UTRECHT UNIVERSITY

Going Full Circle

The Developments in Life Cycle Assessments to Deal with Circular Economy Problems

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Master's thesis Sustainable Development: Environmental Governance

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Abstract

Scientists, government officials, firms, and other actors around the world are discussing ways to create a sustainable economic system. One often heard option is the circular economy. This is based on the idea that by cycling materials continuously, waste can be prevented and the pressure on the natural system reduced. The circular economy also requires becoming sustainable in order to stay within the natural boundaries of the planet. Currently, the main tool to assess the environmental impacts of products throughout their lifespan is the lifecycle assessment or LCA. Recent developments within the LCA methodology have increased its scope and ambition to also quantify economic and social impacts. Because the LCA methodology assesses lifecycles, and the circular economy thinks in lifecycles, LCA seems a logical choice to support a transition towards a circular economy. However, the major problem with LCA is the fact that it is a highly flexible tool resulting in conflicting and inaccurate results. By recreating the material and socio-economic principles of the circular economy, this research created a transition model of four phases of circular economic development. When the flexibility of the LCA methodology was identified and categorised in various levels of flexibility, it was possible to compare LCA flexibility to the circular economic principles in the various development phases. This provided the ability to identify the maximum acceptable LCA flexibility in each phase of circular economic development if LCA was to continue supporting the circular economy. This resulted in the insight that although the LCA methodology can currently play a positive role in the development of a circular economy, when the economy transitions towards circularity it becomes increasingly necessary to reduce the flexibility in LCA. This is vital because throughout the development of a circular economy actors become increasingly interconnected and must stay within the planet's natural boundaries. Consequently, they need to be able to rely on the quality and precision of LCA studies for their decisions. Therefore, this research concludes that the LCA methodology can play a positive role in the development of a circular economy, but needs to be regularly updated in order to ensure that the maximum allowed flexibility remains acceptable for the phase of circular economy development society finds itself in.

Preface

When I first learned of the existential threat that environmental problems pose to my generation and those to come in the future, I was stunned. I could understand how humans have brought the pending disaster over them, but I could not understand why they did so little to prevent the danger presented to them. Over time, I have learned that there are many reasons why humans act, but the economic reality of a separation of economy and politics in a capitalist system is one of the main reasons. This understanding has given me the conviction that I must do my utmost best to prevent the most serious consequences of this disaster from occurring.

For some of my colleagues and friends, the subject of this thesis will therefore come as a large surprise. To those peers I would like to say that I think the way forward lies in a combination of economic democratisation, as explained in "After Capitalism" by David Schweickart, and sortition democracy, as explained in "Against Elections" by David van Reybrouck. However, both of these paths must operate within the natural context, and therefore I have chosen to focus on helping to design a system that enables economic development within the natural boundaries of the planet.

An important attempt that might be able to achieve just that is the circular economy. The circular economy seems to me one of the most promising economic systems with the potential to return society to a place within the planet's natural boundaries that can emerge from our current economic system. Therefore, I considered it useful to create a little bit more understanding of this circular economy and tried to discover how the largest private environmental assessment tool in existence can help to bring this circular economy closer to realization. This research is an attempt to bridge the gap between industry, science, and government by assessing the LCA methodology throughout the transition towards a circular economy.

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And finally, to my loving partner, Joyce Rave, for her continuous support throughout the past two years without which this thesis would not have been possible.

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List of Acronyms

Acronym	Meaning
3Rs	Reduction, Reuse, and Recycling
BE	Blue Economy
C2C	Cradle to Cradle
CE	Circular Economy
CP	Clean Production
ELCA	Environmental Lifecycle Assessment
EPR	Extended Producer Responsibility
EPS	Environmental Product Statement
IE	Industrial Ecology
IS	Industrial Symbiosis
ISO	International Organization for Standardization
LCA	Lifecycle Assessment
LCC	Lifecycle Costing
LCI	Lifecycle Inventory
LCIA	Lifecycle Impact Assessment
LCSA	Lifecycle Sustainability Assessment
MLP	Multi-level Perspective
OLCA	Organisational Lifecycle Assessment
PLE	Principle of Least Effort
PPA	Precautionary Principle Approach
PSS	Product Service System
R&D	Research and Development
SLCA	Social Lifecycle Assessment
SOLCA	Social Organisational Lifecycle Assessment

Introduction

Throughout the world different ideas are being formulated and implemented to create a more sustainable society. One that is currently extensively discussed by governments and scientists alike is the circular economy (CE). Unlike ideas that promote the necessity to let the economy shrink in order to make it sustainable, a CE leaves room for economic growth. Moreover, while some people believe that technological progress will solve the big environmental and social issues societies are facing, a CE leaves room for active management and steering by public and private actors to reach sustainable development (De Nooij, 2016; Jonker, 2016). Unfortunately, even though the CE has a nice ring to it, its principles and consequences are often not well understood (Jonker, 2016).

The idea behind the CE is that climate change and the other negative effects of human behaviour on ecology can be addressed by changing the structure of the economic system (The Ellen MacArthur Foundation, 2013). Instead of wasting resources in a linear system, a circular system continuously, in each stage of a product's life cycle, tries to capture waste flows and use them as new inputs in a different phase (figure 1). Ideally, this leads to a situation where it will be no longer necessary to acquire new raw materials from nature for production because the continuous flows of recycled materials can support the economic system. Thus the sustainability of a CE is found in the ideal to create a society without waste and activities that deplete the natural resources of the planet.

When thought through properly, it becomes clear that a CE tries not only to change the production system of the economy, but also the logistics, competition, and cooperation between firms and other actors. Unfortunately, it remains unclear whether a CE will be a truly sustainable economy (Genovese, Acquaye, Figueroa, & Lenny Koh, 2015; Mark Goedkoop, 2014; Robèrt, Daly, & Hawken, 1997). The devil is, as always, in the details, and these details are currently still being debated in scientific, business, and governance settings, and are expected to be debated for years to come (Jonker, 2016). However, it is understood that a CE takes a systems perspective, deals with the entire lifecycle of a product, and consists of societies whose entire production and economic systems are interconnected. Because products, materials, systems and actors are interconnected extensively in a CE, if it is to function effectively it should arguably be known in detail what is occurring during the various phases of a product's lifecycle. Without this knowledge, managing the materials will be more difficult.

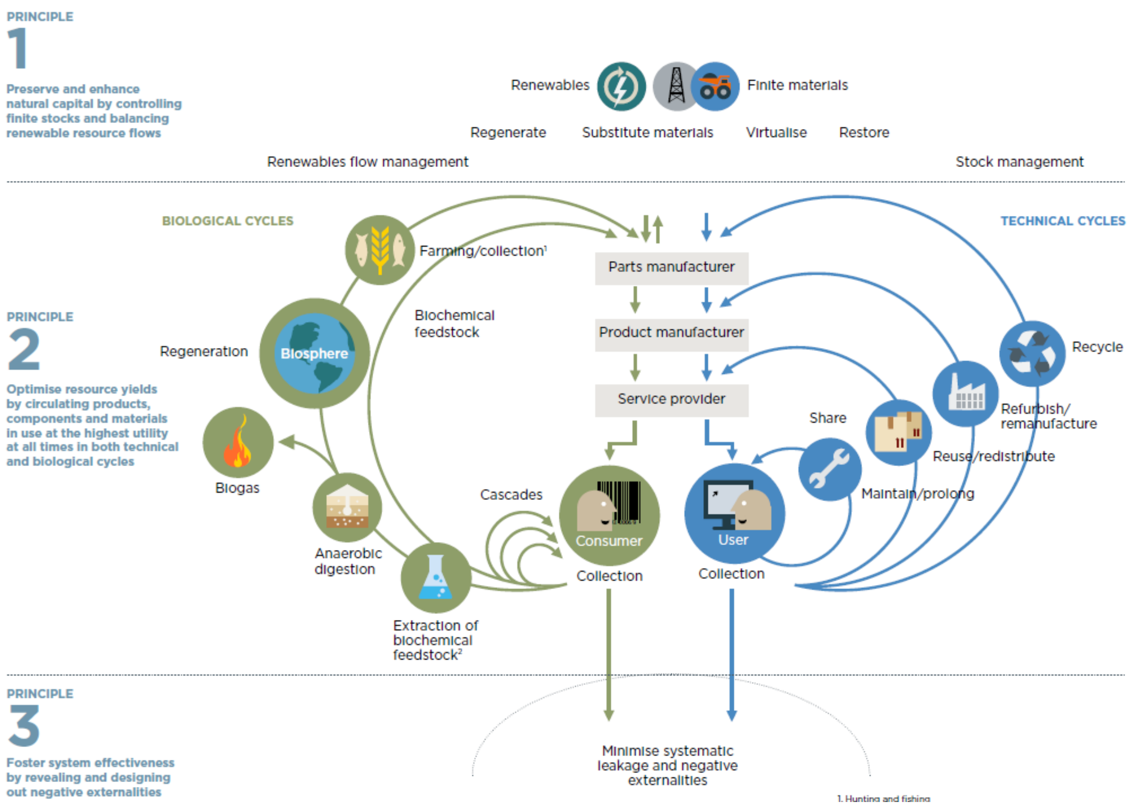

Figure 1: Influential circular economy model as developed by the Ellen MacArthur Foundation (The Ellen MacArthur Foundation, 2012).

In industry, the main tool that is used to map and assess a product's lifecycle and its impacts is the 'lifecycle assessment' or LCA (Guinée et al., 2011). The LCA methodology allows an actor to map a product in detail, and to assess all its impacts has during the various phases of its life, from raw material extraction to production, use, and disposal. Thus the LCA methodology seems a logical match with a CE. Unfortunately, the application of LCA within a CE is not a clear-cut case.

First of all, the CE concept is still under development because many aspects and consequences of it are still unknown, such as the kind of business models that are to be used, how to deal with value-creation, or what the consequences for society are (De Nooij, 2016; Jonker, 2016). This research continues and pilot programmes are being developed for designing and producing some circular products. Thus the CE is still in the experimental research phase. Secondly, private firms in increasing numbers turn to mapping the environmental impacts over the lifecycles of their products (Heijungs & Guinée, 2012). Most of the time they use the LCA methodology for this mapping process, but the LCA methodology is also still under development and certainly not without its critics (Heijungs & Guinée, 2012). Even though the LCA methodology has been standardized to some extent and is under constant development, such as the attempt to also include social or economic impacts or the creation of methods to deal with uncertainty, the LCA methodology remains a highly flexible tool, in which many different methodological decisions can be made by the practitioners (Baumann & Tillman, 2004; Guinée et al., 2011; Heijungs & Guinée, 2012). Because of the methodological flexibility and complexity within LCA, different results can emerge when researching the same product (Baumann & Tillman, 2004; De Nooij, 2016; Heijungs & Guinée, 2012; Huijbregts, 2016). It is not difficult to imagine that it is problematic when the main methodology, practiced according to the rules applicable today, to map and assess a product is prone to producing different results of the same product, while at the same time an economic development begins to unfold that requires reliable information in order to integrate materials, products, firms, consumers, and systems much more than is presently the case.

In other words, it might be the case that the development of LCA and the development of the CE might not overlap. Therefore, it must be assessed whether LCA and its recent developments, because of its increasing popularity, complexity, and methodological flexibility, can be a useful tool in reaching a CE. If it is not, than the LCA can instead of being supportive to a CE, act as a barrier to a CE (Sauvé, Bernard, & Sloan, 2015).

Knowledge gap and scientific relevance

As can be seen in figure 1, a CE is based on a never-ending process of constantly cycling renewable and non-renewable in- and outputs within and between firms and consumers. Consequently, a proper understanding of a product's lifecycle is vital knowledge because that allows actors to make the various in- and outputs of the various products in a circular cycle match. Thus it would be expected that CE plans would, at least partly, focus on lifecycles. However, the policy documents of the Dutch government on CE do not mention the importance of these lifecycles (Rijksoverheid, 2014a, 2014b, 2014c). Within the scientific debate on CE, the importance of the lifecycle is discussed, but not so much in terms of lifecycle mapping and the conditions under which LCA can play a role in a CE (Bonciul, 2014; Genovese et al., 2015; Ghisellini, Cialani, & Ulgiati, 2016; The Ellen MacArthur Foundation, 2013, 2015). However, this lifecycle mapping is crucial for understanding a product's impacts and the potential integration of different production and consumption systems into one circular system.

Because the Dutch government aims to build a CE within a context where in science it is understood that knowledge of lifecycles is important and where increasing numbers of LCAs to map these lifecycles (in more than just environmental terms) are being conducted by private organisations, it is important for science to also understand to what extent the methodological flexibility of such an important assessment tool as LCA aligns with the CE principles. Subsequently, the results gained from this research can be used to provide insights on the methodological necessities of a LCA study if a practitioner wants to effectively use LCA within a CE context.

Research objective and research questions

The objective of the research project is to assess the relationship between LCA and the circular economy and provide insights that can contribute to the sustainable development policy debate on the circular economy by critically reflecting on the core concepts of the circular economy and the assessment tool LCA as foundations for a sustainable economy, and by analysing how the methodological flexibility of LCA can play a role in a circular economy. This objective is to be achieved by answering the following research question:

To what extent can the lifecycle assessment (LCA) method and its recent developments contribute to the development of a circular economy?

This research question is supported by a number of sub-questions:

1. What is the current understanding of the circular economy?
2. What is the LCA method and what problems are associated with it?
    a. What are the current developments in LCA?
    b. What is the methodological flexibility found in different LCA procedures?
3. To what extent do the LCA method and the circular economy principles overlap?
    a. How do the types of LCA match circular economy principles?
    b. How do the different levels of LCA flexibility relate to the circular economy principles in various stages of circular economy development?

These questions are important for several reasons. The main research question captures the methodological possibilities of the main LCA procedure, the LCA in its various forms, and uses the analysis of that situation in order to find to what extent it can influence reaching a CE. To research this, it is necessary to understand the current ideas surrounding CE and the principles that it is built upon. The LCA methodology is dealt with in the second sub-question, where attention is also given to current developments in LCA because these developments might influence the methodology and have consequences for the application of LCAs. Finally, the LCA methodology is placed on a CE development framework in order to assess, firstly, what kind of methodological choices in LCA match CE principles, and, secondly, to discover how the level of flexibility in LCA corresponds to the level of CE development. Combined, these insights answer the main question and can help to further the debate on CE.

Research Framework and societal relevance

The framework presented below in figure 2 shows the how the research is set-up. It consists of two pillars, CE and LCA, and is supported by expert interviews. The two concepts are then compared and assessed.

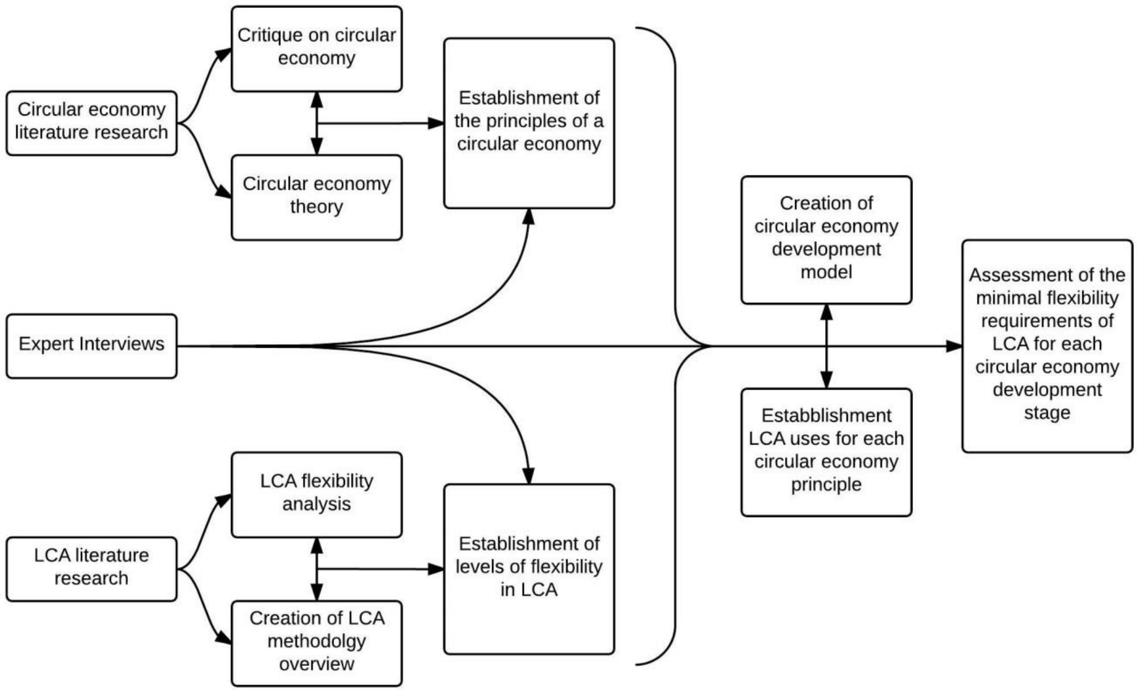

Figure 2: Research framework flowchart

By assessing the congruence of CE and LCA, the CE and the LCA methodology as two parts of the sustainable development debate is extended. By adding to the knowledge on those subjects, and especially by assessing which LCA constellations are (not) useful for a CE, a new perspective on the debate can be added. This is especially important because, at first glance, the CE seems to match the current socio-political and socio-economic practices that operate in at least some of the worlds' societies. In the Netherlands the national government aims to fully implement a CE, in order to let the Netherlands become a "hotspot of the circular economy" by 2020 (Rijksoverheid, 2014a). The government has developed an eight-point plan, with thirty-nine sub-goals, and pursues a strategy to support circular business operations (Rijksoverheid, 2014b; Vermeulen, Witjes, & Reike, 2014). Because in various Dutch sectors some kind of circularity, mainly in the form of recycling, can already be found, and has good international connections, the Dutch context seems adequately located to continue working on a CE (Vermeulen et al., 2014). By developing knowledge on the connection of the main industrial assessment tool and the CE, actors around the world, but specifically in the Netherlands, can gain new insights how to deal with the transition to circularity.

Methodology

This research consists of an analysis of both the CE principles and the LCA methodology. Because it aims to assess to how LCA and CE overlap and how LCA can play a role in a CE there is no real theoretical setting in which this research operates. Instead, only two major assumptions are made about human beings and their actions. These assumptions are explained below, after which the methodology itself will be further stipulated by explaining the methods used and the data collection and usage approach.

Assumptions

This research is based on two major assumptions. The first assumption is that all actors have bounded rationality; the second is the Principle of Least Effort (PLE). These two are important because they set the context in which all the actors in the CE and LCA are located (thus determining the baseline from which actors' decisions are made), and because they set actors' expected behavioural response when confronted with the methodological flexibility of an LCA. In this research, bounded rationality is understood as "the idea that people are bounded by the limits of their capacity to obtain complete information and to deal with complex issues when they make decisions" and people do not try to achieve maximum utility (Conlisk, 1996; Tremblay & Tremblay, 2012b, p. 103). PLE is understood as that actors "tend to choose the way requiring the least effort to finish tasks" (Chang, 2016, p. 1118). Thus PLE in this research is understood as a force that plays a vital role in behaviour, if said behaviour is focussed on the short-term. If however there is a clear vision for the longer term, PLE can be much better resisted (Sawhney, 2012). These assumptions are chosen because companies must make a profit, but have only limited research funds. Thus choices must be made in a context of uncertainty to achieve a profit in that situation.

These two assumptions are included because it is expected that when a firm engages in LCA research and finds itself with a lot of flexibility, it will naturally opt for the choices that are the easiest or to implement in order to save time and costs whilst still attaining the desired LCA report. Thus the minimum amount of effort is expected to be used in LCA research when it is too flexible.

Method

This research consists of a qualitative desk research based on an empirical systematic literature research combined with expert interviews. This approach is chosen for a number of reasons. Firstly, currently the relevant literature on CE and LCA for sustainable development is scattered across the academic world and could use some condensation. There are empirical researches that use LCA methodology; various guidebooks exist that explain the methodology; and reviews are present that identify main problems and developments within the LCA world. For example the articles by Reap et al. and Guinnée et al., and the book edited by Curran can be seen in those three lights (M. A. Curran, 2012; Guinée et al., 2011; Reap, Roman, Duncan, & Bras, 2008a, 2008b). In other words, the literature on CE and LCA for sustainable development is present, but mostly only in small pieces, focussing on a single or couple of elements of the LCA methodology or CE principles. However, a general analysis of the applicability of the two that includes the recent developments in LCA methodology is not yet done. Condensing all this literature systematically into one piece can help scientists to better understand the connection between LCA and the CE.

Secondly, there are a number of organisations and people that have made working with LCA or on CE their professional career. Gaining insights of these highly involved actors can be helpful to understand the connection between LCA and CE. Their input can prove valuable for further improving the hypotheses that are developed by the systematic literature study. Therefore the research is strengthened by some empirical data attained via a couple of semi-structured interviews. Adequately testing these hypotheses will therefore have to be done by researches conducted at a later moment in time.

Thirdly, some argumentation surrounding the CE or LCA that is present is not always found in scientific articles, but in non-peer reviewed articles, lobby organisations or news bulletins. However, these non-peer reviewed arguments might reach third parties easier than peer reviewed academic articles. Moreover, they might in fact determine the principles of the CE. Therefore, weighting these non-peer reviewed argumentations with proper scientific arguments is necessary in order to assess what the real CE principles are and what the value of these non-scientific arguments is. In addition, it is valuable to be able to add expert insights to the thesis through interviews, because talking to the people that are on a daily basis working on the subjects of this thesis can help to understand the subjects better, see them from different angles, and provide additional insights.

