognized as an issue at the *Life Cycle Inventory Phase* and the framework for SLCA based on practice theory (Fig. 19, 20) provides a useful framework, within which to choose relevant indicators at process level, organization level and sector level. Practice theory can contribute to judging indicators relevance by providing an understanding of what is important in a process from social perspective and what aspects need to be included in the assessment of social performance of companies or social impacts on human well-being related to a specific process.

Selecting relevant indicators at the inventory phase is related to the social life cycle impact assessment, where social impacts on human well-being or company performance will be assessed, based on these indicators. As already mentioned, the indicators used at present are based mainly on political targets and less on social theory and social causality. The practice theory provides framework for identifying relevant indicators to include in the assessment: technical, social (working hours, health and safety, psychological aspects, competences, capabilities), environmental (materials, energy, waste), normative (legislative), occupation-related, organization-related, product-, process- or technology related, supply chain-related. In this way, it is also possible to contribute to a better structure of an integrated inventory.

Identifying and collecting data for relevant indicators can contribute to solving another issue - the lack of databases to support social impact assessment. Practice and production are considered the same by Marx (Nicolini, 2012:30), therefore it is possible to say that there is a practice, comprising of certain elements, in each production process, on the basis of which a typology of processes per product, technology, company and sector can be created, based on technical environmental, social, economic (costs, wages) and other aspects. Data for these typologies of products can be found in input-output tables for materials, energy, price, national statistics on health and safety for accidents, stress, illnesses, etc. Such data can be found for different activities, different sizes of companies, etc. This can be a contribution to sector specific assessment.

At the *Life Cycle Impact Assessment Phase* practice theory can contribute to deriving a framework for characterization modeling based on the Driver-Pressure-State-Impact-Response (DPSIR) approach, because practice theory provides an insight into causality within a process (practice) including both social and technical aspects (humans and instruments) and can be a good basis for identification of the driver, the pressure the state and the impact and to design a response. Practice theory can be also be used to identify fate, effect and exposure in social causality within the process or company as a practice. In addition, data on effect can be collected from other information sources. The DPSIR framework serves as a basis for quantitative (characterization) modeling of many impacts in life cycle assessment and is considered a relevant framework to model social impacts. In the framework of DPSIR practice theory can be used to identify the drivers, the pressures and the response (decision making with respect to negative impact, re-design of working environment, social design, innovation, etc.). Practice theory is useful for analyzing a situation and identifying reasons for problems (e.g. accidents) in the working environment. For example, if a company does not have accidents or if it does have accidents, the reasons for either one situation may be found in the practices in the company and in the habitus of the employees in a certain occupation or activity. A possible application can be social design or working environment design by re-designing the social impacts by identifying where in the existing practice there is a problem and how can it be overcome.

Possible contributions of practice theory to better understanding of the Area of Protection in SLCA come from the work of Aristotle, who considers that the knowledge obtained in a practice can lead to fulfillment of human beings (Nicolini, 2012:27), which can have positive impact on human well-being. At the same time, here it is possible to make a connection with the capabilities and social capital approaches because obtaining more knowledge can lead to enhancing individual and collective competences (generic or specialized) and capabilities and thus to a positive impact on social capital. Another link from practice theory to social capital can be made through the work of Bourdieu and his notion of different capitals. Several researchers in SLCA have recognized the need to consider the multiple-capital approach and human capabilities (Feschet et al., 2010;

Reitinger et al., 2011). Reitinger has even provided a theoretical framework of how to apply the capability theory to SLCA.

With respect to social impacts from the use stage of a product/technology, practice theory can contribute to better understanding of whether the product/technology is used in the recommended way and what are the impacts of it use on consumers in terms of impacts on the body, emotions, competencies. These elements correspond to some of the components of well-being (defined as physical, social and psychological) by Pressman et al. (2013).

Well-being is considered in two areas of protection (AoP) in SLCA: human health and wellbeing and human productivity (Weidema, 2006). Practice theory is relevant for both approaches and a combination of practice theory with the suggested approach in Falque et al. (2013) may also be relevant.

