It Depends: The importance of transparent reporting in LCA conclusions.

Exploring key considerations for reporting and communication of LCA conclusions to designers, in the context of allocation and modelling choices regarding recycling in a circular economy.

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SUMMARY

The environmental impacts created by human activity have exceeded planetary boundaries, leading to the need for change towards a circular economy (CE) from a linear economy. The CE aims to reduce environmental impact by focusing on responsible production and consumption. It is achieved by avoiding the outflow of materials and reducing environmental impact as much as possible. Analytical tools such as LCA are necessary to map the environmental impacts of different CE alternatives serving the same product system and assist in finding the most environmentally preferable option. It is essential to make credible, transparent and reproducible assessments of the environmental impact of circular strategies compared with incumbent ways of working. Many databases and software programs used to perform LCAs do not explicitly and transparently solve multifunctionality, which can lead to distorted information and inaccurate decision-making. The report emphasizes the importance of a systematic approach to solve and identify multifunctionality within CE-LCA and improve the reporting of LCAs to make them more transparent. While the CE concept, when implemented in practice by designing products, often leads to reductions in environmental impacts throughout product life cycles, this is not always the case. Design decisions should be based on credible, transparent and reproducible assessments of environmental impacts, and not on assumptions. The focus is on how different choices in modelling recycling and identifying multifunctionality are made in LCA literature, and how reporting can be improved. This report investigates the modelling and reporting of recycling loops in LCA studies that address circular economy systems, with a focus on the ecoinvent database.

This study aims to answer the research question 'How are recycling loops modelled and reported in LCA studies addressing circular economy systems and in the most widely used LCA database ecoinvent; and how can reporting be improved to better and more transparently communicate conclusions of LCAs to product designers?'

Answering this question identifies opportunities to improve current modelling and reporting practices for more accurate and transparent simulations of recycling loops in LCAs.

Two sub-questions were formulated to guide the research:
(1) How are recycling loops currently modelled, identified, and solved in LCAs of circular economy product systems, and what choices are made regarding the supporting ecoinvent database?
(2) How can LCA recycling modelling assumptions and related results be best communicated to product designers to create proper understanding of these assumptions and results?

The first sub-question is addressed through a literature review, which revealed a wide variation in the transparency of current LCAs that contain recycling with a circular economy perspective. The findings suggest that recycling is not always modelled as loops in LCAs, and multifunctionality identification is rarely undertaken. Multifunctionality is typically addressed through partitioning and substitution principles. The solving of multifunctionality is not always consistent in the same system model for the use of recyclable material and the production of recyclable material. The selection of ecoinvent system models is seldom mentioned, and only articles specifically focusing on multifunctionality within LCA show insight that different system models might influence results of an LCA.

To address the second sub-question, the study proposes a 'LCA transparency wheel' tool to help LCA practitioners assess the transparency of their studies and communicate assumptions and results related to the seven key considerations. The seven key considerations are based on the literature review results: modelling of the flow diagram, identification of multifunctionality, solving of the multifunctionality, background database use, modelling of recycling, type of loop recycling, and reduction in virgin material inputs.

The tool can help identify transparency gaps, improve modelling and reporting of LCAs, and this improved reporting can enable designers to understand and improve the environmental impacts of their designs. The proposed tool has the potential to improve the modelling and reporting of recycling loops in LCAs, but further testing and development are necessary to ensure its effectiveness in real-world settings. Overall, this study highlights the importance of transparent reporting and modelling in LCAs for useful conclusions and application of results in design within circular economy systems.

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LIST OF ACRONYMS

APOS - Allocation at the point of substitution

EoL – End-of-life

CE - Circular Economy

CE-LCA – Circular Economy case Life Cycle Assessment

CHP – Combined Heat Power

FU – Functional Unit

IE – Industrial Ecology

ISO – International Organisation for Standardisation

LCA – Life cycle assessment

LCI – Life Cycle Inventory

MF – Multifunctional(ity)

UPR – Unit Process

WoS – Web of Science

GLOSSARY

Activities: → Unit process

By-product: → Co-product

Circular Economy: an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. (Kirchherr et al., 2017)

Co-product: any of two or more functional flows from a co-production process (Guinée et al., 2002).

Flow diagram: a graphic representation of the interlinked unit processes comprising the product system (Guinée et al., 2002).

Functional unit: the quantified function provided by the product system(s) under study, for use as a reference basis in an LCA (Guinée et al., 2002).