By conducting this systematic literature review with expert interviews, a proper scientific understanding of the foundation of the CE as well as the methodological flexibility of LCA will be created. When these two concepts are it is possible to assess to what extent LCA matches the CE principles and to in what way LCA methodology can support the CE. This is especially important when the PLE assumption is considered, because not all LCA efforts might be sufficient in a CE.

Data collection and usage

The systematic literature review proposed consists of a number of steps.

Firstly, the topic of the systematic review consists of the LCA, its developments, and the CE principles in order to find out to what extent the LCA method can influence the ability to reach a CE. With LCA is meant the lifecycle assessment methodology, meaning that all types of research that use the LCA method (such as SLCA, LCSA, and ELCA) are included. CE is understood as an economic system (both small- and largescale) in which outputs of the various processes of a product's lifecycle are constantly serve as the inputs for a new product or entirely different system.

Secondly, the literature to be included in the analysis was selected following a strict set of search terms in the academic literature databases of Scopus, Web of Science, Google Scholar, and the Utrecht University library catalogue. The terms written in table 1 were used to find literature:

Table 1: Search terminology

Life(-)cycle(s) Life cycle(s) (LCA), (SLCA) (S-LCA), (LCSA), (E-LCA) Theory, theoretical, principle(s) Loop(s)	Social Circular Closing, closed Flexibility, possibility, possibilities	Sustainability Economy Barrier(s) Recycling, recycle(d), reuse(d), recover(ed), reprocess(ed), reclaim(ed)	Assessment(s) Product(ion)(s) Problem(s), issue(s) Impact, consequence(s) Procedure(s), practice(s)	Environmental Development(s), improvement(s) Category(ies) Method, methodology, methodological

Once recovered, the literature was selected based on the following criteria:

- The title or abstract had to indicate that the literature falls within the scope of one of the posed sub-questions.

- The literature could not be published before 2004. Only in exceptional circumstances, such as the piece of literature cited frequently by fellow scientists or because it has arguments that are valuable to the research but are not found in more recent publications, was an older piece included. This timeframe was chosen because the influential Hitchhikers guide to LCA was published in 2004 and likely was up-to-date at that specific moment in time.

- The publication had to be in English. Some exceptions in Dutch were allowed when the study was of sufficient contribution to the research.

- The content of the literature had to fall within one or more of the following criteria:
    - It was a study on the positive and negative elements of the LCA methodology.
    - It was a study on the CE principles or the working of the CE.
    - It concerned a study using LCA methodology on circular products or with CE aspects to it.

- The study had to be unbiased. To assess that the finance and origin of the study were checked. If it turned out there were reasonable doubts that the study was biased, it was not included.

Finally, when the literature had been selected, it was analysed. The aim was to stay as close to the intended claims of the authors as possible when the literature concerns theoretical or methodological arguments. When the literature dealt with empirical usage of the method, then the results of that research were less interesting for this thesis than the actual application of the methodology. In those cases, more leeway from the results is justified.

The second part of the study concerns interviews. These are semi-structured around the topics of CE and LCA, depending on the speciality of the person interviewed. Three expert interviews were conducted. One with one of the leading scientists in LCA development, one interview with an expert on the necessary business requirements of a CE, and one with an entrepreneur who has created a tool that incorporates LCA and other methods to measure circularity. These persons are leading experts in their respective fields in the Netherlands and allowed this research ideas to be debated by experts. Their insights are therefore used throughout the research as additional expert input.

1 Circular Economy

Currently, a large part of the world economy follows a linear model. This linearity is found in the fact that the world economy functions as if "raw materials come in at one end and waste goes out at the other" in a limitless world ready for infinite growth with a natural system able to deal with all those waste flows (Mathews, 2015). This linear model is the basis of the current economic system. However, over the past decades, an increasing realisation that the natural world and its raw materials is finite, that the environmental and ecological sinks are not infinite, and that therefore the current economic model cannot endure forever has emerged, as the increasing societal focus on sustainability shows. Consequently, a shift towards recycling has been underway and some economic sectors behave less linearly than others (Bastein, Roelofs, Rietveld, & Hoogendoorn, 2013; Mathews, 2015; Vermeulen et al., 2014). Understanding that a prosperous human future demands a responsible relationship with the Earth, the Dutch government wants to change the general linear economic model into a circular one (Rijksoverheid, 2014c). This section aims to show the current understanding of the circular economy (CE).

1.1 Origin of the Circular Economy

The origin of the CE idea can be found in a number of authors and organisations. Pinpointing exactly who coined the idea is difficult, especially since it builds on various different ideas. However, nowadays, The Ellen MacArthur Foundation is one of the major proponents of the circular model and has identified at least seven scholarly ideas to reach a sustainable future that are merged into the CE framework (Mathews, 2015; The Ellen MacArthur Foundation, 2015). Before turning to those ideas, it must be mentioned that in CE system thinking is crucial, as can also be understood from figure 3. Because of various connections between actors and materials, and because everything cycles, it is important to think in systems. No product is alone, and everything is connected. The seven main ideas on which CE is constructed are:

1. **Cradle to Cradle (C2C).** In C2C thinking, all waste is thought to be possible for reuse in some way or another (either industrial or biological), renewable energy should be maximized, and humans should promote natural and economic diversity instead of relying on monocultures which can create instability (McDonough & Braungart, 2000). All products[1] should be designed according to these three basic principles, because if the biological and technical material cycles function properly they prevent the creation of waste, and reduce or even prevent the use of polluting (Barros, 2010). The outputs of one productive system become inputs for another, resulting in a situation where little to no material loops remains open and ends in harmful waste (Mathews, 2015).
2. **Performance Economy.** The performance economy focusses on extending the lifetime of products in order to reduce material demand and subsequent usage in the economy. One important idea within the performance economy is a change of business models from manufacturers selling products and their ownership to their customers, to a business model where manufacturers sell the use of a product as a service whilst keeping ownership over the product to themselves, allowing for more incentives to create long-lasting products (The Ellen MacArthur Foundation, 2015).
3. **Biomimicry.** Biomimicry is the understanding that in order to create a better world, humans should look towards nature for inspiration because natural selection and evolution have together created natural solutions to problems that humans also have to deal with (Biomimicry Institute, 2015). Thus the idea is that by mimicking the natural systems which have had millions of years of evolution to adapt and optimize its processes, human problems can be solved in an effective and efficient manner.

[1] In this research, the word product is used to mean both physical products and non-physical products such as digital products or services. A product thus should be understood as something that is created by human economic activity in order to be traded with other humans for another product (mainly money).

4. **Industrial Ecology (IE).** (Yuan, Bi, & Moriguichi, 2006) IE aims to upgrade the industrial system to make it align with nature, both at the macro and micro levels of the economic system (Mathews, 2015). This means that at the micro level, firms/groups of firms/cities close the loops of their production processes in a local context by connecting their flows to other operators in the area, for example by delivering excess heat from a power plant to another firm of housing block (The Ellen MacArthur Foundation, 2015; Mathews, 2015). This process of connection waste flows between organisations to serve as input flows is also called industrial symbiosis (IS). At the macro level, the aim to is harmonize industry with nature, meaning that industry becomes a part of the natural system and does not overstep the natural boundaries that exist and keep the natural system in balance (Mathews, 2015). To achieve this, IE focusses mainly on physical flows and technological solutions to reach harmony and sustainability by reducing the need for new raw material extraction and by limiting waste flows, which include emissions (Andersen, 2007a; Mathews, 2015).
5. **Blue Economy (BE).** By redesigning industrial processes from using rare materials and energy intensive production methods towards a system based on simple and sustainable procedures and material inputs, the BE proponents argue that industrial system is expected to become much more sustainable (The Blue Economy, 2015). In BE thinking nature is considered a source of inspiration. Consequently, water plays a large role as a replacement for many chemical solutions, and locally sourced resources and locally sold products are key to developing a sustainable economy (The Blue Economy, 2015).
6. **Regenerative Design.** In regenerative design thinking, lost ecosystems should be able to return by creating a better world than how humans found it (Regenerative Leadership Institute, 2015). Thus when engaging in regenerative design, designers not only try to create products and systems that last, but try to design them in such a way that they create more natural benefits than was put into the process by allowing the product and system to regenerate itself and its surrounding, just like a plant that grows and reproduces (Regenerative Leadership Institute, 2015).
7. **Natural Capitalism.** Natural capitalism is based on the notion that, unlike in the current system, a good economic system is founded on the conviction that business and environmental interests align because they are in reality interdependent (The Ellen MacArthur Foundation, 2015). To achieve a sustainable world, private business should play the largest role, simply because they are most effective institutions that humans have nowadays and will understand that their own survival depends upon nature's environmental well-being (Hawken, Lovins, & Lovins, 2010). This kind of thinking means that when external costs are accounted for, being sustainable makes money. It does so by attempting to let natural capital increase resource productivity; by using biomimicry to reduce waste flows; by creating a service and flow economy to reduce waste flows and create economic value; and by investing in natural capital in order to restore and expand it thus increasing the natural capital base for the economy (Hawken et al., 2010).

1.2 Principles of the Circular Economy

These different scholarly fields all provide insight and input for CE. In the current literature on CE, three important CE principles are written down by the Ellen MacArthur Foundation (The Ellen MacArthur Foundation, 2012). These principles are:

- **Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.** This principle means, among others, to use as little physical resources as possible, to create systems that regenerate nature stocks, and to use the most effective and sustainable resources possible in order to reduce the pressure on the natural system and enable future generations to also have abundant amounts of resources available.

- **Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.** By designing products in such a way that products and materials continue to hold their quality level as much as possible, and by making sure that when reuse is impossible the products can be easily and effectively (also in terms of quality) repaired and recycled, and by allowing products to be returned to nature in a way that adds to the latter, the effective use of each material is to be maximized.
- **Foster system effectiveness by revealing and designing out negative externalities.** This principle consists of the objective to reduce, wherever possible, the negative aspects of a product during its entire life-cycle in order to reduce the pressure on the natural system and thus enable a more sustainable relationship between humans and nature. (The Ellen MacArthur Foundation, 2012).

Together with the figure presented earlier (figure 3), but for convenience placed here as well, these principles define what a CE is according to the Ellen MacArthur Foundation.

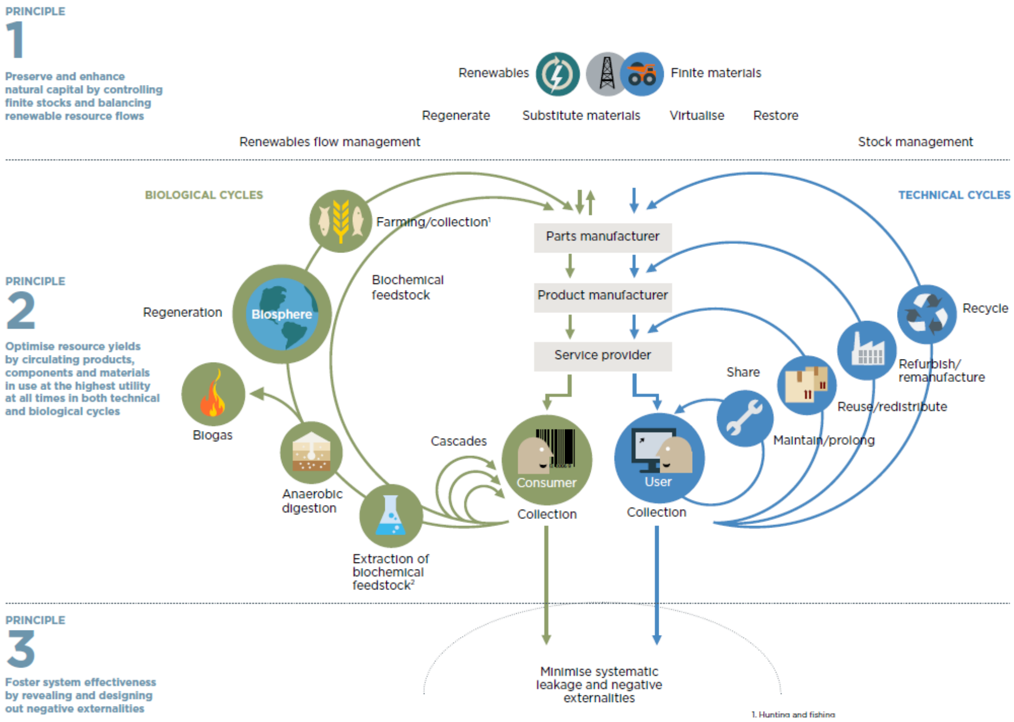

Figure 3: Influential circular economy model as developed by the Ellen MacArthur Foundation (The Ellen MacArthur Foundation, 2012).

However, these three principles are pretty general and lack detail. Additionally, other authors have identified elements that should also be concluded in a CE for it to be an effective economic system. Therefore, a new list of more detailed principles based on the wide variety of ideas available in the literature is shown below that sketch a CE. For organisational purposes, these principles can be categorized in two parts. First there are principles dealing with materials and products. The second category of principles concerns the larger economic changes of a CE.

1.2.1 Production and material principles of a circular economy

The first set of principles deals with the material reality of a CE. First and foremost, the CE is an economic system that changes the way humans engage with natural and technological resources.

Any research into the usefulness of LCA in a CE requires an overview of these material principles that are used in a CE.

i. All production should follow the 3Rs: Reduction, Reuse, and Recycling

Often the 3Rs are mentioned in the literature as the basic principles of CE. These are: The reduction of the use of resources (in the largest meaning of the word), reuse of those resources and the created products and components, and finally the recycling of resources and products (Ghisellini et al., 2016). These 3Rs can be used during every part of a product's lifecycle. The CE uses the 3R processes because they are clear business principles, require relatively little explanation, and cover all options for engaging with resources. They are explained below.

a) Reduce all types of material usage to reduce pressure on the natural system

The first 3R principle is the attempt to reduce all the use of materials in order to reduce the pressure on planet and to give future generations a better chance of having access to those resources. Every material that can be left in the Earth because human activities do not need its use prevents environmentally harmful resource extraction. In practice, this means that the CE must use the concept of cleaner production, or CP (Qiao & Qiao, 2013). CP focusses on continuously decreasing the negative environmental impacts of production processes, by stipulating that producers must reduce all their polluting processes and actively develop more sustainable practices that replace them (Qiao & Qiao, 2013). Consequently, with CP the entire production process of a company is scrutinized in order to assess where environmental gains can be made, for example by using fewer or different resources, technologies, or waste management practices (Qiao & Qiao, 2013). Additionally, products can be designed to require fewer resources or to have an increased lifetime, thereby reducing the need for using as many materials (Qiao & Qiao, 2013). Subsequently, CP practices combined with designing products for sustainability will lead to a reduction of raw material use and other negative environmental impacts. This reduction of resource use is aimed especially at non-renewable and scarce resources because those resources have the most negative effects on the healthy stability of the human and natural world (Qiao & Qiao, 2013). CE thus goes beyond waste reduction or recycling approaches by actively trying to design out waste at every step of a products lifecycle (Razzini et al., 2014).

b) Reuse all materials and products as much as possible to hold on to material quality

The second 3R principle focusses on reusing a product or material, because that can also be an advantageous way of reducing the need for raw material extraction. After all, if a product is used twice for the same purpose, one less product needs to be produced during the duration of that use. By reusing a product, waste is prevented (Ghisellini et al., 2016). One often mentioned way to improve the amount of reused products within a CE is to introduce product-service systems, or PSS (Tukker, 2015). Instead of merely selling products to consumers, producers in a PSS strategy sell services (Tukker, 2015). For example, a consumer no longer buys a car, but buys x amount of kilometre mobility. After the contract has been served, the good that was used to deliver the service, the car, returns to the manufacturer. The manufacturer can then reuse or remanufacture the product and sell it again. This dynamics incentivises the producer to improve the quality, remanufacturability, and recyclability of the product in order to gain higher profits, while at the same time consumers maintain access to the service of the product (Tukker, 2015). In addition, because a product does not change hands from one producer to the next, it allows the producer to cycle the materials of this product in order to try to retain the quality of the material. After all, the producer knows exactly what the product consists of and how it was created, because no other producer has tempered with it. Of course, a PSS system is unlikely to function for all types of products, because some products cannot be returned to the producer after use. For example, food, because of its direct and destructive consumption, is difficult to incorporate in a PSS business model.

Similarly, materials can also be renewed by upgrading them and can be redistributed among various other actors to enable new options. Products in turn can be recovered to be upgraded and reused (Stegeman, 2016). The terms redistribution, recovering and renewing, are sometimes also used as additional principles, extending the 3Rs to the 6Rs. However, the renewing, redistribution, and recovering practices are, in essence, all part of reusing materials and products. They are executive practices of the reuse principle, and thus in this research the 3Rs are maintained as the general principles.

c) Recycle all material flows in order to reduce the need for virgin materials

The third 3R principle deals with recycling. This principle is quite straightforward. After a product has been used and possibly been reused a certain number of times, it has reached the end of its useful life. At that instant, a product can be recycled to recover some, and preferably all, of the materials it consists of. These resources can afterwards re-enter the production system. In other words, a waste flow is reprocessed and turned into a new resource flow for a production process (Ghisellini et al., 2016). However, recycling is only the last stage in the 3R hierarchy to prevent resource exploitation after reduce and reuse respectively (Ghisellini et al., 2016). In a CE, ideally, all materials should be fully recycled in order to create an economic system where no further raw materials are necessary but all production can occur based on the materials that cycle within the CE. However, as the next principle of a CE will explain, there are some complications with this ideal.

ii. A circular economy should recognize the natural limits to circulation

The second main CE principle dealing with products and materials relates to the challenge of thermodynamics and other natural factors that limit resource durability. Basically, the laws of thermodynamics state, firstly, that energy cannot be destroyed, thereby establishing the natural boundaries of any productive system, and, secondly, that with every action the entropy of the system increases (De Man & Friege, 2016; Robèrt, Daly, & Hawken, 1997). The higher the entropy, the more difficult it is to use the energy effectively to do work (Andersen, 2007). An effective circulation of materials and energy can delay this degradation by making optimal use of every increase in entropy along the way by keeping the entropy increase to a minimum with each use of the materials (Andersen, 2007). Additionally, some materials are more prone to quality degradation than other materials. However, regardless of the attempts to cycle products and reduce entropy or quality loss, it cannot prevent entropy or quality loss from occurring. So eventually, new resources must enter into the system. CE can therefore not sustain itself without adding some additional low entropy resources to the mix from time to time (Genovese et al., 2015). Hence, CE is no *perpetuum mobile*. The question is thus raised whether these new resource inputs deplete the finite resource base of the Earth.

To answer that, it must be recognized that a proper CE tries to limit the introduction of new raw materials to the productive system by using renewable resources and energy as input and materials that can be taken up by the biological cycle as output (figure 3) in order to let the waste that would eventually occur be returned as nutrients in nature, thus restarting the material cycle. However, according to authors such as De Man & Friege, complete recycling of all materials in order to upgrade them to better quality (as will be necessary as many materials tend to degrade over time) will result in such high energy requirements that are impossible to maintain sustainably (De Man & Friege, 2016). In general, recycling is very beneficial during the first few recycling cycles, but eventually the net benefit of recycling cycle x becomes negative (Andersen, 2007). When that point occurs differs with every single material, with some degrading quickly and others almost not at all. Thus eventually new non-renewable materials must enter the system if they are not replaced with renewable resources. However, even if complete recycling would be a possibility, and the circular system would bring nutrients back to nature in large quantities, it is recognized that even the natural system has stock levels above which no additional nutrients can be taken up without ecological damage (De Man & Friege, 2016; Reijnders, 2008). This means that once a certain threshold has been reached, nature cannot deal with all the nutrients humans deposit without changing the ecosystem of the area where the deposits are located.

An additional natural barrier to CE is relates to durability. Although the 3Rs stipulate that it is necessary to design products to last as long as possible in order to reduce resource demand, the longest durability option is in reality not always the best option to choose when it comes to a CE. As seen above, a proper CE would propose the use of biological materials over non-renewable abiotic materials, because the biological material can be easily renewed by nature, thus increasing the sustainability of that product (Murray, Skene, & Haynes, 2015). However, biological materials might very well last shorter than non-renewable ones. Therefore, creating products that last long with non-renewable abiotic materials might be less sustainable than creating products that only last a short while but can be fully decomposed by nature (Murray et al., 2015). On the other hand, the biological material might have various negative ecological effects such as land-use or ecosystem change. In other words, choosing the best material is difficult. Although efficiency is important to keep the system functioning at an optimal speed, it is effectives that determines is about whether the system succeeds (Webster, 2013). Therefore, it is important that a CE is not solely understood as an economic system that reduces pressure on nature, recycles all materials, and uses renewable resources. It functions within a natural system, and that system has placed boundaries on the possibilities. Some practices may still change the natural system negatively in a CE, and if the idea is to be in some kind of harmony with it, the barriers must be recognized properly.