The DPSIR approach is a decision-making framework, which has served as a basis for studies in different fields (Smeets et al., 1999). It has been used as an underlying framework for assessment for some of the life cycle impact assessment models and it can be applied for identifying the drivers and pressures in the social system, in the working environment of a process, identifying the state of human capital (resources), social capital (resources), and other capitals from Bourdieu's approach, and the change (impact) on the state of these resources made by producing a product or technology. Drivers and pressures within a production process or a system of processes can be identified by considering risk factors in the working environment, such as physical, chemical and biological, psychological and social factors, etc. Furthermore, it is possible to identify the state of and the impact on these resources. Falque et al. (2013) have an interesting approach based on the multiple capital model, which they connect to the capabilities approach. The suggested approach for identifying and assessing social impacts within and outside the production processes based on practice theory can be connected to the multiple-capital theory based on the connection between Bourdieu's cultural, social, economic and symbolic capital and the economic/technical, social, human, natural and institutional capitals (Falque et al., 2013), but it is also possible to combine and elaborate further a new approach for assessment of social impacts from a process by combining SLCA with the field of health and safety and the causes and causality of occupational accidents (Jørgensen et al., 2010) and drawing from the theoretical fields of practice theory, multiple capital model (Falque et al., 2013) and capabilities theory (Reitinger et al., 2011; Falque et al., 2013). A Framework for Assessment of Social Impacts on (Human) Resources and Productivity from Processes and Organizations is based on the different types of resources (capital) entering in a process from a resource base in different occupations (e.g. a dismantler, a driver, a person, working on a crane) is suggested and illustrated with an example in health and safety in an organization (Fig. 21). Within the process there are several types of causes: external (national policies), management (knowledge, capabilities, behavior of managers), indirect (root) causes due to organizational and technical failure and direct causes due to behavioral and situational failures.

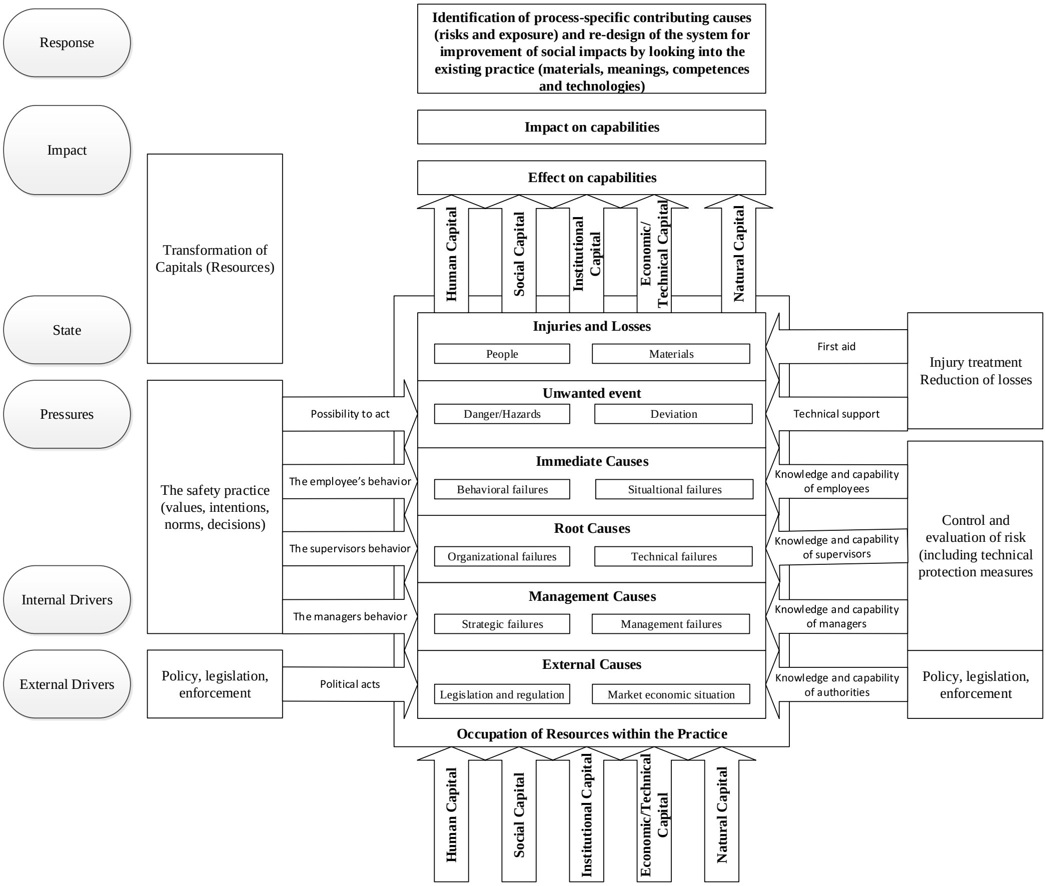


Fig. 21. Illustration of the Framework of Assessment of Social Impacts on (Human) Resources and Productivity from Processes and organizations