Functional flow: Any of the flows of a unit process that constitutes the goal of the unit process. This is the product outflows of a production process (goods) or the waste inflow of a production flowing out of a process or a waste inflow of a waste treatment process (Guinée et al., 2021)

LCA Modelling: Making a graphic representation of the interlinked unit processes comprising the product system, to support the LCA.

Multifunction process: a unit process yielding more than one functional flow, e.g. co-production, combined waste processing, recycling (Guinée et al., 2002).

Multi-product activity: → Multifunctional process

Multifunctionality and allocation: a step of the Inventory analysis in which the inventory model is refined and the input and output flows of multifunctional processes are partitioned to the functional flows of those processes (Guinée et al., 2002).

Recycling: Mechanical reprocessing of material into a product with equivalent properties as the original product (Bocken et al., 2016)

Unit process: The smallest portion of a product system for which data are collected in an LCA (Guinée et al., 2002).

Waste (CE perspective): obsolete material (Bocken et al., 2016)

Waste (LCA perspective): an economic flow with a zero or negative value produced in a unit process and serving as an input to another unit process (adapted from ISO by (Guinée et al., 2002)).

1 INTRODUCTION

1.1 BACKGROUND

Society is currently characterized by high levels of consumption, resulting in the utilization of vast amounts of resources and the generation of significant waste, but more and more awareness of environmental problems is appearing. There is more awareness that the environmental impacts created by humans are exceeding the planetary boundaries, which could potentially lead to abrupt environmental change within continental- to planetary-scale systems (Rockström et al., 2009).

Given the negative environmental impacts associated with the consumption society, there is a need for change. Many products are designed for convenience, but this often leads to the consumption of significant resources to create short-life span products that are then discarded, resulting in a substantial negative environmental impact. In order to reduce environmental impacts, society should aim for the sustainable development goal 'Responsible production and consumption' (United Nations, 2021). One way to reduce environmental impact is a transition from the linear economy towards a circular economy. The circular economy (CE) is a concept aiming to achieve sustainable development by closing material loops and minimizing resource use, and is popular among scholars and practitioners (Kirchherr et al., 2017). CE goals are also implemented in various regulations within the European Union and accordingly in different European countries. The goals of the CE are being implemented in various regulations within the European Union and in different European countries, to achieve the aim of achieving climate neutrality by 2050 (European Commission, 2020). The Dutch government has started its transition to have a fully circular economy in 2050 (Ministerie van Infrastructuur en Waterstaat, 2021).

Earlier than policy makers, designers started to focus more on circular strategies. It is important that their decisions are based on credible, transparent and reproducible assessments of environmental impact of circular strategies compared with incumbent ways of working. While the CE concept, when implemented in practice by designing products, often leads to reductions in environmental impacts throughout product life cycles, this is not always the case. It is thus important to compare the impact of different alternatives, including the incumbent (Dieterle & Viere, 2021). Eco-design methods are used in order to reduce environmental impacts through product design (Karlsson & Luttropp, 2006), as well as circular product design methods (Den Hollander et al., 2017). However, a designer cannot simply assume that the product that is designed has reduced environmental impact, just because it is designed according to the CE concept; the most circular option is not necessarily the environmental preferable option (Haupt & Zschokke, 2017).

Analytical tools, like Life Cycle Assessment (LCA), help assessing these impacts. LCA can map the environmental impacts of different CE alternatives serving the same product system and can assist in finding the most environmentally preferable option. The method can also map the trade-offs between different life cycle stages within a product system. The impact can be compared for different impact categories. The LCA method is often used in the field of Industrial Ecology (IE) to map, quantify, assess and compare the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management (Finnveden et al., 2009). LCA results can be used to improve and develop products on environmental impacts, compare different alternatives of products, and can support strategic planning and public policy making.

Most LCAs mainly address products in a linear consumption system so far, but the number of LCAs of products in CE-systems is rising, as can be seen when searching for CE-LCA literature (Figure 1). When using LCA results, it is important to get credible and reproducible assessments for decision making, however when dealing with circular systems in LCA, reporting underlying assumptions may pose challenges due to increased complexity; this might challenge the credibility and reproducibility of the LCA (Guinée & Heijungs, 2021).