1.2.2 Economic principles of a circular economy

The material principles above prescribe how actors are expected to deal with resources in a CE. However, there are socio-economic consequences that require attention as well. For example, adopting a circular material system leads to the situation that products are returned to producers after a long period of consumption. However, this longevity of products and the effort to remanufacture it reduces the pressure on creating new products, thus changing the economic practices of actors. Logically, that also means that socio-economic changes must be part of the circular economic principles. Without addressing these socio-economic situations, such as developing new circular business models and finding solutions for the change in cash flows, a CE cannot hope to function effectively (Jonker, 2016). Thus it is impossible to fully understand a CE without also addressing these socio-economic principles. And without a full understanding, any analysis comparing CE to LCA methodology to understand their congruence is meaningless. Therefore, any analysis of LCA and CE must look beyond the material principles and also deal with the socio-economic principles.

i. A circular economy should internalise all externalities

When considering the socio-economic situation of a CE, it can be argued that a CE might be suffering from a collective action problem as described by Olson (Olson, 1965). In the current linear model, private interests of selling products do not fully converge with public interests of a clean and safe environment and thus additional action is necessary if a sustainable system is preferred (Sauvé et al., 2015). A CE tries to prevent waste and harmful emissions. Therefore, the incentive to pollute must be tackled. After all, in the current economic system, engaging in sustainable practices is only interesting when it provides a higher benefit to producers than using raw materials does (Andersen, 2007). Therefore, the CE principles must be made to provide an added value to producers and consumers if it is to succeed within the current capitalist system. Without the incentive, CE cannot emerge freely.

One often mentioned possible market based solution to ensure the desired collective action if the CE remains a capitalist system, which is assumed in this research, is to ensure that externalities are as far as possible accounted for within the economic system (Andersen, 2007; Robèrt et al., 1997; The Ellen MacArthur Foundation, 2012). This is important because it would provide an incentive for actors to behave more environmentally friendly, and provides a more equal market situation for more and less polluting actors. What happens with the material output of a product during its lifecycle becomes part of its costs, and hence incentives emerge to reduce those costs and make a more circular product with fewer polluting substances for example (The Ellen MacArthur Foundation, 2012). Without the inclusion of externalities, it becomes even more complicated to create a CE.

However, creating this inclusion of externalities is difficult. Analysing it would be enough work for an entire different thesis. But at least two things can be said about it in relation to LCA. First of all, it is a difficult task because in CE all the externalities of the entire lifetime of a material must be considered when determining the correct price. Secondly, because the price is partly based on rules and regulations that are also currently used, it seems logical that this price-setting may not always be completely accurate because rules can be circumvented, broken, or badly made (Sauvé et al., 2015). Some authors therefore propose that a pricing system should include an assessment based on physical indicators of the sustainability direction a product drives the system (Robèrt et al., 1997). If a product pushes towards unsustainability, the costs should be higher than if it pushes towards sustainability. Such a step, they argue, would enable society to internalize effects that have a long-term future impact (Robèrt et al., 1997). A LCA seems to be a useful method to be used here, which will be explained in chapter 2 in more detail.

A more common way to identify the costs, is presented by Andersen (Andersen, 2007). According to him, these costs can be internalized via taxation, leading to more efficient resource use, replacement of harmful resources with other less harmful resources, more environmental protection measures, more incentives to increase technological development of environmental protection technologies, and can help individual companies to make their own decisions based on their situation instead of on general environmental rules (Andersen, 2007).

However, taxation is only one of the possibilities to internalize externalities. Greyson identifies four basic approaches to tackle this market failure: "*taxes and other government charges,… regulations,… tradable permits,… and recycling insurance*" (Greyson, 2007, p. 1385). The first three of these measures are well known and directly influence the costs, quality, and quantity of products. The recycling insurance works a little bit different, but boils down to the idea that firms insure themselves for the costs of recycling. Thus the more difficult to recycle the product, the higher the insurance costs, and thus the higher the incentive to change the product in such a way that it is easier and cheaper to recycle, which enable better material cycling (Greyson, 2007). This idea internalizes the recycling costs into the price of a product. In a CE, this insurance practice can be extended to all parts of the production process because sustainability costs are internalized in the product price thus enabling improvements to be functional in a capitalist market context (Greyson, 2007). This insurance would operate in such a way that products that pose a larger risk to become waste will receive a higher insurance premium because the insurance firm faces more risk to pay for 3R activities, therefore increasing the incentive for the producers to reduce the environmental risk of their products while keeping the freedom of producers to conduct their own business. To determine the level of these charges or insurance costs, it is useful to know how a product behaves during its lifecycle and. Such information could be attained by a LCA. The material certification method mentioned below can function as an additional source of information in these choices because it can help identify how harmful or sustainable a producer is regarding resources.

Regardless of the method chosen, a CE must internalize the externalities because without it the market failure continues to exist and a CE will be far more difficult to develop in accordance with nature.

ii. A circular economy requires incentives and information to circulate products and materials

As explained earlier, a PSS can give producers the incentive to produce more circular products. Especially when this is accompanied by the internalisation of externalities However, in a CE all products that cannot fall under a PSS scheme because they cannot be returned to the producers for remanufacturing, such as food, should also be designed, created, and processed according to the material principles. Thus it is necessary for actors to be correctly incentivised. A possible incentive programme that might also be applicable to some non-PSS firms could be the Extended Producers Responsibility regime, or EPR (Ghisellini et al., 2016; Tukker, 2015). Under an EPR regime, producers are responsible for an end-of-life treatment of their products. The costs of end-of-life processing fall also upon the producer. Therefore, the costs for production rise, especially if highly toxic or otherwise environmental harmful products are used, incentivising the firms to develop more sustainable products.

However, in order to cycle materials it is especially important to keep track of the raw materials in the economic system (Mathews, 2015). This not only means that the quantity and quality of each individual material used in products is known, but also how it has been treated, for example what of alloy has been created. Without this knowledge, the materials cannot be used as effectively as possible because the material needs to be researched or treated before it can be used again (Jonker, 2016). Thus all materials, Mathews argues, should be accompanied with a certificate that states exactly how the material has been treated and what its history has been (Mathews, 2015). Some kind of material passport. Additionally, full information is needed with the producers on when a product, or material, is waste or when it still fulfils a useful function. Such information would inform the producer what to do with a material to ensure it is being recycled or reused optimally from an environmental point of view (Razzini et al., 2014). Unfortunately, this is problematic to achieve because sharing such critical information about products publically and enabling the reusability of products currently goes against the trend among producers to secure their products better against "hacking and repurposing" making the reusability of the products further away than before (Gregson, Crang, Fuller, & Holmes, 2015). Thus the production secrets of firms must be kept within a context of increased product transparency in order to circulate products. This is a difficult problem to solve practically, but one that is necessary. Without information on material history and cycling, a CE becomes far more difficult to exist.

iii. A circular economy requires industrial symbiosis

This difficulty is even more paramount when it is considered that a CE requires of all its actors to connect as much input and output flows to each other in order to turn waste flows in input flows. As explained earlier, when this is applied to producers it is called industrial symbiosis (IS). If the interdependency between firms that participate in IS becomes large enough, one consequence is that it forces them to bond together, integrate, and "take care" of each other, lest they themselves get into trouble when one firm has to cut its production or goes bankrupt and thereby fails to supply its waste flows to the other firms causing supply problems (Qiao & Qiao, 2013). This is a significant point to consider. In a CE, firms become integrated by necessity across economic sectors, simply because they share their production processes. This will inevitably change the entire global socioeconomic structure, because instead of more-or-less individual firms must surviving more-or-less in one sector, entire industrial parks of interdependent firms must survive in their various sectors simultaneously. Without going into unnecessary detail here, because discussing IS has an entire research field, it is understood that a CE requires that new business models are developed and used (Jonker, 2016). The old competitive business models are inadequate when one actor's waste is used as an input in a new production process and is given additional value by additional actors. Entire different business model must be developed that can capture the cooperative nature of a CE, create value in cooperation from waste, sharing assets, and creating value out of creating fewer products. Concordantly, value changes from being a private good to being a collective good (Jonker, 2016).

iv. A circular economy should not neglect the social side of economics

The final important principle found in the literature deal with social issues. An economic system is always a social system. It has social effects, and operates within the social setting of society. However, if CE only focuses on the environmental and economic effects of the economy and neglects the social issues, it might prone to negative responses that will reduce the implementation possibilities of a CE because society does not support the system (Greyson, 2007; Murray et al., 2015; Sauvé et al., 2015). Therefore, the social aspects of the socioeconomic system should also be considered when implementing a CE. This means that the socio-economic effects of a circular production process should also be included in the considerations for developing circular economies. This is especially important when considering feedback loops (Zamagni, Guinée, Heijungs, Masoni, & Raggi, 2012). When a production processes changes to a circular process, it will change the way humans interact with nature. Especially when fewer products are produced, or when a lot of jobs open at the lower end of the labour market to recycle and remanufacture product components, the social effects can play a significant factor in determining the political reaction to circular developments (Jonker, 2016). Therefore, the socio-economic consequences of changing production patterns must be addressed within the systems perspective that the CE adopts.

2 Lifecycle Assessment

Having created an overview of the understanding of a CE, it is necessary to look into the second element of the thesis, the lifecycle assessment or LCA. An LCA is an assessment tool that describes, assesses, and interprets a product's lifecycle (Baumann & Tillman, 2004). In short, this means that all inputs and outputs of a product from beginning (cradle) to disposal (grave) are incorporated within the LCA. These in- and outputs are described in quantitative terms, matched to certain environmental impact indicators, and interpreted (Baumann & Tillman, 2004). Thus the LCA results of a product can be used for purposes as far removed from each other as marketing to identifying hotspots of environmental impacts in order to reduce the negative effects of production (Baumann & Tillman, 2004). LCA is used globally, and its usage is still increasing every year (Guinée et al., 2011). It must be mentioned that although the LCA method aims to be as close to reality as possible, "it is not an exact scientific tool, but a science-based assessment methodology of the impacts or system" (Winkler & Bilitewski, 2007, p. 1030). It is an assessment of a situation, leaving room for interpretation and subjectivity (Winkler & Bilitewski, 2007). This section provides a short introduction to the past of the LCA method, introduces and explains the current standardized methodology, and afterwards goes into the various recent developments that have occurred within the field. The chapter concludes with a section that analyses the methodological flexibility that exists within LCA.

2.1 Origin of the Lifecycle Assessment

It is generally accepted that the first LCA type of researches were conducted in the late 1960s as a response to the environmental issues raised by social movements (Guinée et al., 2011). The following decades, more experiments with LCA type of researches were conducted that tried to assess the environmental impacts of a product's lifecycle from its origin, the cradle, to the final resting place of the product, the grave (Guinée et al., 2011). During the 1980s, various organisations in some developed countries developed guidelines for LCA practitioners[2] amid the first attempts to quantify the environmental impacts to different categories (Guinée et al., 2011). During those first decades, there were various LCA methodologies that were being used by practitioners, who also called their assessments differently, and there was only a limited debate on LCA going on. As a consequence of this diversity, one product could have very different environmental impacts based on the method that was chosen (Guinée et al., 2011). The result was that the LCA methodology was not accepted by a broad audience (Guinée et al., 2011).

After two decades of LCA experimentation with various ways of determining the impacts and developing better impact assessment methods, the 1990s saw a large increase in the debates surrounding LCA (Guinée et al., 2011). Academic scholars started investigation and developing the LCA methodology, international gatherings were held to discuss its future, and additional guidelines were published, all of which were trying to get some sort of harmonisation in the LCA sector (Guinée et al., 2011). Eventually, the International Organization for Standardization (ISO) created a standardized LCA methodology (Guinée et al., 2011). This methodology is nowadays used most of the time. The standardization has resulted in a large increase in the number of LCA studies being conducted globally (Guinée et al., 2011). Other LCA methodologies do still exist, but this research focusses mainly on the ISO-LCA because it is the global standardized version. The standardization by the ISO must be understood correctly however, in that it "never aimed to standardize LCA methods in detail" but only sets the guidelines, requirements, and the framework and principles which LCA practitioners should follow (Guinée et al., 2011, p. 91).

[2] The term practitioner is used in this research to identify a person conducting an LCA study.

2.2 The principles of the LCA

Building on the ISO framework, there have been various versions of the LCA developed over the decades. This section introduces the general framework, the environmental LCA, and other more recent developments.

2.2.1 The General Framework of the Environmental LCA

In the past, the LCA method used to be solely applied to assess the environmental impact of products. In this section, this environmental LCA (ELCA) is sketched because it can be considered the baseline of LCA research nowadays.

Following the ISO standardization of the LCA, an LCA:

> addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave) (International Organization for Standardization, 2006).

An LCA study follows the general framework that can be seen in figure 4 and consists of four phases. In other to introduce the reader to the method properly, these four phases are explained below.

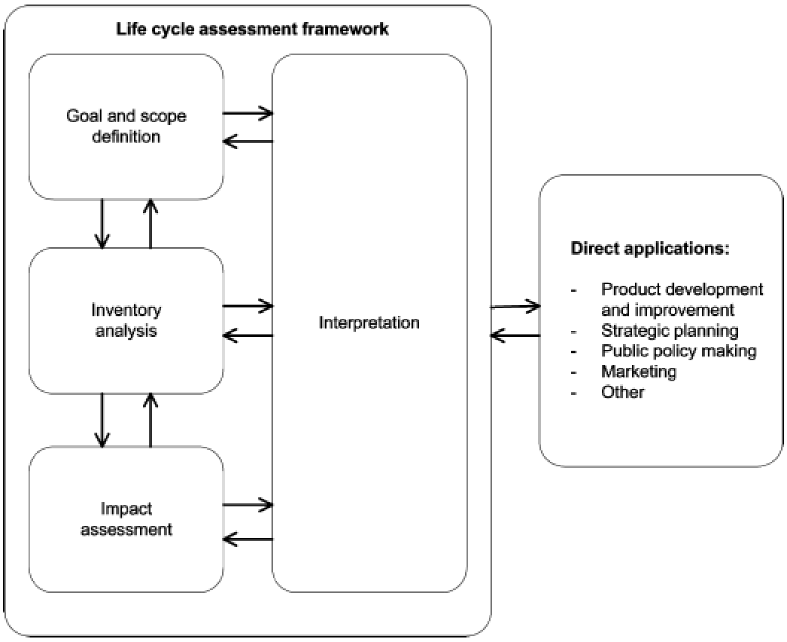

Figure 4: The basic LCA framework (Guinée et al., 2011).

Phase 1: The Goal and Scope definition.

The first phase is the time during which the LCA practitioner develops the research plan.

> [It] centers around formulating the research question and stating the context of answering this question. In the goal and scope definition, no data is collected and no results are calculated. Rather, it is a place where the plan of the LCA study is defined as clearly and unambiguously as possible (Heijungs & Guinée, 2012).

In short, this phase must address "the application, the reasons for carrying out the study, the intended audience, and whether the results are to be used in comparative assertions disclosed to the public" (Heijungs & Guinée, 2012). Furthermore, the boundaries of the studied system, the function of the system (normalised to a functional unit that allows for comparison of different products that provide the same function (for example "lighting a standard room of 15 square meters with 1000 lumen for 1 hour")), the impact categories that are to be used to identify the environmental damage that occurs during the product's lifecycle, and the procedure regarding uncertainty, are all introduced in this phase (Heijungs & Guinée, 2012).

The goal can be varying in LCA research. It is possible to assess the impacts of a single product at a specific side, but also to compare multiple products to each other across an a entire lifecycle (Sauer, 2012). It can for example serve to find so called hotspots of environmental impacts (the product's processes that impact the environment most during its lifecycle) in order to assess at what place in the lifecycle an intervention will have the greatest environmental benefits. But it can also serve a marketing purpose, to inform the consumers or investors of the environmental impacts of a product compared to the products of competitors (Sauer, 2012). This part of the process is thus relatively easy.

Based on the goal, it must be decided whether the LCA is supporting decision-making or not, and whether or not the system affects other systems to a minor or large extent. If the LCA supports decision-making, it does so by looking at the changing impacts of a decision and is called a consequential LCA. If it is not supporting decision-making it provides an overview of the current situation and is called attributional LCA. If the LCA thus considers the present and only describes the current situation, it is attributional, but if it describes how the system's flows will change and how the situation will be in the future based on a decision that is modelled it is consequential (Ekvall et al., 2016). Recently, consequential and attributional LCAs have also been called A, B, and C situations, as can be seen figure 5 (European Commission, 2010). While situations A and B provide information on the changes to the studied system and product if a certain decision is made and the expected consequences to other systems (consequential), situation C provides an overview of the current or expected impact situation without considering other systems (attributional) (European Commission, 2010). Thus the practitioner must determine which type of LCA matches the goals.

<table>
<tr><td rowspan="4">Decision support?</td><td rowspan="3">Yes</td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Situation A
"Micro-level decision support"</td><td>Situation B
"Meso/macro-level decision support"</td></tr>
<tr><td>No</td><td colspan="2">Situation C
"Accounting"
(with C1: including interactions with other systems, C2: excluding interactions with other systems)</td></tr>
</table>

Figure 5. LCA situation options A, B and C (European Commission, 2010, p. 11).

The methodological process gets more complicated in the scoping section. During this process, a number of crucial decisions must be made that determine the direction of the research. Firstly, the practitioner must determine how broad the system under study will be in the analysis and how detailed this analysis is going to be (Sauer, 2012). Because an LCA study must meet its goals, it is necessary to assess the product's system to such an extent that the goals are met. For example, if an LCA is conducted with the sole interest of understanding the impacts of the production processes at a production facility, then a different set of processes and details must be analysed when compared to an LCA of the entire lifecycle of a PET bottle. Thus during this phase, a number of choices must be made (International Organization for Standardization, 2006; Sauer, 2012). The main choices are explained below.

i. Determining the functional unit. The functional unit consists of two elements: function and unit. With function is meant what the product does. So the function of a car is first and foremost personal transportation. However, a product can also have multiple functions because a car can also have a social function such as to impress the neighbours (Reap et al., 2008a). The unit is the quantification of the function. Usually, the main function that meats the identified goal is chosen for analysis (Baumann & Tillman, 2004). Thus, in case of the car, one possible functional unit could be *number of kilometres of personal transportation*. However, it is also possible to expand it with a timeframe and at what level of quality the function must be performed (European Commission, 2010). The functional unit is therefore the quantification of the function of the product under study and is used throughout the LCA to ensure that all the relevant process flows are related to a single functional unit, in order to gain a proper overview of the flows per 1 amount of functional unit (Baumann & Tillman, 2004).

ii. Setting the system boundaries. This means that the practitioner must determine what system is going to be assessed. Usually there are five lifecycle stages (see figure 6) that can be included in the analysis, from the extraction of raw materials to the final end-of-life phase of a product (Sauer, 2012). Every stage has input and output flows as well as transportation effects, which must all be quantified in the inventory analysis later on (Sauer, 2012). The goal of the system boundaries is to "capture all stages and operations that are needed for the functional equivalence basis that has been selected for the analysis" (Sauer, 2012, p. 48). Consequently, a flow-chart is created where the various processes are represented to provide a visual overview of the system.

However, determining the system processes is not enough. A system's impacts of an identical product can be different because of the global location of its processes. For example, electricity inputs in Europe may have different environmental effects compared to electricity inputs in Africa, simply because the respective power plants have different environmental impacts. Therefore, the geographical boundaries must be determined (Sauer, 2012). The same logic applies to time issues, which should be included as well (Sauer, 2012). It is, for example, highly likely that a product that uses x amounts of electricity has different environmental impacts now than in 50 years when the electricity mix is likely to be different (Sauer, 2012). Technological progress can thus also be considered, but this choice should be adequately defended by the practitioner.

iii. Choosing impact categories. The goal of an LCA is to measure the environmental impact of the product. This means that the categories of impacts, for example water acidification and global warming potential, that represent environmental consequences and to which the individual processes are related, must be decided upon. This must be done before the actual data gathering, because different categories may require different data inputs (Sauer, 2012). Additionally, it should be decided whether these categories are midpoints, for example global warming potential or water acidification, or endpoints, such as human health damage, in which various midpoints are combined into a single category (European Commission, 2010). Next to that, it must be determined when a physical flow is considered important for the impact categories and when a flow can be neglected. Thus *cut-off criteria* that set these rules must be determined (Baumann & Tillman, 2004). Because of data unavailability, time/funding difficulties, or because there is a lack of knowledge about the consequences of a flow, the cut-off criteria are used to enable the practitioner to create an accurate model as possible (Sauer, 2012).

iv. Setting the weight of the impacts. When the impact categories and the system boundaries have been established, the interpretation values of the impact categories can be determined. This means that individual impact categories are given a weight factor that shows the relative importance of the various categories (European Commission, 2010). For example, oceanic acidification might be deemed less of a problem than ozone depletion, thus ozone depletion is given a high weight factor. However, weighting is a controversial phase because it can be quite subjective. After all, is water acidification worse than biodiversity loss? Because of the normative nature of such questions, practitioners not always include weighting in an LCA.