These causes lead to unwanted events, which can be deviations, risks, hazards e.g. in the working environment, which cause injuries and losses (to people and materials). These injuries and losses have an effect and impacts on the capabilities of the resources. Looking backwards into the impacts and their causes gives good opportunities for process- re-design and implementation of prevention measures. This is relevant for the industrial activities in any sector, but especially in the construction sector, which has high accident rate. Re-designing of the practice is an intervention, which can be done based on looking in the meanings, competences, technologies and materials in the system (process, organization) and finding out what has to be changed in order to improve the impacts from the system (process, organization, etc.).

This is an example referring to one of the aspects (body in the materials aspects), but the same thinking can be applied to skills and knowledge and the external and internal factors, which influence them. The fact that diseases and accidents will have also influence on the skills of an object, in addition to the training in a company and by the care of the company to develop these skills, only shows the interrelation of the social factors to well-being.

8. Discussion

LCSA is an approach to sustainability assessment, which generally faces many challenges, some of which are:

- Different level of development of the different assessment components (LCA, LCC and SLCA);
- Difficulties with data collection due to data confidentiality and non-availability of data bases for the economic and social assessment;
- Difficulties in developing of a single inventory with data for environmental, social and economic assessment for all processes;
- Difficulties with relating the social impacts to the functional unit of the LCSA study and with characterization modelling, especially with unclear definition of well-being;
- Difficulties to compare SLCA results, because they are performed with different indicators;
- Interpretation of the results obtained with different assessments, expressed in different units.

These difficulties are complex and interrelated and require a theoretical and methodological approach, which is capable of handling them together. The MLP theory provides a good framework for a LCSA of technological innovations, which involve different levels of assessment. Practice theory provides a good basis for assessment of the way the two technologies are implemented. Interpretation of results and decision-making on the basis of the three assessments can be facilitated by multi-criteria assessment techniques, in addition to the efficiency (performance) calculation of an environmental impact for an economic value.

The compatibility of LCA and SLCA can be increased with respect to boundaries if SLCA databases are developed and if there is no problem with data confidentiality. Using input-output tables and statistical information for the working environment part of the social life cycle assessment will increase the number of quantitative social indicators used. Another option is to find a way to express the results from the SLCA for the functional unit of the study. To this purpose a
a calculation model for SLCA is developed, which is able to handle different indicators with different units, and to relate the results to the functional unit. The model increases the computational compatibility between the environmental, social and economic LCA.

In terms of strengthening the SLCA methodology, it is necessary to consider the knowledge of social sciences in order to improve the methodological development of SLCA. The compatibility of SLCA and practice theory was assessed to serve as a basis for a process-based understanding of social impacts and to support a framework for assessment of social impacts on human resources and productivity.

Another contribution to SLCA is the recognized need to identify the sector-specific impacts for different sectors, so that in addition to generic, there are also sector-specific indicators and impacts, assessed. Such sector-specificity may depend on the practice in the sector and on the production and process activities in the sector. Environmental impacts specific to the sectors in the case study are noise from the crushers, vibrations from the sieves in the concrete recycling, different accidents with falls, muscular-skeletal diseases, conditions of work and pay, etc.. With its consideration of materials, technology, competences and meaning, practice theory provides a good approach for analyzing the impacts in the construction and waste recycling industry.

Waste and resource management systems are very complex and may require the combination of several tools for better representation of the results. Material flow analysis is a useful resource management tool and system dynamics is another one. The combination of LCA with MFA is an opportunity to upscale the impacts from a process/product to a sector/economy-wide level without losing the specificity of the process and keeping the physical units.

Enhancing the LCA into LCSA provides the opportunity to assess environmental, economic and social sustainability, but at the same time increases the uncertainty of the results because of the higher complexity of the assessment. Improving the SLCA assessment methodology is a high importance for decreasing the challenges in LCSA outlined among others by Klöpffer (2008) and Zamagni (2012).