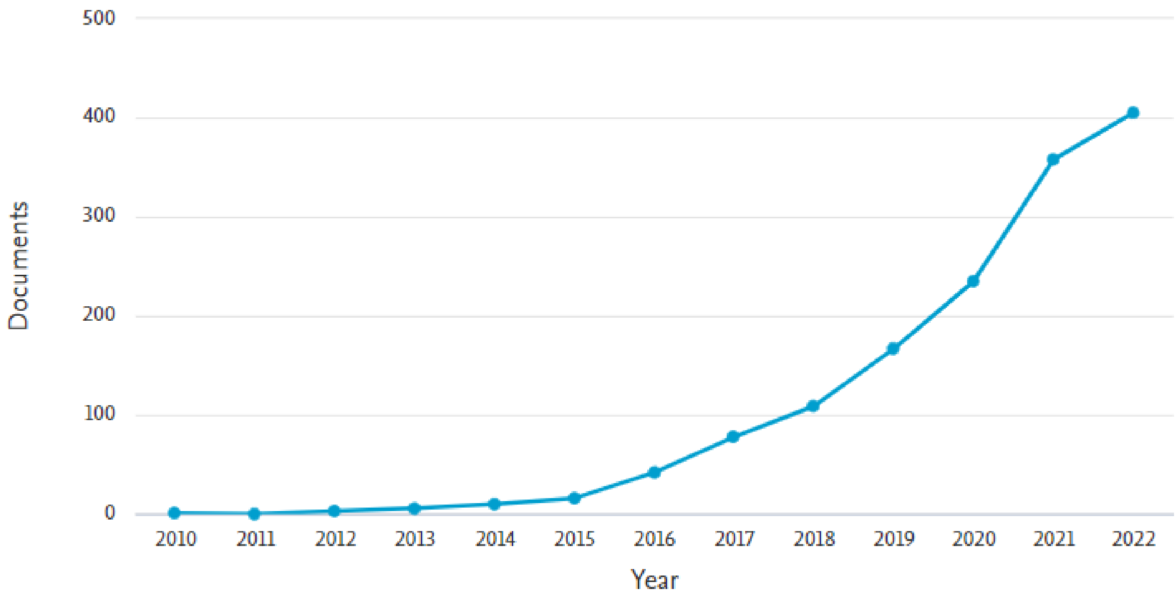


FIGURE 1: SCOPUS SEARCH RESULTS 2010-2022, DOCUMENTS BY YEAR, SEARCH TERMS: (TITLE-ABS-KEY (LCA OR LIFE AND CYCLE AND ASSESSMENT OR LIFE AND CYCLE AND ANALYSIS OR LIFE-CYCLE AND ASSESSMENT OR LIFE-CYCLE AND ANALYSIS) AND TITLE-ABS-KEY (CIRCULAR AND ECONOMY))

In an LCA study one or multiple product systems are studied. A product system is a set of different processes that are interlinked by material, energy, products, waste or service flows and serve a defined function. Most LCA studies focus on one specific product system. However, some processes of the product systems may serve more than one product system; the system contains multifunctional processes. In order to achieve LCA results, multifunctionality should be identified and (Guinée et al., 2021). A circular economy system is a system of products that is based on replacing the 'end-of-life' concept with the aim to accomplish sustainable development (Kirchherr et al., 2017). A CE system could serve more than one product system, which means that in a CE system the impacts of the processes should be distributed among the different products that the product system is serving. This referred to as solving multifunctionality. How these environmental impacts are distributed depends on the methodological choices made in the background data used for the LCA.

Within the CE, obsolete material, often referred to as waste, is designed out of the system. Even after the product under study is used longer, more recycling should take place. Recycling means the mechanical reprocessing of obsolete material into a product with equivalent properties as the original product (Bocken et al., 2016). Within the LCA method and the step of solving of multifunctionality, the moment of when something is considered obsolescent and valueless (and considered waste) is important. This moment influences the identification of multifunctionality.

The Swiss database ecoinvent is widely used for LCA assessments and is the largest LCA database worldwide (ecoinvent database, 2022). Within the used ecoinvent data, ecoinvent solves multifunctionality in a certain way, without explicitly sharing with the practitioner exactly how this done. Data decisions made in the background influence the outcome of the environmental impact assessment and thus the results of the LCA. Therefore, it is important to understand what happens in the background of the data retrieved that is used for the assessment. Regarding recycling, ecoinvent has different background system models that all solve multifunctionality differently and in this way the selected database choice is influencing the outcome of the LCA.