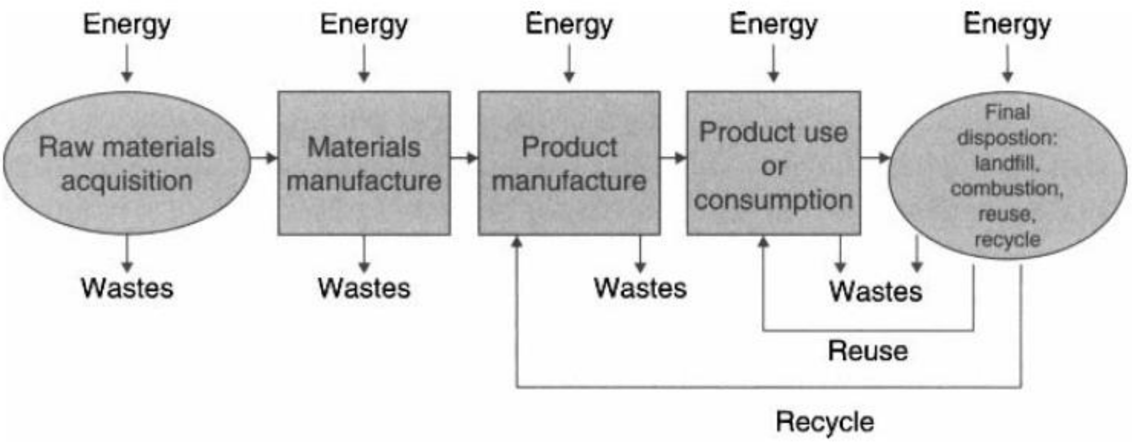

Figure 6: The five stages of a product's lifecycle (Sauer, 2012, p. 48)

v. Dealing with allocation. If a lifecycle process produces outputs that fall within the boundaries of the system that is being investigated, those outputs must be quantified and connected to the correct impact categories. However, it is possible that an input is the result of a process that also produces different outputs that fall outside the scope of the LCA. For example, in the production of lumber, the sawing of the logs in a mill also produces sawdust. That sawdust might be used in a biomass electricity facility. Therefore, the environmental impact of the milling must be quantified and allocated to all the outputs of the process in order to determine how much of the environmental impact of the milling can be attributed to lumber (Sauer, 2012). The ISO has a preference how to deal with such allocation issues: It is best (1) to "avoid allocation where possible", but if (2) "allocation cannot be avoided" it is best to "allocate inputs and outputs among useful coproducts in a way that reflects physical relationships" unless (3) "where physical relationship alone cannot be used" making it best to "allocate based on other relationships" (Sauer, 2012, p. 57).

To deal with this allocation issue, it is recommended to either subdivide the process into smaller sub-processes in order to have processes that only fall within the system boundaries (Sauer, 2012). If that is not possible, the system boundaries need to be expanded (Sauer, 2012). The co-products under system expansion can also be quantified and can offset some of the impacts of the main process (Sauer, 2012). For example, if a firm uses electricity from a electricity facility that also produces heat that is used to heat another process, than that heat (as co-product) can offset some of the electricity impacts. Allocation for recycling loops can occur in a similar fashion, but more on recycling later on.

vi. External Review Decision**.** The final major choice in the first phase concerns the review. If the study is partly or completely used for an audience outside of the organisation, it is necessary to have an external review to control the report in order to determine its adequacy (Baumann & Tillman, 2004; Sauer, 2012). It is also recommended to already have decided who the reviewers will be and what kind of review is to be conducted (European Commission, 2010).

Phase 2: Inventory Analysis. This is the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (Heijungs & Guinée, 2012). In other words, a list of all the in- and output flows must be created and quantified vis-à-vis the functional unit. This is accompanied by a flowchart of the unit processes (the processes that are to be quantified) with in- and outputs of the system based upon the system boundaries (Baumann & Tillman, 2004). All unit processes together form the product system. For each unit process, data is collected in this phase order to quantify the unit process (Heijungs & Guinée, 2012). Generally speaking, LCA practitioners advise to use different types of data when conducting different LCAs. An attributional or situation C LCA should use average data because they must represent the current situation in the sector, while a consequential or situation A or B LCAs should use marginal data of the specific situation under study to represent as accurately as possible the context in which the changes are going to take place (Ekvall et al., 2016; European Commission, 2010). If during the life cycle inventory analysis (LCI) it turns out that some of the decisions made during the goal and scope phase were wrong, those decisions can still be changed if adequately defended in the research paper (European Commission, 2010). In the LCI, all flows within each process step of each lifecycle stage of the identified system are quantified in respect to the functional unit. Of each individual process, every single environmental load is collected and quantified, except for those processes or flows that are cut-off.

Phase 3: Impact Assessment. This phase is "aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (Heijungs & Guinée, 2012). In other words, in the Lifecycle Impact Assessment (LCIA) the individual environmental loads that are created in the LCI, such as x tons of CO_2 or S_2O, are translated into a handful of environmental impact categories that these loads impact, such as global warming potential, eco-toxicity, and abiotic resource depletion (Baumann & Tillman, 2004; Heijungs & Guinée, 2012). These impact categories were established in the goal and scope phase, but now in the LCIA phase they are to be finalised and used (UNEP Setac Life Cycle Initiative, 2009). By doing so, the individual environmental loads are converted into the total environmental impacts of a process, making the environmental impacts of a product's lifecycle visible. As mentioned earlier, these impact categories can be chosen based on endpoint categories (which provides a more understandable picture, but has more uncertainty), or midpoint categories (that are more difficult to interpret but have lower uncertainty) (Heijungs & Guinée, 2012).

Phase 4: Interpretation. In the final phase the practitioners evaluates "the findings of either the inventory analysis or the impact assessment, or both, … in relation to the defined goal and scope in order to reach conclusions and recommendations" (Heijungs & Guinée, 2012). This phase thus deals with presenting results, and conducting uncertainty or sensitivity analyses in order to check the robustness of the results. The acquired results are "analysed in the light of accuracy, completeness, and precision of the applied data, and the assumptions, which have been made throughout the LCI study" (European Commission, 2010, p. 92). A sensitivity analysis can be conducted to see how sensitive the obtained results are to a situation when different assumptions, weighting factors, emission load translation factors, or other changes are being put into the LCA model (European Commission, 2010). If analyses indicate that the results are weak, a practitioner can try to improve the robustness of the study by continuing the research.

2.2.2 Different LCA types

The four phases sketched above identify the main way of engaging with an ELCA. The ELCA focusses solely on the environmental effects of a product's lifecycle. As a tool it is quite successful in quantifying the environmental impacts of a product during its entire lifecycle (Haes, Heijungs, Suh, & Huppes, 2004). However, it must be noted that within the sustainable development debate, it has been for a long time understood that social and economic aspects should also play a role when building a sustainable world (Brundtland, 1987). It has been decided on the highest international political level that socio-economic development is a key aspect of sustainable development (United Nations Framework Convention on Climate Change, 2015). Scientists have taken up that challenge and argued that looking at solely the environmental impacts of production is not sufficient from a sustainability point of view (Haes et al., 2004; C. B. Norris, 2012). Instead, the social and economic impacts of a product should also be included (C. B. Norris, 2012). Especially since the globalisation has caused social impacts to occur across different countries and societies, there is an increasing global interest in the social and economic impacts of global production processes (C. B. Norris, 2012). Therefore, methods such as the social lifecycle assessment (SLCA), lifecycle costing (LCC), lifecycle sustainability assessment (LCSA), organisational lifecycle assessment (OLCA) and the social organisational lifecycle assessment (SOLCA) have been developed recently.

Social Life Cycle Assessment

The "Social Life Cycle Assessment [SLCA] is a technique making use of the modelling capability and systematic assessment processes of LCA for the analysis of the positive and negative social impacts engendered by production activities" (C. B. Norris, 2012, p. 445). The SLCA can help organisations to gain insights in the social impacts of their supply chains and identify points for improvement (C. B. Norris, 2012). Practitioners argue that the SLCA can be beneficial to decision-makers because it can provide them with additional input on some possible social effects of their decisions (Souza, Watanabe, Cavalett, Ugaya, & Bonomi, 2016). To actively achieve that, it is suggested by Souza et al., to combine a process-based model that quantifies the effects at the studied site based on scenarios, with an input-output analysis that allows the quantification of the effects down- and upstream of the studied site (Souza et al., 2016). The SLCA framework consists of social impact categories that function similarly to the environmental impact categories in an ELCA (C. B. Norris, 2012). According to UNEP, "social impacts are consequences of positive or negative pressures on social endpoints (i.e. well-being of stakeholders). Social impacts are understood … to be guidelines of social relations (interactions) weaved in the context of an activity (production, consumption or disposal) and/or engendered by it and/or by preventive or reinforcing actions taken by stakeholders (ex. Enforcing safety measures in a facility" (UNEP Setac Life Cycle Initiative, 2009, p. 43). These impact categories are determined by looking at five stakeholder groups, namely "Worker, Local Community, Society, Value Chain Actors, and Consumer" (C. B. Norris, 2012, p. 438). Additional stakeholders can be added if deemed necessary (UNEP Setac Life Cycle Initiative, 2009). However, the impact categories can also be derived from general impact categories such as "human rights" or "health and safety" (C. B. Norris, 2012, p. 438). Regardless of the method used, every impact category in turn has several subcategories (UNEP Setac Life Cycle Initiative, 2009). The subcategories in turn have indicators that are measured in the lifecycle inventory phase (see figure 7) (UNEP Setac Life Cycle Initiative, 2009). So they function like the indicators, mid- and endpoints in ELCA.

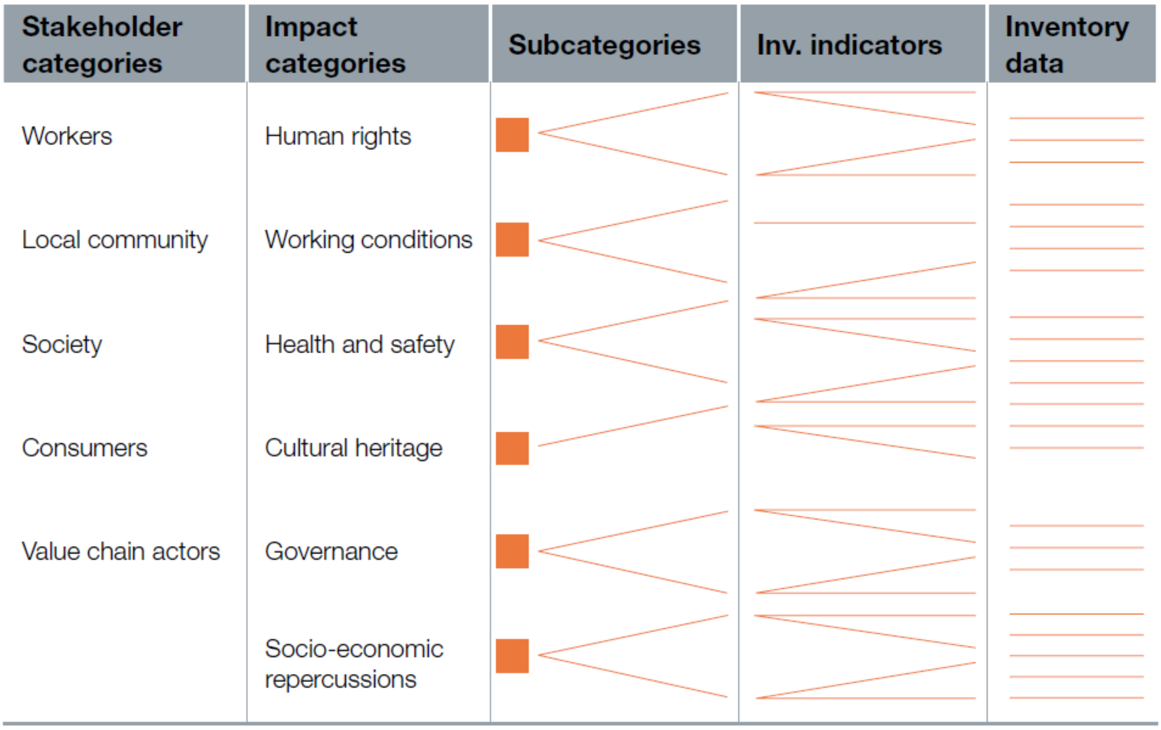

Figure 7: The SLCA impact category method.

The SLCA uses the same four phases as the ELCA. However, it also adds a "social hotspot assessment" to increase the efficiency of data collection procedures (C. B. Norris, 2012, p. 441). This assessment, using the same four phases as an SLCA, is used to reduce the number of unit processes that are to be quantified in the main SLCA study by identifying the processes that are most likely to have positive or negative social impacts (C. B. Norris, 2012). In other words, it is an assessment to determine which elements can be cut-off.

Unlike in an ELCA, in an SLCA stakeholders are important because they provide important input for the assessment, and can also be used to determine and improve the impact categories that should be included or excluded (C. B. Norris, 2012). The assessed impact categories must, logically, be relevant for the specific lifecycle that is being analysed, and therefore it is possible that different studies use different impact categories (UNEP Setac Life Cycle Initiative, 2009). When the social life cycle inventory is completed, the individual data must be aggregated and summarized to the impact categories. For this end, a scoring system that ranks the individual impacts can be used (C. B. Norris, 2012; Parent, Cucuzzella, & Revéret, 2010). Such scoring systems can also provide an additional method to ensure that special stakeholder issues, such as the example above, can be incorporated in the SLCA (C. B. Norris, 2012). It is also possible to determine the importance of the impacts by assessing the causal relationship between the subcategories and the impact categories (G. A. Norris, 2006; Parent et al., 2010; Souza et al., 2016). Logically, subjectivity plays a role in the construction of the impact categories, the scoring, and the interpretation of the impacts (C. B. Norris, 2012).

Another large difference between an ELCA and an SLCA is the fact that while in the ELCA a functional unit is the foundation of the study, in an SLCA that relationship is more complicated. In an SLCA the functional unit is important for the assessment, but some impact flows cannot always be expressed per unit. In those cases, the functional unit does indicate the system that is being studied, but is used less to relate the impacts to (UNEP Setac Life Cycle Initiative, 2009). Similarly, the data that is being used in an SLCA should be based on the hotspots methodology to determine the required date on a national level combined with the necessary geographically specific data that the study requires (UNEP Setac Life Cycle Initiative, 2009). In ELCA, the latter is not always that important (UNEP Setac Life Cycle Initiative, 2009). The data in ELCA consists often of scientific data on flows. In SLCA, however, it might be good to use subjective data because the social realm itself is a subjective reality (UNEP Setac Life Cycle Initiative, 2009). In some cases, subjective data will result in more certain results when dealing with social realities.

A major problem of SLCA is that, currently, it is difficult to quantitatively assess the social impacts of products since the social impacts themselves are difficult to measure or difficult to match to a specific product; because there are difficulties in weighting social impacts against each other; because the differences in impacts are often site-specific and can differ therefore from location to location; and because data collection is a difficult process without adequate databases (Martinez-Blanco, Lehmann, Chang, & Finkbeiner, 2015; Souza et al., 2016). Ideas are currently developed to deal with these problems. One example is the Oiconomy standard which attempts to monetize the impacts of a product on all three aspects of sustainability (economy, social, environment) by trying to calculate the mitigation costs of the damage done by the product through its entire lifecycle(Croes & Vermeulen, 2016). The standard would allow firms to present site-specific data, instead of relying on average data from databases (Croes & Vermeulen, 2016). The mitigation approach together with certification and transfer of lifecycle information thus allows for one type of quantification of social effects. However, a lot of work still needs to be done before SLCAs can be fully implemented.

Life Cycle Costing

Whereas an ELCA deals with the environmental impacts and an SLCA with the social ones, "[l]ife cycle costing, or LCC, is a compilation and assessment of all costs related to a product, over its entire life cycle, from production to use, maintenance and disposal" and thus deals with the economic costs of a product (UNEP Setac Life Cycle Initiative, 2009, p. 35). In other words, it uses the lifecycle thinking approach to quantify all the economic costs that a product consists of from cradle to grave, and to specify for each phase of the product's lifecycle which amount of economic costs is occurring. Unlike the ELCA, it has no impact categories, but only deals with financial costs (Kloepffer, 2008). It is useful because it can identify how different product behave cost and thus show how products with different levels of sustainability but with the same function differ in terms of costs during a lifecycle (Kloepffer, 2008). When the method would also be improved by allowing it to assess the economic consequences for other entities than the producer of the product, the usefulness of the LCC method is likely to increase substantially (Haes et al., 2004; Sala, Farioli, & Zamagni, 2013). It is a useful tool to assess the economic aspect of a product, especially when the macroeconomic aspects are measured with an SLCA.

Life Cycle Sustainability Assessment (LCSA)

Attempts have also been made to combine the three LCA methods. One way to understand LCSA is to see it as the combination of ELCA, SLCA, and LCC. It is not a method in itself, but more a framework in which the three individual methods are incorporated. It aims to deal with all the three aspects of sustainable development: environment, economics, and society (Guinée et al., 2011). In doing so, it not only looks at the impacts of individual products at these three different levels, but can also be used to assess economic sectors or (inter)national economies (especially when additional methodologies are added to create an entire sustainability framework) (Finkbeiner, Schau, Lehmann, & Traverso, 2010; Guinée et al., 2011; Sala et al., 2013). The logic behind combining these three methods is that the clear distinctions "between behaviour and technology and between technosphere[3] and ecosphere" made within LCA methodology do not always adequately reflect reality (Guinée et al., 2011, p. 93). For example, the human system is far more complex than the ELCA models depict. The environmental impacts (and thus the natural

[3] In short, the technosphere is the area where humans act, while the ecosphere is nature itself.

system) are affected by human actions, but there are feedback loops that are not incorporated within the current LCA methods (Guinée et al., 2011; Zamagni et al., 2012).

It is also possible to understand the LCSA as the next evolutionary step, in which an ELCA study is expanded with LCC and SLCA elements (Kloepffer, 2008; Sala et al., 2013). In practice, Kloepffer argues, that means that after the LCI, three individual LCIAs must be completed (Kloepffer, 2008). In the first option (paragraph above) of LCSA, the individual studies all have their own different phases, which increases the transparency but disables the opportunity to weight the different methods and determine whether, for example, socio-economic costs might outweigh environmental harm (Kloepffer, 2008). The second option, on the other hand, uses the same system boundaries and functional units, which allow for such weighting between the three methods, and for comparison with the same individual LCI (Kloepffer, 2008; Valdivia et al., 2013).

If the second (merged) LCSA method is used, the standard four phases are used. Aspects that are not incorporated within the ELCA method, but should be part of the LCSA can be summarized to the following main points: the system boundary should be determined by incorporating all product processes that are important to one (or more) of the three methods; qualitative data is also included in the LCI; and every method uses its own relevant impact categories (Valdivia et al., 2013).

Regardless of the approach taken, an LCSA allows the practitioner to structure all the different types of data that are used in the three individual methods in such a way that a more total sustainability picture emerges (Valdivia et al., 2013). Thus it can be seen how sustainability plays out in a product system and creates valuable insights in the interaction between these three aspects of sustainability (Valdivia et al., 2013). By gaining these insights, or by having a method that creates the possibility to understand the interactions between the three aspects of a product system, it is argued that the incentive to innovate and improve the overall sustainability of the product system increases (Valdivia et al., 2013). It also allows organisations to back up their sustainability claims and sustainability efforts with hard data, thus providing marketing or labelling opportunities (Valdivia et al., 2013). However, decision-makers can also benefit. For example, when buying products, LCSA allows them to choose products that meet their sustainability criteria best (Valdivia et al., 2013). Or when policies are being created, the LCSA can identify in which parts of the lifecycle, an intervention can be beneficial or what decision might be more beneficial to the situation. The various actors along a lifecycle can thus all benefit from the increased knowledge, because their choices can be made on a stronger scientific foundation.

Organizational Life Cycle Assessment

The Organizational Life Cycle Assessment (OLCA) is another recent development in the LCA field. Instead of using the methodology to assess the impacts of a single product throughout its lifecycle, the OLCA focusses on the impacts associated with the lifecycles of an organisations entire product portfolio (UNEP SETAC Life Cycle Initiative, 2015). This includes assessing the lifecycles of the used processes of all the actors that are active in one of the products of the portfolio (UNEP SETAC Life Cycle Initiative, 2015). UNEP gives the example of assessing the lifecycle of the diesel that is used by a distribution service that is used in a lifecycle (UNEP SETAC Life Cycle Initiative, 2015, p. 30). The insights can, like with product LCAs, be used for many different reasons, from intervention in the value chain and production processes, to marketing and evaluation. OLCAs have a number of benefits over individual LCAS. Firstly, it is possible to conduct one study for an entire firm instead of having to conduct numerous individual LCAs, which probably reduces the costs. Secondly, it allows for a thinking in systems instead of individual products and allows a firm to assess the impacts of the entire firm

(Huijbregts, 2016; Martinez-Blanco et al., 2015). Thirdly, it could reduce the amount of allocation that needs to occur within a study because internal allocation disappears (Huijbregts, 2016).

Sustainability Organizational Life Cycle Assessment

Some authors argue that the SLCA method has not shown enough progress over the past years to adequately map social impacts of products (Martinez-Blanco et al., 2015). However, the recently developed OLCA method is according to them a good method to solve some of the problems SLCA is struggling with (Martinez-Blanco et al., 2015). It is especially useful, they argue, to deal with social impacts because the impacts are not related to individual products but to a company as a whole, and, because of that, is better able to gather information because most social information occurs at the organisational, not the product, level (Martinez-Blanco et al., 2015). Therefore, its methodology combines OLCA with SLCA (Martinez-Blanco et al., 2015).

2.3 Difficulties of the LCA method

Now that the LCA methodology and its main recent developments have been introduced, it is possible to look at the main problem that is researched in this thesis. One major issue in the light of the assumptions underlying this thesis, namely the principle of least effort and bounded rationality, is the problem of choice. LCA methodology leaves ample room of choice. The various ways in which the flexibility can occur within the LCA methodology is explained below.