9. Statement of the PhD's Project Achievements and Contributions

In summary, the main contributions of the PhD project are:

1) Elaboration of an integrated multi-level LCSA framework based on Klöpffer (2008) and Guinee et al. (2011).
2) Elaboration of a conceptual model for LCSA as a basis for a multi-objective LCSA tool.
3) Application of the LCSA framework to a case study.
4) Elaboration of a social performance model for SLCA and its application to a case study
5) Analysis of the applicability of practice-theoretical approach to SLCA and elaboration of a framework for SLCA based on practice theory, capability theory and multi-capital model.

The contribution of the research to the research questions is provided in Table 2.

Outlook and insights for future work:

The following recommendations for future work are made:

- Creating a practice-based socio-technical inventory of construction processes sector-specific and generic. This approach to inventory is not applicable only to social life cycle assessment, but also for sustainability in general;
- Sector-specific indicators: identifying sector-specific indicators, supported by the knowledge of the practice in the sector and statistical information.
- System dynamics and optimization for environmental or all three aspects: making a system dynamics model can contribute to dynamic simulation and better visualization of the sustainability performance of the system.

Table 2. Contribution of conducted research to the research questions

Research Questions	Research Contribution
Main research question	
In what way can environmental and social LCAs complement each other in life cycle sustainability assessment and what methodological development is needed in S-LCA for a potential integration?	Provides a structured approach for multi-level LCSA.
Sub-research questions:	
Methodology-related sub-research questions:	
• What is the baseline for sustainability assessment for decision-making by using environmental, social and economic life cycle assessment and what are the similarities and differences with other methods?	LCSA is an assessment producing results in different units. The interpretation of the results may be easier if a product is doing well on all pillars of sustainability, otherwise it might be necessary to use other methods allowing for interpretation of results with different units, such as the MCDM methods.
• In what way can the compatibility of E-LCA and S-LCA be increased with respect to boundaries?	Applying IO analysis allows for a more complete economy-wide assessment, which can provide support for LCC and SLCA with respect to including the background system, for which it is often difficult to collect data.
• In what way can experience from other assessment tools and theories be used to strengthen SLCA methodology?	SLCA methodology can be strengthened in the following manner: on the basis of a composite indicator calculation procedure the robustness of an aggregated result can be improved, on the basis of the practice-theoretical

	approach and multiple capital theory – the understanding of social impacts can be improved and the connection between social impact and work process can be increased.
• What else can be included in the SLCA methodological sheets for stakeholders in the construction sector in order to improve them?	Practice-theoretical approach to SLCA could be an option for an alternative as to what needs to be included.
• What other methodologies can be used to support the LCA in the case study?	LCA can be combined with MFA (e.g. Annex 1 and 7), with IOA and with MCDM.
• What are the strengths, weaknesses, opportunities and threats of performing an integrated social, economic and environmental LCA in comparison to a non-integrated LCA?	Included in different places in the thesis.
Case study-related sub-research questions:	
• What environmental and social-economic inventory indicators and impacts are applicable to the sector?	Analysis of sector-specific environmental and socio-economic impacts is made.
• What are the environmental and socio-economic impacts of the substitution of raw with recycled materials?	Assessment of the environmental and socio-economic impacts.

10. Conclusion

The issues and challenges in life cycle sustainability assessment and in social life cycle assessment are numerous and research efforts need to be directed for solving these challenges. The integrated multi-level perspective for life cycle sustainability assessment provides a solid, yet dynamic framework for implementing life cycle sustainability assessment for technological systems, which need to be assessed at several levels. The multi-level perspective strengthens the communication of the results to researchers from other scientific fields and enhances the possibility of a LCA or a LCSA study to explain a context.

Another interesting theory is the practice theory, which provides many insights for strengthening social life cycle assessment by grounding it in social sciences, by providing a consistent social life cycle inventory concept, by providing a framework for assessment of social impacts at process and sector level, for supply chains of companies.

It can be concluded that combining theories from science and technology (MLP, practice theory) with life cycle assessment has been very useful in the specific case study because they complement each other. While theories of science and technology usually explain historical transitions, by combining them with life cycle assessment it is possible to use these theories to make predictions.

SLCA is a methodology in its early development and needs methodological support. The current state-of-the art methodology can be supported by the social performance model, while conceptual methodological improvements can be made by applying practice theory in combination with multiple capital model and capability theory.

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