1.2 PROBLEM DEFINITION & KNOWLEDGE GAP

Since many databases and software programs used to perform LCAs, don’t include ways and data to solve multifunctionality explicitly and transparently, it is generally unknown how current LCA practice handles multifunctionality in CE systems and which underlying assumptions are included in the analysis performed (Guinée et al., 2021; Guinée & Heijungs, 2021).

It is important that multifunctionality in CE systems is modelled, identified and solved explicitly and transparently (Guinée et al., 2021). If untransparent assessments are used as a basis for decision-making in product innovations or regulations, decisions could be made on distorted information. This is possibly leading to different effects than expected or desired and non-optimal circular strategies might be selected (Dieterle et al., 2018; Dieterle & Viere, 2021; Haupt & Zschokke, 2017). Therefore, it is important that a systematic approach for solving and identifying multifunctionality within CE-LCA is used and that the influences different modelling decisions have, are transparently reported.

This study specifically focuses on LCAs done on products and products systems that include the recycling of material back into the product system, in a CE context. Looking into the multifunctionality issues arising with recycling processes is the scope of this research.

This study focuses on LCA studies and the ecoinvent database to research the way multifunctionality is currently handled. The focus is on the different choices that are made in LCA literature in terms of modelling recycling and identifying multifunctionality and how the reporting of these LCAs can be improved in order to make conclusions of LCA studies more transparent.

1.3. RESEARCH QUESTION AND SUB QUESTIONS

In this thesis report, the following main research question is investigated:

‘How are recycling loops modelled and reported in LCA studies addressing circular economy systems and in the most widely used LCA database ecoinvent; and how can reporting be improved to better and more transparently communicate conclusions of LCAs to product designers?’

To answer the main research question, the following sub questions are defined as intermediate steps:

> (1) How are recycling loops currently modelled, identified and solved in life cycle assessments of circular economy product systems and what choices are made regarding the supporting ecoinvent database?
> (2) How can LCA recycling modelling assumptions and related results be best communicated to product designers in order to create a proper understanding of these assumptions and results?

1.4 RELEVANCE FOR SOCIETY, SCIENCE AND INDUSTRIAL ECOLOGY

This study is focussing on explicit and transparent reporting and modelling of recycling loops in LCA and understanding what influences reporting different modelling decisions have as effects on the conclusions of such LCAs that include recycling. A result of better understanding the influences of modelling choices within LCAs that include recycling with a CE mindset is that the practitioners can display their results more credible and reproducible and the people using these LCAs (e.g., designers and policy makers) can build on transparent and understandable LCAs. In this way, LCA practitioners can improve the credibility and reproducibility of their LCAs.

Designers can learn a lot from the insights gained by LCA practitioners, just as LCA practitioners can improve the communication of their results a lot when realising in which way the LCA results can be applied by designers. It is important to know what influences different modelling choices of circular product systems and the reporting have on the outcome and conclusion of LCA, in order to conclude if further structuring and improvement of the identification, modelling and solving process of multifunctionality is needed. This is relevant for society, because the transparent and explicit assessment of sustainable initiatives is important when decisions are often based on LCA outcomes.

The field of Industrial Ecology (IE) and its assessment methods like LCA are still developing. It is important for the field of IE to keep doing so because the methods and how they are used should stay up to date with current societal changes and are, the other way around, capable to influence societal changes itself. Therefore, it is important to use the methods correctly and transparently, so the influences from the results are based on understandable conclusions.

This overall scientific improvement will be highly relevant for the field of Industrial Ecology as overall improvements for the LCA method used as a method within the system analysing discipline will also result in strengthened results within the IE study field.

1.5 OUTLINE OF REPORT

The report is structured as follows. The theoretical background of the LCA method, the topic multifunctionality within LCA, and the principles of the circular economy and circular product design are introduced in chapter 2 'Theoretical background'. In chapter 3 'Approach', the approach for addressing the research questions is described, followed by the literature review to answer the first sub question in chapter 4 'The state of the art of CE-LCAs: Two literature studies' . In chapter 5 'Transparent LCA communication to designers – making LCAs more accessible to designers', the second sub question is answered and a tool is suggested to improve the transparency of LCA studies.

The results and methodology are discussed in chapter 6 'Discussion and limitations' , followed by the conclusion in chapter 7 'Conclusion'. Further research recommendations can be found in chapter 8 'Recommendations'.