2.3.1 Flexibility

One important thought to remember about the LCA is the fact that the ISO has created the general LCA framework, on which the other new developments also build, but does not explain step-by-step how the framework is to be implemented (Heijungs & Guinée, 2012). Thus a lot of freedom remains for practitioners within the LCA framework (Van der Harst & Potting, 2013). That freedom enables both the occurrence of contradicting results on similar issues, as well as large acceptance of the method by researchers because the freedom enables them to research the way they see fit (Heijungs & Guinée, 2012). Thus flexibility is at the same time problematic and useful.

In this assessment of possible problems, it is assumed that the LCA methodology is correctly executed and that the required steps in a LCA study are correctly taken and matches the standards. That means that some problems that Reap et al. have identified in table 2 that occur on a regular basis that relate to making a decision that forces the model to misrepresent reality are not considered in this analysis (Reap et al., 2008a, 2008b). This analysis holds that such mistakes can always occur, but diminish with experience and education.

Within each LCA study, there are different scientific, technical, and social factors involved that can produce different results in the same study (Reap et al., 2008a). In the end, however, it mostly boils down to choice. The choices an practitioner makes influence the outcome tremendously, reduces (or improves) the trust in the accuracy of the study, and thus impact its usefulness (Reap et al., 2008a).

Table 2: Identified problems within the LCA framework (Reap et al., 2008a).

Phase	Problem
Goal and scope definition	Functional unit definition[a]
	Boundary selection[a]
	Social and economic impacts[a]
	Alternative scenario considerations[a]
Life cycle inventory analysis	Allocation
	Negligible contribution ('cutoff') criteria
	Local technical uniqueness
Life cycle impact assessment	Impact category and methodology selection
	Spatial variation
	Local environmental uniqueness
	Dynamics of the environment
	Time horizons
Life cycle interpretation	Weighting and valuation[a]
	Uncertainty in the decision process
All	Data availability and quality

[a] One might reasonably consider these problems to be pivotal decisions. Unlike the others, their partial dependence on study goals limits the capacity to generate solutions via scientific and technical consensus building. However, their strong influence on a study's outcome makes the inaccuracies introduced by an inappropriate decision high. It might, therefore, be more appropriate to think of these problems as problematic decisions

This flexibility must therefore be described before the LCA can be compared to CE. Thus the key areas of methodological flexibility in LCA and the choices that can be made are explained below. Currently, the ISO has standardized the LCA methodology using an open approach, meaning that only a general baseline of practices is constructed but that each practitioner can determine how to behave within the freedom that remains in the model (Heijungs & Guinée, 2012). However, it can be argued that a more closed model can be beneficial for reducing the flexibility and thereby the variety in results of identical products. After all, the fewer paths a person has to reach a goal, the fewer possibilities for substantial deviation exist, resulting, most likely, in more coherent results. Therefore, for each of the main methodological choices a practitioner has to make, a scoring system of up to four levels is created. Level one considers the choice in a situation of full flexibility. At each consecutive level, the amount of flexibility is reduced. The levels represent a possible situation of flexibility, wherein each time the flexibility reduces. The choice for each individual level can of course be debated and the levels definitely do not indicate finite boundaries. Instead, they serve mainly to indicate an amount of flexibility on a scale from full flexibility to little or no flexibility. Additionally, for each level of standardization it is assumed that the LCA is conducted to assess products. When the goal of the LCA is differently, for example to conduct an LCA for (scientific) methodological development, then the standardization attempt described might not apply. In those cases an LCA is likely to need different choices.

Phase 1

Functional Unit Choices

The functional unit is in the literature often understood as a source of uncertainty and flexibility (Reap et al., 2008a). Every practitioner must determine the functional unit that is used in the study to match the goal of the study (Baumann & Tillman, 2004). Sometimes a wrong functional unit is chosen, but that happens because of misjudgements. However, because the functional unit must represent the function, little room for deviation is possible. It is assumed in this research that practitioners are able to properly implement the method they are using, and that the only flexibility occurs from correctly practiced choices. Thus flexibility occurring because of mistakes is excluded. Consequently, the functional unit is not a cause of flexibility and not considered further in this research.

Boundary Selection Choices

Early in the LCA study, the practitioner must set the system boundaries. This activity allows the practitioner quite some freedom to determine how the study is structured and the direction of the assessment (Reap et al., 2008a). Unfortunately, LCA studies of similar products have shown quite some different impact results because of different system boundaries (Singh et al., 2010; Winkler & Bilitewski, 2007). Because a practitioner can determine how a life phase is modelled, studies use different definitions of what the various life phases look like (Andrae & Andersen, 2010). Sometimes, this occurs because the practitioner lacks inside knowledge of the system, thus causing possible major emissions not to be included in the study (Santero, Masanet, & Horvath, 2011). At other times, different considerations are important to varying system boundaries.

Some authors argue that especially the cut-off criteria, which determine when a flow is quantified or neglected in the study, are too subjective (Suh et al., 2004). Practitioners use these cut-off rules to reduce the complexity of the model. But some argue that cutting of process flows that are expected to be minor is quite unscientific when these expectations are not assessed at all (Suh et al., 2004). Moreover, even if the cut-off rules function properly and only small individual flows are neglected as a result, the flows that are cut-off can, in fact, cumulatively be a significant part the final impacts (Santero et al., 2011; Suh et al., 2004). However, because those flows are not assessed, it is impossible to falsify or verify that assumption based on the conducted research. And if a practitioners does calculate the flows, why cut them off at all, other scientists ask (Finnveden et al., 2009; Sala et al., 2013). If a practitioner has proper knowledge of a system than perhaps an educated guess is possible, but it is general knowledge that the many aspects of material and environmental behaviour, now and in the future, are quite unknown, especially when feedback loops are considered (Jonker, 2016). Especially when dealing with entirely new materials or materials on which barely any data is available, it is nearly impossible to make the educated guess. Thus, some argue, gathering all data is necessary, but gathering all data diminishes the need to cut-off (Reap et al., 2008a). Attempts by authors to solve this issue by taking a different approach to boundary selection are all also struck with similar problems, such as the unreliability of their data assumptions/databases or the cutting off of end-of-life phases (Reap et al., 2008a). However, a choice must be made.

Similarly, the practitioner must decide the range of the research. The choice whether for example it will be cradle-to-gate (factory) or cradle-to-grave, and how the cradle and gate/grave are defined, are important for the final impacts. After all, if the grave includes recycling, it must be decided how many cycles of the recycling process of the materials are included in the LCA.

In the end, boundary selection choices matter. Therefore the following four phases of flexibility can be established.

1. The practitioner is completely free to determine the system boundaries and cut-off rates. There is no restraint to their freedom. This matches the ISO standard, where every system boundary is allowed as long as it matches the goal and scope of the study.
2. If some criteria are introduced that reduce flexibility and create a more common approach to LCA, one of the easiest options that still leaves substantial space for other choices would be the obligation to adopt a cradle-to-grave approach in order to map the impact of a product's entire lifetime. If other choices were standardized, for example assumptions and cut-off rules, that would have a larger impact on the freedom to determine the modelling process.
3. A next standardization step could ensure that the other choices such as cut-off rates and data assumptions are standardized in order to limit differences in approaches. This is a large-scale standardization.
4. In a final standardization attempt to reduce flexibility, the cut-off rates are removed altogether because it has been argued extensively that cutting off requires large insights and

data into the system under study. It is nearly impossible to take out assumptions from LCA studies, because using assumptions are necessary in scientific tools in a context of incomplete scientific certainty and understanding. However, cut-off rules are not assumptions; they are modelling choices which can be removed to reduce flexibility.

Allocation Choices

The allocation choices concern ensuring that the impacts from processes producing multiple products, or processes requiring multiple inputs, are allocated in such a way that each product is allocated the impact that it causes. A practitioner must determine how much of the flows are allocated to each product, but different allocation procedures have different consequences on the calculated impact (Luo, Van Der Voet, Huppes, & Udo De Haes, 2009; Wardenaar et al., 2012). Many solutions have been proposed to deal with allocation, but none of them can be applied generally to all cases (Reap et al., 2008a). According to the ISO standards, it is best to avoid allocation as far as possible by either expanding the system boundaries by looking at alternative production processes, or by dividing the process in sub-processes (Reap et al., 2008a). If that is impossible, it is best to allocate based on physical relationships of the processes, or if that is impossible, on other relationships (Reap et al., 2008a). If recycling takes place that replaces new raw materials from being used, closed-loop allocation should take place, in all other circumstances open-loop allocation (Reap et al., 2008a). Unfortunately, expanding the system or subdividing it is a tiresome task that requires more data, which is not always available and might in turn also have allocation issues (Reap et al., 2008a). If the allocation is to be resolved based on the causal (physical) relationships, the causal process must be understood really well, which in some cases is not always the case (Reap et al., 2008a). In fact, often the practitioner can chose between different causal physical connections (Wardenaar et al., 2012). Additionally, it is possible to use various physical relationships for every connection, (Wardenaar et al., 2012). After all, a product can be compared not only on mass, but also on energy, molecular structure, density and other aspects. Unfortunately, not every choice may represent the processes that occur in reality in the best possible way (Wardenaar et al., 2012). In the end, it is the practitioner that must take the difficult decision what kind of allocation tactic is used.

Therefore flexibility allocation can be measured in four phases. In each successive phase, the flexibility is reduced.

1. Because it is necessary to have reliable results, a practitioner must allocate. In order to have maximum flexibility, the practitioner should free to decide how to allocate. This level of flexibility is greater than the current ISO structure provides for, but remains a possibility.
2. A next step is to follow a standardized approach to allocation choices, such as the ISO standardization, which guides practitioner which type of allocation procedure should be used for the situation of the specific study. However, if the practitioner feels that a different allocation method is better for the case at hand, for example because of practical considerations, such a choice is allowed. The allocation procedure is merely a guideline at this level.
3. A second step is to change the coerciveness of the standardized allocation procedure. Instead of being merely a guideline that practitioners can follow, it can be changed into a mandatory procedure. Thus, practitioners must follow the rules of the allocation procedure and cannot choose other allocation procedures. However, the actual methodological implementation of the procedure remains free.
4. If flexibility is further reduced, then the allocation methodology could be standardized as well. Thus the practitioner is prescribing not only what type of allocation procedure should be used, but also how that procedure is to be executed. This increases uniformity among LCA studies.

Spatial choices

A practitioner has the option to use uniform global input data for the LCA study (Reap et al., 2008b). However, it is also possible to acquire input data from a specific location (Ekvall, Assefa, Björklund, Eriksson, & Finnveden, 2007). The same option is available for practitioners to determine how the data corresponds to impact categories: it is possible to use globally standard criteria how indicator flows relate to impacts, but it is also an option to take the local situation, which might influence the way the flows interact with nature, into account (Reap et al., 2008b). Some authors argue that the local environment is often something that should be considered when dealing with impact flow, because for some locations and emissions negative effects are much more likely to occur or be mitigated than for other situations (Bare, 2014; Reap et al., 2008b). Moreover, some decision-makers are not interested in global effects, but merely in the local situation (European Commission, 2016; Seidel, 2016). Thus, the choice the practitioner makes influences the outcome. Unfortunately, inclusion of localized data remains difficult (Huijbregts, 2016; Reap et al., 2008b).

Therefore spatial flexibility can be measured in three phases. In each successive phase, the flexibility is reduced.

1. Because it is possible to conduct an LCA study without spatially specific data inclusion, the fullest form of flexibility is found when the practitioner can determine freely to include or exclude spatial data.
2. A first standardization attempt to reduce the flexibility could be the agreement to use as relevant locally sourced data as possible in order to stay as close to the factual situation as is possible within the studies' context. This provides the practitioner with flexibility how to deal with spatiality, but standardizes the approach towards inclusion of spatial data. Thus studies that do not deal with a local situation, but take a global approach, do not suffer from this standardization.
3. A final step to reduce flexibility of LCA, while maintaining its usefulness as an assessment, could be the situation wherein it is required to include site-specific emission data and to use localized normalisation rates for the data based on standardized measurement approaches, in order to have a common method to determine the spatial consequences of flows. This would ensure that that local context of the emissions is considered and to understand the emissions in their relevant natural context. Additionally, this would occur similarly in all LCAs, creating uniformity. However, it does lead to an expansion of the workload necessary in an LCA, and perhaps modelling difficulties.

Scenario selection

Practitioners must also decide whether or not a scenario is included in the study. Because many LCAs not only consider the current impact of a product (attributional/situation C) but also at future impacts (consequential/situation A or B), scenarios can be used that describe a certain path in the future in order for practitioners to model their LCAs on (Reap et al., 2008a). However, because the future is inherently unknown and uncertain, these scenarios are difficult to create and might anticipate the future incorrectly. Many scenario's that have been developed in the path, in various scientific fields, were proven to be wrong in retrospect (Reap et al., 2008a). The scenarios inclusion or exclusion of technological progress and discount rates also matters in the final impacts. It is therefore important for practitioners to carefully consider the scenario that is being used, because it has great consequences for the final results.

Thus four levels of flexibility can be identified.

1. It is a fact that an LCA study can be conducted regardless of whether a scenario is included or not. Because LCA results can be achieved with either option, full flexibility is possible when the choice to include or exclude a scenario is left free.

2. A first reduction of the flexibility would be the agreement that if scenarios are included, then they are to be used alongside a sensitivity analysis that would show how different scenarios would change the results. This would still allow the freedom to choose whether or not to include scenarios, but would create a more coherent approach when they are included.
3. A next approach to reduce flexibility even further could be to stipulate in which types of LCA studies scenarios are mandatory or forbidden. That way the choice for practitioners to include scenarios or not is removed, but freedom which scenario is included is still free to decide upon.
4. A final step could be to standardize the scenarios in line with scientific consensus that can be included in LCA studies in order to create a common understanding of the scenarios used. This is a large intrusion on the freedom of practitioners to model freely, but does create a common scientific baselines and thus some reliability.

Phase 2

Data collection

Every practitioner must determine how and what data will be collected. It is recommended that for a consequential LCA (situation A or B) the practitioner would use marginal data that represents the situation at the site, while a attributional LCA (situation C) would be created with aggregate data of the entire sector (Ekvall et al., 2007). However, it is up to the practitioner to actually gather the data and chose which data to use. The practitioner must also determine to what extent data is up-to-date and thus useful for the study (Reap et al., 2008b). Sometimes, the way data is collected and what assumptions were used in its collection and reporting by third parties is unknown (Reap et al., 2008b). Thus the practitioner must decide whether the data is trustworthy or not. Similarly, the choice which level of data is used, meaning local data or from a higher organisational level, is likely to influence the results because at different levels emissions can behave differently or have more options to behave (Singh et al., 2010). Therefore, it is possible to have data differences.

To deal with these differences, some authors argue that it is important to use the most accurate local data as possible, because not every facility functions in the same way and uses exactly the same inputs as other similar facilities even when they use the same technology (Reap et al., 2008a). Unfortunately, others have argued that the choices LCA practitioners make when determining the marginal data to be included in the analysis are not always the real marginal data and fail to accurately reflect the future (Mathiesen, Münster, & Fruergaard, 2009). Moreover, the different choices the various LCA practitioners make lead to an incoherent LCA practice (Mathiesen et al., 2009). Therefore, flexibility is a factor and the following levels can be identified.

1. It is a fact that data is necessary for the LCA, but also that it is possible to collect data under complete flexibility. Thus the most flexible approach would the situation where practitioners are free to choose which data is gathered, how it is collected, and which data is eventually used.
2. A first step to reduce the flexibility would be the use of standardization guidelines, for example to ensure the quality of the data. By creating standards for data quality, the practitioner is free to collect and use the data freely, but third parties know that the data is of sufficient quality.
3. A final step would be a standardization of data collection processes. For example, for attributional LCAs data could be acquired from certain attributional databases, while for comparative studies the marginal data could be acquired via a standardized data collection approach or from marginal databases. That way, the type of data that is gathered remains free of interference, but the trust in the data increases. This means that the type of data

remains freely chosen by practitioners, because it is nearly impossible to standardize that aspect of LCA since each production process is different and has different consequences.

Database selection

To enable practitioners to conduct their research efficiently, large LCA databases have been created. Some of these databases are also coupled to LCA software tools that enable the practitioners to make the required calculations efficiently. These tools and databases often have predefined impact categories, indicators, normalisation rates, weighting factors, and scenarios (M Goedkoop & Spriensma, 2001). Furthermore, most databases allow industries to provide environmental information of their processes without the practitioner being able to pinpoint exactly which firm has the best organisational performance because the data are aggregated in the database (Finnveden et al., 2009). Consequently, the different databases and tools have different inputs and settings, resulting in different impact results for the same process (Andrae & Andersen, 2010; Finnveden et al., 2009; Speck, Selke, Auras, & Fitzsimmons, 2015, 2016). Thus the choice of LCA software and databases matters, and therefore four levels of flexibility can be identified.

1. For practitioners, the greatest flexibility is found in the free choice on database usage and selection. With this freedom, it is possible to conduct an LCA study.
2. A first step to reduce the flexibility could be to allow practitioners to freely choose whether or not to use a database, but if a database is used they should conduct a sensitivity analysis with a different database in order to show the differences if a different choice was made. This would increase the robustness of the results.
3. A second step could be to conduct the sensitivity analysis with databases that adopt a precautionary principle approach (PPA), because then LCA studies will provide the same basic scientific understanding of a product for comparison. The use of PPA in this standardization process can be justified on the grounds that the LCA is a tool that attempts to create knowledge on the impacts of a product. However, in science not every connection is understood and therefore the PPA is often invoked to be as least likely to cause harm. Assessing all products with PPA databases would ensure that every study will use a similar approach to deal with uncertainty. The PPA database would function as a baseline.
4. A final step to could be the standardization of databases themselves in order to stipulate which database a practitioner must use. Such an approach would lead to the situation where every practitioner uses generally identical data, resulting in a lower spread of impact results.

Phase 3

Impact Category

A practitioner must also determine which impact categories are included in the study. When LCA software is used, sometimes those decisions are made for them by the software builders (M Goedkoop & Spriensma, 2001). Some authors argue therefore that because of a lack of impact category standardization, differences between LCA studies exist (Reap et al., 2008b). Moreover, when impact categories are developed with the use of stakeholders, which is essential for SLCAs, even more room is left for the practitioner to influence the LCA direction. At the same time, some impact categories, for example land use change, are barely included in LCA studies even though the impacts those categories represent are actually considered important for the environment and sustainable development (Haes et al., 2004; Reap et al., 2008b). Similarly, some impact categories are unlikely to become accurate any time soon because the amount of available input-data is currently only a fraction of the total amount of inputs that enter nature and because the interaction between the inputs and nature are unknown or not understood sufficiently (Finnveden, 2000; Haes et al., 2004; Reap et al., 2008b; Sauer, 2012). Additionally, for some materials it is simply unknown what their impacts are (Reap et al., 2008b). As a consequence, the data gaps do not allow LCA studies to always accurately assess the impacts of these products.

A practitioner must also decide how the indicator flows relate to the impact categories. This relation and normalisation is debated as well. For example, does a ton of CO_2 cause x amount of damage to human health, or 5x amount of damage? And also how much CO_2 equivalent is one ton of CH_4? Because there are different perspectives on the translation of the environmental loads, LCA practitioners can use different LCIA models with different weighting factors (Van der Harst & Potting, 2013). Sometimes the databases make these decisions for the practitioner.

Likewise, in SLCA it is important to note that the practitioner can chose between assessing the impacts based on causal relationships between process and impact, or based on scoring systems that "allows the evaluation of the *position* of the unit processes assessed *relative* to the performance expected" as set by the practitioner (Parent et al., 2010, p. 167). Thus it is a choice, Parent et al. argue, between assessing "social performance" and "social impact" (Parent et al., 2010, p. 168). However, according to the guidelines, both methods are allowed.

Overall, the flexibility of impact categories can be classified in the following way.

1. In a fully flexible system, the choice of impact categories, indicator connections, and normalisation rates can be free. It is possible to create LCA results with complete freedom of these elements.
2. A first step could be to provide guidelines which impact categories are at least to be measured when studying certain product groups. This step would force practitioners to create an assessment that includes a general set of impact categories applicable to their sector, thus increasing comparability, while providing them the freedom to add additional categories that they deem important or interesting.
3. A second step to reduce the flexibility could be to use scientifically determined indicator connections for impact categories, meaning that it is standardized how an emission corresponds to impact categories. This standardization would allow impact categories to be based on similar data inputs, while maintaining the freedom which types of impacts are measured in an LCA apart from the common ones.
4. In the final step, flexibility can be further reduced by standardizing how much indicator flows impact a category. Thus the normalisation rates are standardized based on scientific consensus, in order to create a common understanding of impacts. It remains possible for practitioners to add assessments with different normalisation rates, but at least a common approach is established on which products can be compared and which increases interpretation possibilities.

Midpoint versus endpoint decision

It must also be decided by the practitioner whether to use midpoints that increase the accuracy of the projected impacts compared to the real impacts in nature, or endpoints that are more easy to understand for by the intended audience (Finnveden et al., 2009; Reap et al., 2008b; Seidel, 2016). According to some authors, the freedom that practitioners have in choosing midpoints and endpoints, which exists partly because they are still under development, "are confusing, and often unnecessary" and could perhaps use some more guidance by standardization organisations such as the ISO or organisations that produce LCA guidelines or software (Finnveden et al., 2009, p. 10; Seidel, 2016). Regardless, the fact remains that practitioners must chose and thus flexibility exists, and can be described in the following way.

1. An LCA study with full flexibility can allow the use of both midpoint and endpoint categories, because with both methods the impacts of the product can be represented.

2. A first attempt to reduce the flexibility could be to standardize the way in which midpoints are translated into endpoints. Currently, the translation is not always the same and thus the endpoints can differ in their inputs. Common midpoints could be matched with endpoint categories in order to create a basic common foundation of the endpoints, while maintaining the freedom to model as practitioners desire.
3. A second step could be to standardize the criteria that for decision-support LCA studies, it is important to use midpoint categories because those provide the most accurate projection of the product's impacts and the least translation subjectivity from the LCA practitioner. Like in science, the introduction of subjectivity should be introduced preferably by decision-makers instead of LCA practitioners. For other LCAs, the choice could remain free.
4. The final approach would be to use the PPA and to thus always portray midpoints in order to show the impacts with the greatest certainty. Endpoints can only be added as an additional analysis to indicate how the midpoints relate to generalized categories of harm.

Weighting impacts

How much of an impact an individual process flow causes, and how much an individual impact influences the system as a whole are decisions that a practitioner must think about and is often subject of debate (Finnveden et al., 2009). Different methods exist to gain clarity, such as determining the weighting factors by asking a group of experts about their opinion, by trying to monetise the impacts and thus weight them, or by using other scientific valuations to attach a weight to them in order to compare the impacts (Finnveden et al., 2009). However, those choices impact the results. For example, when scoring systems are used to weight the various impact categories, the way the scoring system are developed influences the final results. In LCSA, the choice between having one system boundary and functional unit, or three separate studies of the same product, result in different opportunities to use the results and thus will produce different impact results (Kloepffer, 2008). Especially when weighting the different type of impacts (environmental, social, and economic) to identify which impact is more harmful, subjectivity plays a major role (Souza et al., 2016). In addition to portraying the correct weight of an impact, weighting can also be used to reintroduce PPA to the decision-makers relying heavily on LCA studies. After all, because LCAs aims to model the system as adequately as possible, the modelling might interfere with the adoption of a precautionary approach by portraying results or dealing with uncertainty certain ways (Finnveden et al., 2009; United Nations, 1992). Weighting choices can reintroduce the PPA because it allows the practitioner to assign additional weight to those impacts that require a precautionary approach (Hofstetter, 1998). Thus there are merits and disadvantages to weighting, and different choices can be made. Therefore the following flexibility levels can be identified.

1. Because weighting is not necessary for obtaining impact results, full flexibility consists of the ability to include weighting or not.
2. A first step of flexibility reduction would be a standardization that if weighting is included, it occurs based on expert or consensus-based scientific input. Thus the practitioner must find adequate sources and this would improve the quality of the weighting. Such a rule would leave the freedom to weight and the choice how to weight with the practitioner, but would ensure that the choices are based on science and thus increase its reliability.
3. A second step could be to deal with the weighting process itself by using standardized weighting factors in order to increase comparability in weighting results across different studies. Thus for common categories, a common weighting factor is used.
4. A final step to reduce weighting could be to translate impacts into a common denominator, such as a monetary value, in order to create a common weighting factor to which everything is related and translated.

Temporal choices

Sometimes an emission is more harmful if emitted at a certain moment in time than when it would be if it was emitted later on (Reap et al., 2008b). Moreover, sometimes impact flows only start to impact nature when the systems boundaries, or nature's ability to sink emissions, are crossed (Reap et al., 2008b). Thus to quantify the impacts of certain flows properly, even though it might be difficult, the temporal scope must be addressed (Haes et al., 2004). However, some authors argue that to accurately model a dynamic system non-linearly requires an entire different set of data that accurately maps the state of the environment and the input flows over time by industry than is currently available (Haes et al., 2004; Reap et al., 2008b). However, they also have sincere doubts whether that will be possible, and consider it more likely to be too complex to do properly (Haes et al., 2004). Thus the accuracy of the LCA is limited by this. Nonetheless, practitioners must make a choice regarding temporal issues and thus flexibility exists.

1. Because impact results can be acquired without temporal considerations, full flexibility consists of the free choice to include a temporal scope or not.
2. Because it is difficult to model these temporal issues, standardization of it serves currently no real purpose. Therefore, it is probably best to wait with standardization until it is understood whether temporal factors can be accurately modelled at all. If it is possible to model temporal issues within the LCA framework, a standardization attempt could be to require practitioners to firstly use a general temporal scope and in further developments of the method a more individualised temporal scope that matches the actual emission release that is present in the studied system. That would reduce the flexibility for practitioners to choose temporal scales to suit the outcome but fail to accurately represent reality.

Phase 4

Review decision

According to the ISO standards, in some LCA studies a review is mandatory. In others it is optional and the practitioner is allowed to decide on that issue, as well as who is ordered to conduct the review. Currently, there is quite some flexibility that exists and this can be summarized in the following four levels.

1. It is possible to have LCA results without a review. Therefore full flexibility consists of the free choice to include a review or not.
2. A first reduction of flexibility can consists of the necessity to conduct reviews according to ISO standards, but only for external usage. For LCA studies used internally, a review can be included or excluded and executed freely. The review committee can still be chosen freely.
3. A next step of reducing flexibility could be that only certified organisations are allowed to review LCA studies that are to be used externally. Thus the quality of the review is also guaranteed.
4. A final reduction of flexibility could be the requirement of mandatory review for all decision-support LCAs because a choice might have external consequences.

Uncertainty

A lot of LCA studies have a significant level of uncertainty in their results (Bare, 2014). Some might argue it is inherent to LCAs because it deals with subjects and feedback loops which are not completely understood (Huijbregts, 2016). However, these uncertainties are not always mentioned (Bare, 2014). Thus a decision based on a LCA might be based on uncertain or incorrect results, which will reduce the trust in the methodology eventually (Seidel, 2016). Finnveden et al. define uncertainty as "the discrepancy between a measured or calculated quantity and the true value of that quantity" (Finnveden et al., 2009, p. 14). The flexibility in uncertainty is found in the fact that uncertainty occurs whenever a choice is made by the practitioner in the study or when the wrong type of data is included in the study (Finnveden et al., 2009; Reap et al., 2008b). However, the fact that uncertainty exists also lends itself to new types of research opportunities using statistics or by combining a large number of studies and aggregating them to reach a consensus figure (Huijbregts, 2016). If solutions such as this were adopted, uncertainty might not be a bad thing after all (Huijbregts, 2016).

A practitioner can choose to reduce the uncertainty by expanding the research efforts or to discuss the study with other practitioners to create a consensus (or use a predefined model or approach) (Finnveden et al., 2009). It is also possible to use statistics to get an understanding of the level of uncertainty that is found in the study (Finnveden et al., 2009). Sensitivity analyses can also help to identify how different decisions impact the results (Santero et al., 2011). However, in the end the practitioner has to determine to what extent uncertainty is allowed in the study in order to make the results understandable to the decision-maker (Reap et al., 2008b). It can be argued that this is especially important considering that in reality results are often presented with more certainty than they actually have, resulting in wrong information being delivered to third parties (Bare, 2014). Thus the following levels of flexibility can be constructed.

1. It is a fact that uncertainty is inherent to LCA, or nearly impossible to prevent because of the choices and assumptions used. However, some analyses can be conducted in order to reduce the uncertainty. Therefore, full flexibility would consist of the situation when a practitioner can determine all choices related to dealing with uncertainty freely.
2. If the flexibility is to be reduced, the first step could be to use statistical analyses in order to identify the level of uncertainty in the study. Similarly, sensitivity analyses can be used as input for the statistical analysis of uncertainty. Such an action would not force a practitioner to act on reducing uncertainty, leaving complete freedom, but does create more understanding of the uncertainty for third parties the study is presented to.
3. A second approach could be look into similar studies and analysing them in order to create a consensus model of the system under study (Huijbregts, 2016). That way, it is possible to deal with uncertainty by combining the insights and results of various studies. Such consensus models can be used by practitioner as common baselines for their individual studies.
4. A final approach to reduce flexibility in uncertainty choices is standardization of the LCA method and its choices. With detailed standardization, there is no more room for uncertainty deviation.

Interpretation

LCA studies require interpretation in order to be useful for decision-makers. The method leaves the normative judgement to the policy- or decision-makers (UNEP Setac Life Cycle Initiative, 2009). LCA is a supportive tool, not a decision-making tool. Even if a product has very negative impacts, there might still be merit in deciding to engage in the activity. Weighting interests in order to make decisions in not the subject of LCA practitioners. However, that does not mean that the practitioner has no influence on the interpretation whatsoever. Results can be interpreted differently. Haes et all. give the example of a product that requires a lot of labour input (Haes et al., 2004). Depending on the perspective one takes, this can mean, according to them, at least two things. It can mean that the product requires a significant amount of employment, which is a positive thing, but might also mean that the product is created using a highly inefficient production method, which is negative (Haes et al., 2004). Thus care must be taken how these results are represented by the practitioner. The flexibility can therefore be defined as follows.

1. Full flexibility with interpretation of LCA results is possible, and results in a freehand for practitioners on portraying results.
2. A first attempt to reduce this flexibility is to refrain from any subjective claims on the found results, but to portray them as objectively as possible. That way, the practitioner holds the

freedom how results are portrayed, but third parties can be more certain that the results are objectively processed and presented.

3. A further attempt could be to translate every individual impact with a common denominator. Thus every impact is translated to a single value, for example money, damage, or sustainability. To ensure the quality of this translation, the value most be standardized and the translation process must be scientifically sound and based on a consensus.

3 Combining Circular Economy and LCA

Now that the CE and LCA method have been explained, and the principles of CE and the choices of the LCA practitioner have been identified it is time to compare the two.

3.1 CE Principles compared to LCA methodology

The first step in this assessment is to understand how LCA methodology in its current form can help CE. This is done by comparing the principles identified in chapter 1 with LCA methodology to see where, in theory, LCA might be beneficial to CE. The second step (next section) concerns how the flexibility of LCA plays a role in the success of CE and how the flexibility can be dealt with at different levels of CE. `

All production should follow the 3Rs: Reduction, Reuse, and Recycling

The LCA method seems adequate to use in the reduction principle (Castellani, Sala, & Mirabella, 2015). Because of its possibility to identify environmental impacts, it allows the decision-maker and product designer to know which areas of the product's lifecycle have the highest impact. Therefore, resources can be directed to deal with these highest impacts first in order to try to make large environmental progress in those areas in accordance with CP thinking. LCA can also be used to assess various production processes or product designs in order to find out which have the best environmental performance for decision-support and design questions. LCAs are especially well suited to assess the impacts during a use phase of a product, because some products might use more materials, but have a far better use phase because of that, which causes the total impact to be better than the product with less resource inputs. Such information is vital for consumers and businesses alike. Additionally, the LCA can help to identify exactly which materials are used in the lifecycle processes, in order to give the producers a good overview of the make-up of their product and thus enable them to use that information to find circular replacements for those materials. LCAs could also be useful for understanding the material flows within an economy, or can be used to compare similar lifecycle processes in terms of their impact on the natural system in order to discover which kind of processes are less harmful to the environment. Especially the ELCA at different levels of analysis (micro/meso/macro) as identified in the LCSA method can be useful for such purposes.

The reuse principle on the other hand is less helped with LCA methodology. After all, the reuse principle is mainly concerned with organisational, logistical, and marketing related questions and solutions that enable products to be returned to the producer for remanufacturing or to a second consumer for usage. An LCA can play no real role in this development, other than identifying whether the reusing of products is better than reusing the products for new, and more technologically advanced, products.

Finally, for recycling, LCAs can be used to identify the impacts of recycling processes in order to let decision-makers determine to what extent recycling provides added value to society. It provides information how different recycling methods and facilities operate and what the impacts of these methods and facilities are. It can, however, not help in identifying how a product can be practically recycled.

A circular economy should recognize the natural limits to circulation

It has been argued in chapter 1 that a CE is no *perpetuum mobile* but is limited by the laws of nature. A CE tries to be an optimal socio-economic system within those natural boundaries. LCA cannot provide the information a CE requires to optimally use resources. It can, however, assess from which source it is best to gather resources because they have the least negative effects, if the impact categories are adequately structured to account also for resource depletion. However, LCA is limited in its usefulness by the level of scientific understanding of natural limits and the material impacts and changes.

A circular economy should internalise all externalities

An important principle of CE is the inclusion of all types of external effects into the economic system. It proposes to do so by internalising externalities into the price of a product. The mains proposed ways this can be achieved, via taxation, insurance, regulation, and permits, all require that it is known what the externalities actually entail. Without a proper understanding of the externalities of a product, it is difficult to determine the impacts of the externalities and therefore complicated to pinpoint what the costs of the levy should be. Therefore, the LCA methodology is useful to assess how much positive and negative external effects are occurring within the various lifecycle stages of a product. It is also argued that it is especially important to use LCAs to measure the factual situation, because otherwise environmental burdens might be shifted to other areas or impact categories to which they in reality do not belong (Bare, 2014). Such information can then be used to determine for each actor what their individual responsibility for the external effects is and how high much of the costs they should offset. That does require that externalities are monetised. How that can be done is too much detail for this thesis. It is enough to note that LCA can play a vital part in the cost determination process and that the more scientific knowledge of the impacts of a product expands, the more useful LCAs will become.

An economy requires incentives and information to circulate products and materials

If all materials and products are accompanied with the information how that specific product has been treated in the past, which is necessary if materials are to be cycled properly, and what its current material quality is, then producers and remanufacturing/recycling organisations know exactly what the status of a product is. LCA can be used to create an understanding among producers how their supply chain is constructed, mostly via the Goal and Scope and Life Cycle Inventory phases, but it cannot be used to determine the quality of the material or identify its long-term history. The LCA can, however, definitely be used for environmental product statements (Schuuman, 2012). These can statements can be used by other actors to identify whether the product matches their circular demands. But, LCA can be used most effectively to assess what type of material a producer could use best and from what source that material should, preferably, be originating from. The preferred material origin does require the use of site-specific and local information, while the type of material to be used can be determined with the use of average data.

A circular economy requires industrial symbiosis

LCA can be used to help firms cooperate by identifying exactly how the firms are dependent on each other (Schuuman, 2012). It can also help to identify different materials that can be used throughout the supply chain that have a better performance (Schuuman, 2012). LCA is especially useful for understanding how materials flow between companies and flows within a more complex eco-industrial complex and can identify possibilities for further industrial symbiosis within such conglomerates. The LCC methodology can also be used to assess the various economic costs of this industrial symbiosis within these conglomerates. Especially if such eco-industrial parks become highly interdependent than OLCAs become useful in order to determine the individual impacts of the products, because individual products will require a large amount of allocation solutions to deal with the various waste-to-input flows.

A circular economy should not neglect the social side of economics

Sustainable development is a combination environmental, social, and economic issues. If one of those three is lacking behind in its development, it is likely to have some negative effects on the other two. Because the CE must deal with social impacts as well as the environmental and economic consequences, SLCAs and SOLCAs can be used to determine the impacts of the products. This can help decision-makers to weight which processes or materials should be used.

3.2 CE principles in practice: LCA flexibility related to a simple CE model

After identifying where LCA could potentially play a role in supporting a CE, the research can move to its final stage. When a CE is emerging, it will undoubtedly go through various stages of development. This is considered by governments and scientists alike to be a long term process (De Nooij, 2016; Jonker, 2016; Scottish Government, 2016). After all, it not a simple task to restructure an entire economic system. Thus it is useful to have a model that, crudely, assesses the various steps in the transition towards the CE in order to understand how these phases generally look like. Multiple theories exist that describe these stages, but for this research going into detail on these theories is not necessary.

To construct the phases of the development of the CE, a multi-level perspective (MLP) like figure 8 from transition theory can be adopted to explain how innovations spread throughout an economic system. In this model, at the local (niche/micro), sectoral (regime/meso), and societal (landscape/macro) levels of society, changes can influence the entire system and trickle down or up the hierarchy to change the status quo (Geels & Schot, 2007). This thesis uses the idea that of that model that a change towards a CE can occur at many different levels simultaneously, but is likely to begin small and end large. Thus the model is not used as a framework, but as an inspiring notion. This research further takes Schumpeter's notion of creative destruction as described by Espen Moe in his analysis of the Japanese energy sector (Moe, 2012). Creative destruction is chosen because in this research the CE is seen as a type of organisational innovation, both at micro and macro levels. Basically, the idea of creative destruction is that industries emerge, grow, mature, decline, and disappear with the development of new and more advanced technologies that replace them (Moe, 2012). First, the industry that has developed or uses a new technology grows in a niche of the market where it can operate, but is no threat to the status quo of the market. Secondly, the new technology grows and competes with the incumbency. In the third phase it becomes the major player in the market and the old incumbency disappears. Fourthly, a new technology appears that starts the process anew. However, Moe argues that because the incumbency gets powerful over time, it is able to influence the political system to support its business model and thereby increases the barrier to new technologies or business models that wish to enter the market (Moe, 2012). The CE can be seen to fit the creative destruction ideas, because it uses an entirely different business practice that gives it comparative advantages towards the old incumbency which is likely to be favoured by the current set-up of the economic system (Moe, 2012). This combination of creative destruction and transition theory is used to construct a model of the development of CE.

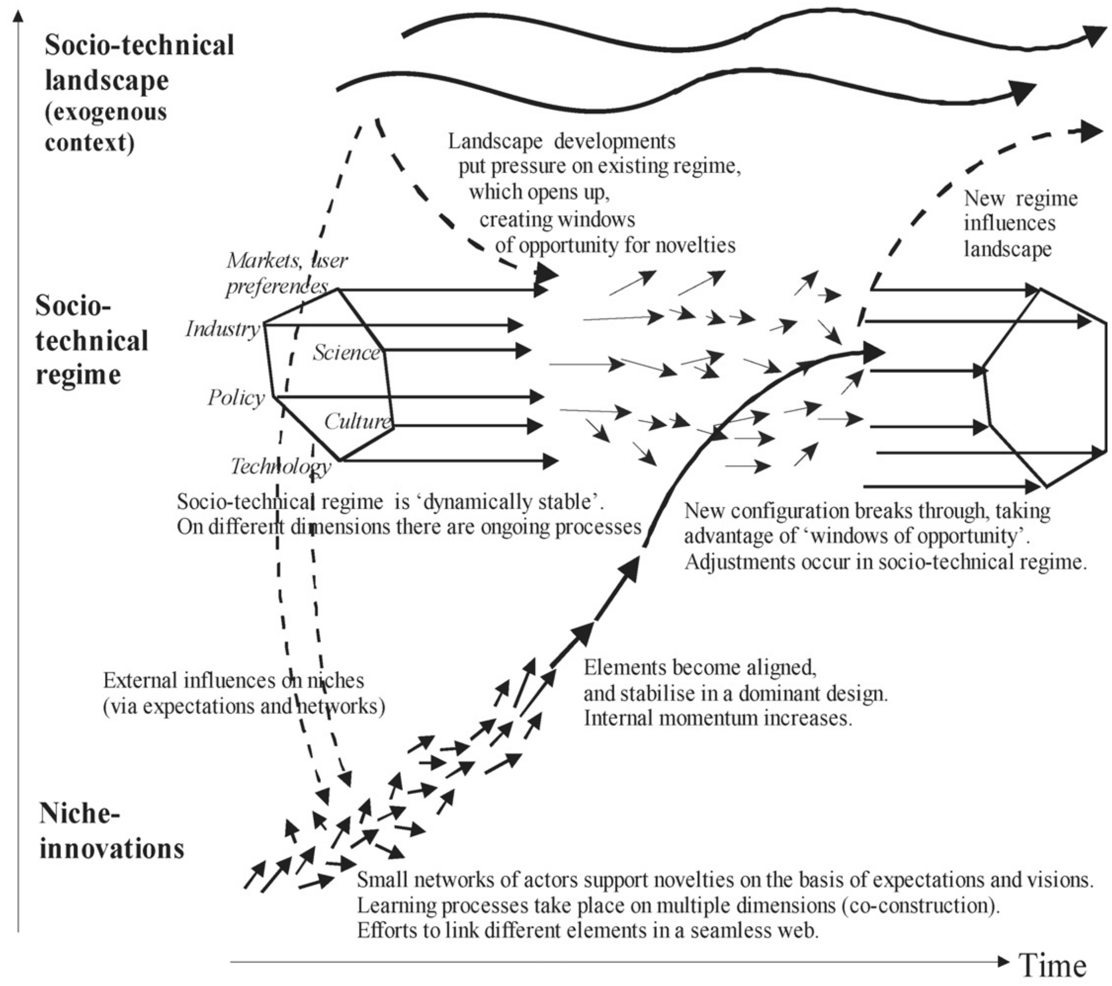

Figure 8: A multi-level perspective model of transition (Geels & Schot, 2007, p. 401).

3.2.1 Circular Economy Model

The CE model that is presented below will consist of four economic stages, beginning with linear and ending with fully circular.

Linear Efficient

The first noticeable step towards a CE is based on efficiency and recycling. It is characterized by an attempt by firms to reduce their natural resource costs. Virgin raw materials are still extracted, but producers try to decrease the amount of resources they need for their products in order to reduce the costs of production. This is called eco-efficiency (Ghisellini et al., 2016). However, this reduction only occurs at the production level of the individual firm, not throughout the supply chain. The material input during the use phase is not considered in this approach, because only the position of the firm is considered important. At the end-of-life part of the lifecycle, recycling begins for some sectors in order to reduce landfill necessity and use the recycled materials for production if the recycled materials are cheaper than raw materials and if regulation allows for its use. At the same time, incineration techniques are used to capture energy from burning waste.

Niche Circularity

During the second phase, producers not only try to develop eco-efficiency for their own benefit, but also try to reduce the material input during the use-phase. Thus the focus also includes the use-phase and causes firm behaviour to change. The first firms begin to sell services instead of products or sign agreements to take back the products at the end of their life via reversed logistics, but such contracts are still only a niche of the entire market. Through this change in business behaviour, business incentives change as well. For PSS firms it is less beneficial to follow the old model of designing products that break relatively quickly in order to sell more products. Instead, it is more beneficial for them to design products that can be updated and remanufactured quickly and effectively in order for the producer to limit production costs. The profit does, after all, not come from selling goods, but from leasing and remanufacturing goods. Thus they have an incentive to design products for long term usage, and are supported by organisations and consumers that promote buying circular products. Simultaneously, non-renewable resources are beginning to be replaced with renewable resources, where that is economically viable, either because of costs or availability, or because pressure is mounting to change their material mix. However, in this phase the firms that use PSS or transition to sustainable practices form only a niche.

On a societal level, experiments are also being started to test how external effects can be internalized and to promote circular entrepreneurship. Reuse is growing in society because local communities create second-hand markets where products are sold, repaired, shared, or given away to other consumers. Recycling is also promoted by governments continuously improving their collection methods and asking consumers to separate more and more waste flows. Circular and sustainability thinking is also penetrating education and R&D sectors in order to improve the current methods and ideas. However, the main mode of organisation is still eco-efficient linear.

Transitional Circularity

During the third phase, the CE leaves the niche phase and becomes a general mode of economic practice because the concept has proven that is can add positively to society and businesses. In order to create a level playing field and progress towards sustainability, governmental subsidies on harmful materials, such as petroleum and coal-firing power plants, need to be removed and replaced with a system that ensures that all external effects, positive and negative, are internalized in prices. Additionally, producer responsibility is extended to cover more types of products and firms, brining further incentives to become circular. Because of the scale of CE, enterprises increasingly become interconnected and share input and output loops, causing material loops to begin to close as a result of the reuse and recycling processes. This requires opportunities to receive information of the materials history that one uses. Material passports that are kept in secure databases might provide the required setting for this information.

In society, the transition to renewable forms of energy is nearly completed, and renewable materials are increasing in popularity and usefulness because products are designed in such a way that they can last for a long time and can be easily repaired, upgraded, and remanufactured. As a consequence, the differences in ownership among consumers change drastically. Consumers allow companies to retain ownership of their products because they understand the benefits it brings them, such as clear transparency about the total costs of a product instead of just the price and lower risks (Reichel, De Schoenmakere, Gillabel, Martin, & Hoogeveen, 2016). Consequently, cash flows change as well and become more continuous during an entire lifecycle, instead of lump-sum at the start of the use phase (Reichel et al., 2016). Additionally, the industries find themselves more often than not as part of a web of eco-industrial parks, where waste flows can easily be transported to other firms. As a result, the companies must organize themselves and cooperate their investments together along the entire supply-chain (Preston, 2012). That means that cooperating firms must be transparent about their business and processes. The old linear incumbency is facing increasing competition from the new circular firms.

Full Circularity

In the final phase, CE is fully implemented in society. That means that not only is the system circular, it also follows the sustainability principles, because without providing positive benefits to society a fully circular system is impossible to create in a free society.[4] Therefore, the 3R principles are implemented in every production process, ensuring that materials cycle as long and as effectively as possible. Thus different, renewable (or near-infinite recyclable non-renewable) resources have replaced non-renewable and toxic materials. Many of these products have a modular design that allows for efficient and effective and remanufacturing (Bermejo, 2014). To achieve this, full disclosure on the used materials in products as well as the materials' history is available. In recycling, materials are recycled as far as is technically and socially possible in order to hold on to as much quality as possible. After all, it is possible that a recycling process will require an amount of energy or money that is too much for society to provide. Thus recycling continues as far as society receives positive benefits. Consumers share products and process all their products at the end-of-life according to the regulations and contracts provided by government and corporations in order to allow reuse, remanufacturing, and recycling. With the reduced production costs through increased material efficiency and product lifespan, more money is available for consumers to spend on other products and services, increasing employment. This increased employment might offset the losses in the manufacturing industry, some organisations report (The Ellen MacArthur Foundation, 2012). Others argue that in fact the economy will shrink and the created jobs will be low-end jobs in recycling materials (De Nooij, 2016; Jonker, 2016). However, it might also turn out differently because forecasting large economic changes is quite a challenge.

Because a CE stays within the natural boundaries in order to have sufficient resources in the future, waste is nearly eliminated. In practice, this means that there is extraction of raw materials only until the carrying capacity of that raw material. Thus only renewable forms of material are being extracted from nature. Non-renewable resources are not extracted, because the current stock of raw materials is used continuously and matches the demand for those resources. At the end of a lifecycle, the biological resources are returned to the natural system in such a way that the carrying capacity of the natural system can deal with these biological flows without experiencing negative effects. This requires intimate knowledge of local natural conditions. Luckily, because the use of all products is as circular as possible and the flow of remanufacturing or decomposing goods can be predicted by analysing the data of the contracts that consumers and producers sign, the flow of used materials can be predicted and becomes reliable (Andrews, 2015, p. 310).

If the CE is also to be truly sustainable, eco-efficiency must be turned in resource-efficiency where firms not only focus on economic and environmental gains but also consider the social consequences necessary for sustainable development (Ghisellini et al., 2016). The circularity is inclusive, meaning that it does not occur at all costs and hurt the social wellbeing of the system. As a consequence of this system, there are no more waste flows that do not have a positive influence on the sustainable system. The social goals of sustainable development are fully incorporated in the CE. This means that it is preferred circular processes have positive social results. It is up to decision-makers to determine how social consequences of a process correspond to the environmental consequences. The SLCA can thus be used to identify the social costs of a circular process. However, before the SLCA can be a beneficial tool for a sustainable

[4] A CE is possible without being sustainable, because if CE is interpreted as mainly a material cycling economy, it is possible to create a system that is in fact unsustainable. For example, recycling every rare material might require amounts of energy or chemicals that cannot be provided without extraction large amounts of virgin material or the dumping of toxic waste in the environment. Similarly, this can also occur by using humans to separate the materials by hand, which might be beneficial for material recycling but harmful to the social goals of sustainable development.

circular assessment, the SLCA method must be developed further. However, unlike the ELCA which aims to be as scientific as possible, the SLCA method allows for more subjectivity in its implementation. Especially when dealing with sustainability, different SLCA methods could be used in different situations because socio-economic and cultural situations differ between locations.

3.2.2 Providing the CE stages with LCA input

Because it is assumed that actors follow the principle of least effort, this analysis tries to assess what the LCA method should at least look like to play a role in the various CE stages and principles. It is important to note that only LCAs conducted for external purposes by businesses or for governance purposes are likely to need some restriction on the freedom of LCA practitioners. All scientific, educational, and internal non-governance reports are free to be conducted as the practitioner sees fit, because those types of LCA require freedom to improve the methodology or are not used for external purposes and are thus not of interest to other players, unless governance rules require organisations to conduct their LCAs in a certain fashion before making a decision.

For each of the four CE phases it is assessed what role LCA can play within each of the CE principles. Thus per development stage the usefulness of LCA and the minimal requirements of LCA to function properly are assessed. The focus is on the minimal requirements because of the assumptions made about human behaviour, especially PLE.

Linear efficient

All production should follow the 3Rs: Reduction, Reuse, and Recycling

LCA methodology can be used to identify where the costs of a product are located during the production of a product and which material compositions might reduce those costs. LCC can be used to assess the costs of the product and compare the costs of different material compositions. Producers are not so much interested in environmental or social impacts of these materials. Thus, flexibility is an asset that allows practitioners to pinpoint exactly which materials are being used and where the costs are located during the lifecycle. For all flexibility elements identified earlier, a fullest form of flexibility can be adopted. After all, all that matters is gaining results to cut production costs, not costs occurring in a use phase, nor environmental or social impacts. The results are mainly used for internal reasons. Cutting the system of to end at the factory-gate can hence be useful. For reusing or recycling no LCA is needed because the information provided by a LCA would not benefit reuse practices (since reuse is not supported by LCA in general) nor recycling activities (since choosing a recycling method is not part of the production requirements in this phase).

A circular economy should recognize the natural limits to circulation

This principle is unimportant in this phase of circular development because the natural limits are not yet recognized as important limits to the economic system. Thus LCA cannot be beneficial to CE in this phase.

A circular economy should internalise all externalities

Under eco-efficiency, LCCs can be useful for designers to know in which process and lifecycle stage the costs and material use of are highest in order to focus on those areas in order to increase the efficiency of the production process. Flexibility is important for these internal processes and the use phase is again unimportant, unless a firm wants to reduce the impact during that phase for marketing purposes.

A circular economy requires incentives and information to circulate products and materials

In these phases there is no circulation of products and materials, nor a need to know all the environmental consequences of a product. LCA therefore cannot provide any useful information for this principle in this phase.

A circular economy requires industrial symbiosis

There is not industrial symbiosis in this phase of development, and thus there is no need for LCA support.

A circular economy should not neglect the social side of economics

Because only the micro-economic situation of individual firms matters in this phase, there is no interest in LCA information on social aspects.

Niche circularity

All production should follow the 3Rs: Reduction, Reuse, and Recycling

The use phase becomes important in this CE phase. Firms that operate in a circular way will try to reduce the material input in all product phases, in order to reduce the pressure on the natural system, gain a marketing tool towards competitors that do not reduce material input in the use phase, and to reduce costs and emissions in general. LCA methodology can be used extensively to discover which type of production processes and material inputs perform better in terms of environmental impact or economic efficiency. Thus the ELCA and LCC are useful. Both can be flexible approaches, because there are no other actors directly dependent on the accuracy of the LCA results. The results serve mainly as decision-support within a context of setting the first steps towards circularity and sustainability. For some elements, some standardization or basic requirements are necessary to ensure LCA is useful in this phase. For example, because the use phase is included, a cradle-to-grave approach is not enough anymore. A cradle-to-grave approach will need to be introduced. Thus LCA methods can be used with large amounts of freedom to discover optimal processes that provide comparative advantages to firms and reduce the pressure on the natural system. This includes assessing different recycling processes.

A circular economy should recognize the natural limits to circulation

Because firms operating circularly in this phase try to reduce the impacts of their processes throughout a product's lifecycle, they look at all lifecycle phases. One element is to assess which externally procured inputs are more environmentally friendly or circular in order to support the less harmful production processes. Because this is a general assessment, flexibility is no issue.

A circular economy should internalise all externalities

Apart from reducing costs, externalities are not yet important in this phase, and therefore there is no demand for LCAs assessing it. However, actors are free to conduct them for any reason, for example for marketing or information purposes. They can also be used as a supporting tool for identifying where material reduction efforts should be directed towards. For this purpose, an ELCA can be useful. Flexibility of the practitioner is relatively unproblematic in this phase as long as the choices are transparent and fairly represented for external audiences.

A circular economy requires incentives and information to circulate products and materials

In this phase of CE, first try to create an overview of their entire supply-chain in order to gain a holistic view of their products. This assessment requires no specific LCA criteria, thus flexibility is no issue. If actors opt for an environmental product statement (EPS), than an ELCA can be used following general ISO-guidelines and the specific requirements of the EPS organisation. Generally, flexibility is an asset in this phase.

A circular economy requires industrial symbiosis

With the knowledge how the supply-chain is structured, firms can try to improve their circularity or sustainability by engaging with their supply-chain. LCAs can play a role in identifying which types of actions could be possible to improve the supply-chains circularity or sustainability. However, because the supply-chain actors are likely to be mostly linear firms (since only a few firms are circular), it is doubtful how much successful the attempts will be. To improve the odds, flexibility is useful to focus the study on what interests the actors mainly, such as insights into general environmental impacts or the costs. Thus flexibility in ELCA and LCC can be useful.

A circular economy should not neglect the social side of economics

Social issues are not very important in this phase, apart from a marketing perspective. Therefore, SLCAs can be used. If SLCAs are conducted, flexibility is not an issue because few actors actually use SLCAs and thus a lack of detail or accuracy is better than no study whatsoever.

Transitional Circularity

All production should follow the 3Rs: Reduction, Reuse, and Recycling

Because in this phase CE becomes a general mode of production, the products become circular by nature. This means that the 3Rs principle is constantly active. Under guidance of CP, this means in turn that there is an effort to prevent negative environmental impacts design practices. These designers need adequate information how the various designs, materials, and production processes behave in relation to the environment. Therefore, LCA methodology and especially ELCA can play a large role in this phase of development. Simultaneously, the number of firms operating on PSS basis increase and more and more products are being reused. In this phase, the some reused products are assessed to see how they fare against other products. ELCA can be used just fine for that. Similarly, because recycling is a key element of the circular system, it is especially important that also different recycling methods are compared to each other in relation to the environment in order to assess which recycling processes are best used for a certain product. Again, ELCA can play an important role here. For these 3Rs, resource reduction no longer just means reduction of raw materials, but also a prevention of reduction of the general natural capital base through designing products that harm the environment less. As a consequence, reliable information is necessary. With wrong results, the designers might think the new design is better for the environment, when in reality it is worse. Therefore, LCAs must become less flexible in order to increase the trust that the results are reliable and representative of reality. If full flexibility is maintained, it is simply impossible to have a coherent economic system where products cycle in an environmentally sound way.

A circular economy should recognize the natural limits to circulation

With CE being a general mode of production, the material loops are also closing and some might already be closed. Therefore, it is essential that it is understood how the biological cycles of these products are functioning in terms of the ability of nature to reuse the nutrients. Therefore, the natural system itself must be studied extensively and especially also in local or regional settings where the nutrients are being returned to nature. Thus it will be necessary to have some temporal and spatial inclusion of nature's ability to incorporate the nutrients into her ecosystems. ELCAs can help to assess how a product relates to this and how many nutrients and the type of nutrients a product is expected to return to nature at a certain location in order to assess the impact of this nutrient flow. This requires also that impact categories include categories that can assess this phenomenon.

A circular economy should internalise all externalities

When considering the natural system in this phase of CE, it no longer suffices to solely look at resource depletion. Instead the entire natural capital base must be assessed, and thus a product's externalities must be known. The external effects of a product in a circular system should not be limited to the production phase, but include all phases of a lifecycle. It is through the LCA methodology that it is possible to determine these external effects in quite some detail. By assessing the impact of a product in its various life phases on natural capital, ELCA can help to identify what the external effects of a product are. If these external effects are then translated into economic costs, it is possible to put a price on the external effects of a product. However, because costs are directly related to the competitive position of a firm, it is impossible that firm A uses method A to assess the costs, while firm B makes other choices because they chose differently. Such practices will distort the market and are a large threat to the continuity of the internalisation of external effects. Therefore, flexibility must be prevented and a single coherent set-up must be used to assess the externalities.

A circular economy requires incentives and information to circulate products and materials

In this phase of development, when firms are made responsible for the end of life treatment of their products, they will require intimate knowledge of their products and materials in order to design their products in such a way that they are more easily remanufactured or recycled. For such purposes, an ELCA is useful to assess whether products can be better recycled if different materials or processes are used. The flexibility in this case can be relatively large, because it mainly concerns individual firms and their decisions. However, LCA methodology cannot go much beyond such uses for this principle.

A circular economy requires industrial symbiosis

Because in this phase circular firms are becoming highly interdependent, it is necessary to understand how the flows within such a conglomerate of firms operate. For this purpose, mapping the various flows within a conglomerate with an LCA is useful. LCCs can assess the costs and benefits of these connections over obtaining inputs from different sources, and can also provide information on other production processes within the conglomerate that might benefit some of the actors. Additionally, because the firms no longer act on their own but increasingly cooperate and need each other to survive, it might be advisable to use OLCAs to assess the entire conglomerate of product portfolios. By doing so, the firms can bundle their resources and conduct a proper OLCA, instead of having to pay for various LCAs that might, because of a lack of funding, be less detailed or useful. This interdependence does require that each firm can trust the results the other firms provide them with. Therefore, within these conglomerates a common LCA methodology is necessary.

A circular economy should not neglect the social side of economics

In this phase, the social effects are becoming increasingly important because CE has become a general mode of production. Therefore, the social effects of this system must be positive, otherwise civil society might withdraw its support from it, or the political system might create extra rules and regulations. Without continued support, it is difficult to make the final step to a fully circular system. Furthermore, especially if CE is developing alongside sustainable development, the social consequences of products and decisions must be known. Therefore, SLCAs for individual products, and SOLCAs for conglomerates can be useful, if these methods are more rigorous than they are nowadays. The methods need further development and standardization to create trust and reliability, while still maintaining the flexibility to measure the relevant impacts for each social situation, which will differ in every situation because no social setting is similar. To gather support for the cause, LCSA can also play a useful role by identifying how a decision will impact the environmental, society, and economy differently. This information is crucial information for decision-makers in an increasingly interdependent system.

Full Circularity

All production should follow the 3Rs: Reduction, Reuse, and Recycling

In the final stage of the CE, all production occurs based on the 3Rs and sustainable development criteria. This means for reduction purposes that the reduction of materials and impact on the environment must not only be environmentally beneficial, but also socially acceptable and economically viable. Thus a LCSA methodology might be preferable over individual ELCAs to discover not only what reduction designs might be beneficial, but also how those designs impact the social and economic realms, because effects in those realms will cause effects in the environmental realm. Moreover, because of the heavy interconnectedness of actors in this phase, it is vital that the LCA results can be trusted. Because a CE is a system, and builds upon system thinking, a LCA should also adopt a system perspective where individual changes in one of the three realms, impacts the other two. For recycling purposes, the barriers to socio-ecological beneficial situations, must not be crossed. For this reason, conducting solely an ELCA is insufficient. SLCAs must be added, preferably LCSAs to identify the larger picture. For all these cases, because of the interdependency of operating in conglomerates and the need for reliable information for, among other, design purposes, standardization of the LCA methodology is necessary. For recycling and reuse practices, the same logic applies.

A circular economy should recognize the natural limits to circulation

In a full CE, it is necessary that all activities occur within the natural boundaries. Therefore, knowledge of natural systems must be as great as possible. Depending on the level of this understanding and the ability to model with temporal and spatial factors, the nutrients returning to nature can be managed by assessing the nutrient content of waste flows using ELCAs or OLCAs. For products that have a negative impact on the environment, such as the few non-renewable extraction to enter the cycle to upgrade recycled materials, ELCAs or OLCAs can be used to assess whether the emissions do not exceed the carrying capacity of an area or the quota of emissions allocated to the firms (Bare, 2014). Thus products can also be compared to a general natural capital base. When quote are implemented, the used LCA methodology is similarly executed by all actors. For all other types of LCAs, some flexibility can be an asset, as long as the results are not used by others when the quality cannot be guaranteed.

A circular economy should internalise all externalities

When a CE has been fully implemented, then all externalities should be accounted for. These externalities arguably also include social and economic externalities. Therefore, a LCSA methodology sounds logical to assess these impacts. However, because firms are also highly interdependent in conglomerates, OLCAs, SOLCAs, or a combination of an LCSA and an OLCA might be necessary to map the impacts. Similarly with the previous phase, the externalities must be measured similarly. Thus little flexibility can be allowed.

A circular economy requires incentives and information to circulate products and materials

When comparing to the previous phase, little has changed in the transition to the final phase for this principle. The EPR was already fully implemented, and the same requirements and uses for LCA apply. However, especially when determining which material should be used the LCA methodology can be useful in this phase. Because there is full availability of material composition and impact in this phase, it is possible for producers to use LCA methodology to discover which material will match their production process best. Flexibility is an asset individually, but because each firm requires accurate and reliable information from other firms, some standardization will be necessary in order to prevent free-riding behaviour.

A circular economy requires industrial symbiosis

In a fully circular system, nearly all firms are incorporated in an IS arrangement. Therefore, the same rules apply as in the previous phase. These conglomerates can be the size of a couple of firms, but plans in China suggest that also entire regions can become conglomerates (Yuan et al., 2006). Regardless of the level chosen, OLCAs and LCSAs can be used to assess the situation and to choose the options that match the conglomerate best in a context of sustainable circular development. Individual products can also still be assessed, but because of the large interdependency and sharing of waste flows, the allocation factors would most likely lead to complex and large models. However, as long as the quality is guaranteed, both an organisational and product LCA are useful in this phase.

A circular economy should not neglect the social side of economics

In full circularity, it is especially important that decision-makers continue to consider the social side of the system. Otherwise the circular system will eventually fail. If circularity focusses solely on the environmental aspects of sustainability, it will most likely. Therefore, assessments are necessary just like in the previous phase, with the main differences that SOLCAs are arguably more useful than SLCAs because of the fact that conglomerates are the main form of industrial organisation. However, the usefulness of these social assessments will be determined by the developments of the coming decades. It is, however, certain that looking at just individual products or firms will not be sufficient for social effects. Individually, a product might be beneficial to society, but when the entire conglomerate where the product is made is considered, the results might be different.

3.2.3 LCA requirements model

Having established the usefulness of the LCA methodology in each of the four CE phases, these phases can be connected to the flexibility levels identified in chapter 2 in order to find the LCA flexibility requirements for each CE development phase (table 3). For each of the identified flexibility categories, the maximum amount of flexibility is presented at which the respective CE development phase as described above can still function. For flexibility categories that can require different levels of flexibility during a single development phase, both levels are mentioned.

Table 3: The LCA flexibility levels compared to the CE development phases.

Linear Efficient	
Useful LCA methodology	LCC, ELCA
Boundary Selection	Level 1 A cut-off at the factory gate is sufficient, unless the firm wants to focus on the use phase for its business strategy.
Allocation	Level 1 No requirements necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Spatial choices	Level 1 No requirements necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Scenarios	Level 1 Different material availability and pricing scenarios might be beneficial for the LCA results, but it remains free to choose by the practitioner. It is not necessary to be included.
Data collection	Level 1 It is only necessary to include material composition and costs in this phase, nothing more.
Database selection	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Impact category	Level 1 The practitioner can be free to choose which factors to include in the LCC and the ELCA because there are no external consequences.
Midpoint / Endpoint	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Weighting	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Temporal choices	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase. It could be useful for cost predictions in LCC, but that remains a free choice.
Review	Level 1 It is unnecessary to review when dealing with internal studies, but it a free choice when aiming to publicize the results
Uncertainty	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Interpretation	Level 1

	No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Niche Circularity	
Useful LCA methodology	LCC, ELCA, SLCA
Boundary Selection	Level 2 A cradle-to-grave is necessary because all phases are important.
Allocation	Level 1 or 2 Free to choose how to deal with it. Level 2 can be necessary if externally demanded, for example for EPS.
Spatial choices	Level 1 There is a free choice whether to include it or not, because it is not necessary.
Scenarios	Level 1 There is a free choice whether to include it or not, because it is not necessary.
Data collection	Level 1 or 2 There is a free choice how to deal with data, but the data has to be of sufficient quality if externally demanded.
Database selection	Level 1 or 2 There is a free choice, but use a common set of impact categories should be used if it is externally demanded.
Impact category	Level 1 At least resource depletion should be included because resources matter in this phase of CE. If pressured some other categories could also be added to the assessment, but this is not necessary for a useful LCA in this phase.
Midpoint / Endpoint	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Weighting	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Temporal choices	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Review	Level 2 It is necessary to follow ISO guidelines to show the study applies to the standards in order to create trust in the results and to show to third parties the organisation has complied with the rules.
Uncertainty	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.
Interpretation	Level 1 No requirements are necessary in this phase because it plays no necessary role in the LCA usefulness in this phase.

Transitional Circularity	
Useful LCA methodology	LCC, ELCA, SLCA, OLCA, SOLCA, LCSA
Boundary Selection	Level 2 or 3 For individual or conglomerate assessments level 2 suffices, but for design purposes and product assessments, reliable information of materials and products is necessary. Therefore, level 3 is needed for those cases. Without this standardization, designers cannot function properly because the data would not be reliable enough in a context of interdependency.
Allocation	Level 3 or 4 For general LCA usage, level 3 suffices, but level 4 is necessary for all calculation of externalities because this must be done correctly in order to have a fair market. For this, a standardized methodology is necessary.
Spatial choices	Level 1 or 2 Level 1 is useful for general LCA usage, but level 2 could be adopted for externality research in order to incorporate the local environmental sinks and impacts. Those might reduce or increase external effects and are therefore interesting for firms and governments alike.
Scenarios	Level 2 or 4 Level 2 would suffice for individual firms, because it would provide third parties with the necessary information regarding their choices. A level 4 standardization is necessary for conglomerates because they need a common framework to work with; otherwise the LCAs they build upon will be of lesser value and might point in wrong directions.
Data collection	Level 2 Level 2 is necessary for general LCAs because the data is guaranteed to be of sufficient quality. Also for conglomerates, a level 2 suffices because the quality is guaranteed and that is all that matters in this phase.
Database selection	Level 2 or 3 It is necessary to have a sensitivity analysis to check the results in all settings. However, for decision-support, a level 3 PPA approach might be useful in order to provide a general baseline for decisions.
Impact category	Level 2 At least a level 2 standardization is required because the necessary comparing of materials and products properly needs a common set of impacts that can be compared. This also creates a common baseline for externality research.
Midpoint / Endpoint	Level 1 The midpoints or endpoints debate does not impact the results, as long as third parties are presented at least the midpoints for their analysis.
Weighting	Level 1 or 2 Generally, weighting is not important, unless it is for decision-support in LCSAs. In those cases, some quality assurance found in level 2 would be necessary for decision-makers in order to be able to trust the results. Level 1 would be insufficient.

Temporal choices	Level 1 Because of difficulties, level 1 should suffice for the demands placed upon LCAs. In time, the inclusion of temporal factors could be useful for more accurate knowledge for externality management.
Review	Level 2 or 3 It is necessary to follow ISO guidelines to show the study applies to the standards. But to ensure the quality of the review for third parties and to increase trust in the results, using a certified LCA review centre might be useful.
Uncertainty	Level 2 The uncertainty of the study should be assessed in order to be able to build on it. This is necessary in this phase because firms are largely interdependent through the connecting of waste flows and PSS.
Interpretation	Level 1 or 2 The practitioner sits on the chair of the decision-maker if interpretation occurs by the practitioner. This is fine for internal LCAs, but for external decision-support LCAs, that is different. Third parties must be able to rely on the objectivity of the results presented in the LCA; otherwise the trust in the LCA is reduced. Therefore, a level 2 type standardization is necessary for those cases.
Full Circularity	
Useful LCA methodology	LCC, ELCA, SLCA, OLCA, SOLCA, LCSA
Boundary Selection	Level 2 to 3 For individual assessments level 2 suffices, but for design purposes, product assessments, and sustainability or externality assessments of conglomerates, reliable information of materials, products, and impacts is necessary. Therefore, level 3 is needed for those cases. Without this standardization, designers cannot function properly. Level 4 might be useful, but the system can function with level 3.
Allocation	For general LCA usage, level 3 suffices, but level 4 is necessary for all calculation of externalities because this must be done correctly in order to have a fair market. For this, a standardized methodology is necessary.
Spatial choices	Level 2 Level 2 is an absolute minimum for this phase because without the local spatial information, it is impossible to actively check whether the CE remains within the natural boundaries. As long as the quality of the results is guaranteed, level 2 suffices.
Scenarios	Level 2 or 4 Level 2 would suffice for individual firms, because it would provide third parties with the necessary information regarding their choices. A level 4 standardization is necessary for conglomerates because they need a common framework to work with; otherwise the LCAs they build upon will be of lesser value and might point in wrong directions.
Data collection	Level 2 Level 2 is necessary for general LCAs, also used for third parties, because the data is of sufficient quality. Also for conglomerates,

	a level 2 suffices because the quality is guaranteed. If the delivered data is not of sufficient quality, then level 3 should be considered. The quality must be sufficient; otherwise the method cannot fulfil its function.
Database selection	Level 2 or 3 It is necessary to have a sensitivity analysis to check the results in all settings. However, for decision-support, a level 3 PPA approach might be useful in order to provide a general baseline for decisions. Especially when the feedback loops between social or environmental impacts are not well understood, a PPA might be useful to stay within the natural boundaries of the system.
Impact category	Level 3 At least a level 3 standardization is required because it is vital to stay within the natural boundaries and that LCAs are of sufficient quality. To that end, the connection between flows and impacts should be scientifically sound and used by all in order to prevent that in study A an indicator produces different effects than in study B.
Midpoint / Endpoint	Level 1 The midpoints or endpoints debate does not impact the results, as long as third parties are presented at least the midpoints for their analysis.
Weighting	Level 2 or 3 When weighting is conducted, which is inevitable when LCSAs are conducted and CE is implemented fully, it is important that it occurs in a common way to prevent actors from greenwashing their results through the usage of low weights. In addition, because a CE system by is a system with a focus on the long term, weighting can allow long-term uncertainties to be weighted more, thus allowing the use of a PPA approach, in order to prevent future harm as much as possible (Bare, 2014; Sandén & Karlström, 2007).
Temporal choices	Level 2 In order to be able to cycle for a long period of time, it is necessary to know what the natural boundaries are within which emissions are possible. This requires modelling that is as accurate as possible, which therefore includes temporal factors.
Review	Level 3 LCA reviews must be of excellent quality so that third parties know that the results presented in the study are valid. Bias by choosing review committees must be prevented to get objective reviews.
Uncertainty	Level 2 The uncertainty of the study should be assessed in order to be able to build on it. This is necessary in this phase because firms are largely interdependent. Any attempt to further increase certainty is positive, but level 2 is the absolute required baseline.
Interpretation	Level 1 or 2 The practitioner sits on the chair of the decision-maker if interpretation occurs by the practitioner. This is fine for internal LCAs, but for external or conglomerate decision-support LCAs, that is different. Third parties must be able to rely on the objectivity of the results presented in the LCA; otherwise the trust in the LCA is reduced. Therefore, a level 2 type standardization is necessary for those cases.

Results

The comparison between the LCA methodology and the CE has provided a rich understanding of their relationship under conditions of further CE development. A number of points are interesting to note.

First of all, the scientific community is still actively working on both subjects. Although the LCA methodology has been around for a number of decades, its recent developments show that the methodology is alive and entering new unknowns with, for example, social impacts, sustainability assessments, and organisational portfolio assessments. However, despite the development and standardization of the methodology by the ISO and scientists, the methodology remains highly flexible. Therefore, for each important type of flexibility that has been identified in this research, a number of steps to reduce that flexibility and increase the standardization have been proposed. It must be noted that these reduction steps are not set in stone. They are indicative and suggest some standardization possibilities that could reduce the flexibility in a structured way. Regarding the CE, the literature review showed that the standard presentation of the CE as presented by the Ellen MacArthur Foundation leaves out important details. These principles of the CE, which are still under active development by scientists, can be divided in two groups. Some principles deal with the material and natural situation of a CE, while other principles specify the social and economic situations of a CE. Because the two set of principles are interdependent, focussing solely on the economic or material principles will not result in the development of a fully circular system. If a CE is to be developed, it is necessary to use a holistic systems approach dealing with the natural, social, and economic realities of a CE.

Secondly, a CE will not develop overnight, nor will the economy suddenly become circular. Instead, it will most likely be a process of transitions, a competition between circular and linear business models, technologies, and firms. Throughout the transition to a CE, the setting will change and therefore the requirements on the LCA methodology in each phase will differ. During each phase of development, the LCA methodology can play a role. For some principles it can play a larger role than others, but LCA certainly has a role to play within a CE.

Thirdly, the possibilities for LCA practitioners to use a flexible approach are numerous within the LCA methodology. Almost all of these choices has the potential to influence the final impact results. Therefore, any meaningful standardization will have to look at the entire method and go through the choices step by step.

Fourthly, when summarizing the results of the comparison between the LCA flexibility and the CE development phases, the graph of figure 9 appears. Because for some flexibility categories multiple levels of flexibility were required, the graph is shown as the average minimal level per phase. Thus the Boundary Selection score of 2,5 during Full Circularity indicates that the minimal requirements for LCA on average reach a level of 2,5. As can be clearly spotted from this graph, the maximally allowed level of flexibility generally increases with each phase of CE development. Even though the exact position of the levels are not immovable, because the levels can be defined differently or because the assessment can come to the conclusion that a different minimal level is necessary, the trend nevertheless is undeniably clear: the further the CE develops, the less flexible the LCA methodology can be allowed to be. After all, with the increasing interdependency of actors within a CE through the increasing amounts of waste flows that are being connected to each other, there is an increasing necessity to have reliable LCAs. These results are especially important when considering the assumption that actors are boundedly rational and therefore do not know everything about their subject of study, and that actors act based on PLE, causing them to take the easiest path towards their goals. Therefore, if standardization is not implemented it is likely that LCA will be unable to play a role in a CE because practitioners will use the provided flexibility fully.

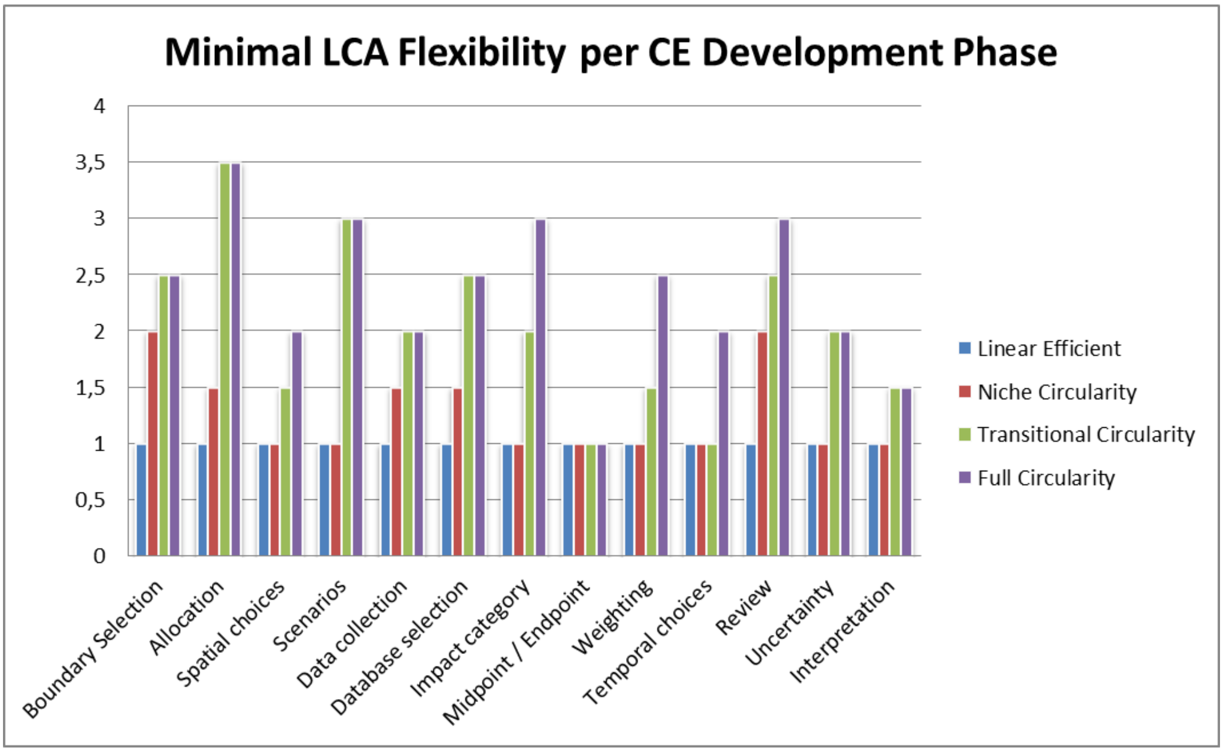

Figure 9: Minimal LCA Flexibility per CE Development phase.

Fifthly, it is also unequivocal that a fully standardized LCA methodology without any flexibility for practitioners is unnecessary even in a fully circular system. The graph shows that even in a fully circular system some flexibility categories can remain at level one. For some categories, however, an extensive amount of standardization is necessary to reduce the flexibility to acceptable levels.

Sixthly, based on these results, it can be argued that a reduction of flexibility is a necessity. However, further standardization in the CE context means also that additional criteria or factors, such as local data or temporal factors, must be accounted for in the LCA studies. This undoubtedly increases the effort for conducting an LCA. Especially for actors with limited resources, such extensive studies might not be possible with their resource or knowledge base (De Nooij, 2016; Huijbregts, 2016; Winkler & Bilitewski, 2007). In addition, it is far from certain whether or not the models are able to incorporate all the requirements effectively and whether they remain practical or become unsuitable for largescale use by actors (De Nooij, 2016; Huijbregts, 2016) The models must remain useful for actors to use them (De Nooij, 2016; Huijbregts, 2016). It has been argued that these models need to become much more dynamic and allow for more modelling options, while on the other hand the dynamic modelling should not lead to another category of flexibility because that would most likely obstruct the development of a CE (Ekvall et al., 2007).

Discussion

This research aimed to assess the connection between CE and LCA in order to discover whether the LCA methodology can contribute to the development of a circular system. To do so, a literature review was conducted of both concepts in addition to expert interviews. However, it was limited in a number of ways.

Firstly, due to a lack of time because of the scope of the thesis and interview refusals, it was difficult to acquire a large number of interviewees for this thesis. However, the interviewees that were willing to participate were experts in their fields and enabled this research to acquire expert insights from both CE and LCA.

Secondly, this theory does not use theoretical lenses to analyse an issue, but instead takes a more pragmatic approach to compare two concepts. Therefore, the research is at the same time unbiased by adopting a theoretical lens, but also loses the ability to actively use theoretical insights that might be useful for understanding policy related issues or economic developments.

Thirdly, the levels of flexibility, stages of CE development, and the comparison of the two, are not finite. They were created by logically reasoning how a situation might develop based on the understanding the reviews provided. This means that they fixed levels that argue how a development should or will look like. Rather, they are indicative of the trend that is a likely possibility to exist. Therefore, the results are also indicative and could be off by a margin. It is likely that different authors would slightly different levels of flexibility. Nevertheless, because this research did not aim to develop models of flexibility or economic development, but instead discover whether or not LCA can play a role in the development of CE, the indications are good enough for this thesis to draw some valuable conclusions on the connection of CE and LCA.

The results and conclusions provided in this research thereby also show a direction for future research. Regarding LCA, this research has given an overview of the various source of flexibility; it could be valuable to create a more detailed understanding of every choice in the LCA methodology in order to fully assess the flexibility that exists in LCA. In addition, it would be useful to further look into the temporal and spatial factors and to create methods or tools to incorporate such factors into the LCA methodology, because this research has shown that these factors are difficult to deal with but important for management of the natural boundaries of the planet. Furthermore, although a substantial amount of data can be assessed using LCA, if the sustainability demands on firms grow in the coming decades, the assessment tools must be ready to provide the information the firms need. This requires additional LCA research and probably standardization because in this thesis it is argued that increasing interdependency will lead to increasing necessity of reliable results. Further research could also look at what possible ways of standardization would work for LCA and how this could be managed effectively in a context of increasing knowledge development and implementation demand by industry.

For future CE research, this thesis has indicated that a lot of factors of the CE are still unknown. Therefore, it could be useful to look into how exactly a circular firm would operate, what that would mean for its business models and necessity to cooperate with its partners in a conglomerate of firms, and what consequences this would have for the macroeconomic setting of competition and capitalism. Furthermore, because this thesis has shown that the CE exists of both a material and economic side which are entirely interconnected, it could be useful to also conduct research from a system's perspective.

Based on the results, a number of advices can be given to policy-makers. The first is that the LCA methodology needs further standardization further in the future. This can be done privately, as in the previous standardization by the ISO, but could also be done publically such as the guidelines of the European Commission or UNEP. Regardless of the choice, if there is no future standardization the LCA methodology will no longer be able to fully support a CE. Secondly, focussing mostly on the material side of a CE might be sufficient for now and the early phase of CE, but if a functioning CE is to be developed also socio-economic policies need to be developed that support a CE. Thirdly, because firms are likely to become highly integrated in a CE and probably need to cooperate extensively to survive, new rules on competition and cooperation between firms are likely to have to be created because the old rules restrict the cooperation between firms perhaps too much for a CE to succeed.

Conclusion

Numerous scientists, government officials, and businesses are developing the circular economy (CE). This CE is supposed to be a waste-free economy where every material is cycled indefinitely in order to stop extracting new raw materials from nature and live within the planets boundaries. Simultaneously to this development, firms and scientists use the lifecycle assessment (LCA) to map and assess the impacts of a product. Although the LCA methodology is mainly used to quantify the environmental consequences of a product, methods are being developed to also map the social and economic impacts. However, the LCA methodology is a highly flexible method in which practitioners can make countless choices. Because of this flexibility, it is often the case that different studies of a similar product produce different results. Consequently, the results of LCA studies are often not regarded as completely. Nevertheless, the use of LCA studies is still increasing. However, because in a CE actors become highly interconnected and arguably require reliable results, it is debatable whether or not the flexible LCA methodology might be beneficial to the development of the CE. To deal with this uncertainty, the following research question was posed:

To what extent can the lifecycle assessment (LCA) method and its recent developments contribute to the development of a circular economy?

To answer this question, the following research practices were completed. Firstly, by conducting a systematic literature review of both CE and LCA into the principles and flexibility of the two concepts, and by incorporating additional knowledge from expert interview, an overview of CE and LCA was developed. Secondly, the two concepts were then compared to each other by placing the LCA flexibility on top of a CE development model in order to discover what level of flexibility was maximally acceptable within each phase of development. Thirdly, by assessing at which level the maximum acceptable levels of flexibility are located in each subsequent CE development phase, the comparison between CE and LCA was completed.

The results of the comparison indicated that when the economy becomes more circular over time, the requirements for LCA studies increase as well. With these results it is possible to answer the question posed. The LCA methodology seems adequately positioned to play a positive role in the development of a CE. Especially during the early stages of the development of the CE, the current flexibility found within the LCA methodology is an asset that allows firms to compete with other firms and become circular. However, in later stages of CE, the interdependency of firms increases because of the increasing integration of waste flows called industrial symbiosis (IS). Alongside the increasing pressure to behave sustainably in order to stay within the planet's natural boundaries, the need for reliable LCA results increases. However, because it is assumed in the principle of least effort (PLE) that actors will take the easy path to their goal, if the methodological flexibility remains similar the LCA results will not be of the quality that is required in that face. Therefore, it is necessary to reduce that flexibility, for example through increased standardization of the LCA methodology.

Therefore, the following conclusion is reached. The LCA methodology can play a supportive role in the development of a CE by providing information for designers, decision-makers, and other actors, but requires to be updated to the changing circumstances within the economic system when it transitions towards circularity.

Appendix 1

List of interviewees:

dr. R.J.W. de Nooij

Prof dr. J.J. Jonker

Prof Dr M.A.J. Huijbregts

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