2 THEORETICAL BACKGROUND

This chapter provides a comprehensive exposition of the theoretical background of the LCA method, the topic multifunctionality within LCA, and the principles of the circular economy and circular product design. The aim is to establish comprehension of the aforementioned concepts.

2.1 LIFE CYCLE ASSESSMENT THEORY

2.1.1 LCA: THE METHOD

LCA aims to map, quantify, and assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management and is often used to compare different product alternatives fulfilling the same function (Finnveden et al., 2009). The results can be used to make decisions in order to improve the environmental impact of a product system.

Different phases for an LCA are defined by ISO, in order to structure LCA studies (International Organisation for Standardisation (ISO), 1997). The ISO framework consists of four phases: The goal and scope definition, the Inventory analysis, the life cycle impact assessment and the interpretation phase. The four phases of an LCA are briefly explained in Figure 2 and Table 1 and the key characteristics of each phase are described in 2.1.1.1-4 (Guinée et al., 2002; International Organisation for Standardisation (ISO), 1997)(International Organisation for Standardisation (ISO), 1997).

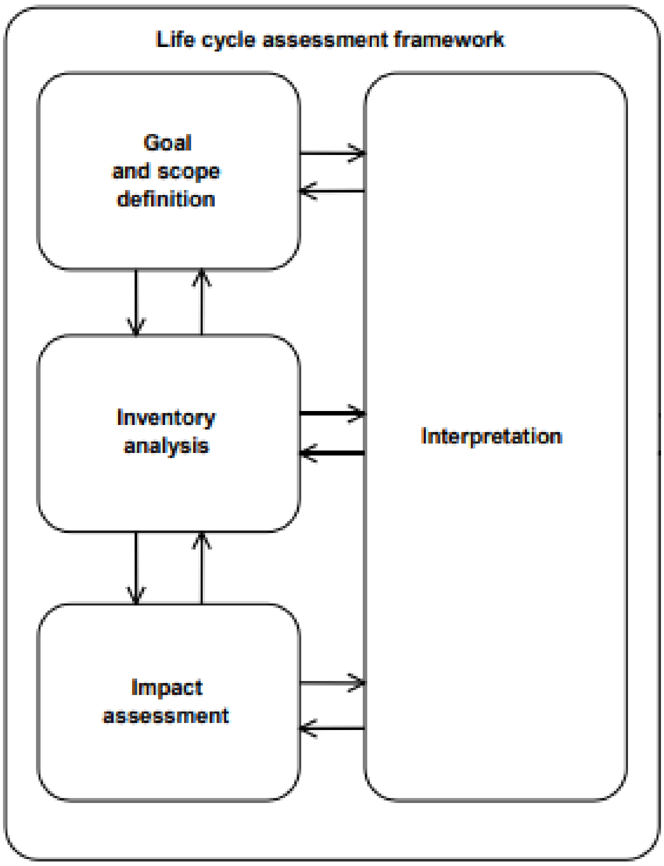


FIGURE 2: THE LIFE CYCLE ASSESSMENT FRAMEWORK (INTERNATIONAL ORGANISATION FOR STANDARDISATION (ISO), 1997)

TABLE 1: EXPLANATION OF LIFE CYCLE ASSESSMENT FRAMEWORK PHASES(GUINÉE ET AL., 2002)

Phase LCA study	Name	What?
First phase	Goals and scope definition	The aim of the intended study, the functional unit (FU), the reference flow, the product system(s) under study and the breadth and depth of the study in relation to this aim are established
Second phase	The inventory analysis	The relevant inputs and outputs of the product system(s) under study throughout the life cycle are as far as possible, compiled, and quantified. In this phase, a Life cycle inventory (LCI) table can be made showing all the environmental interventions associated with a product system, supplemented by any other relevant ones. information.
Third phase	The impact assessment	This phase is concerned with understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study.
Fourth phase	The interpretation	The results of the inventory analysis and/or Impact assessment are interpreted in the light of the goal and scope definition to draw up conclusions and recommendations.

GOAL AND SCOPE DEFINITION

The goal and scope definition phase of the LCA is the phase in which the plan of the LCA is made. During this phase, the research question is precisely formulated, along with the intended application and target audience of the study. The scope of the study is also determined, which includes the temporal, geographical, and technological coverage of the product system under investigation.

Finally, the product(s) under study are defined. The functional unit (FU) and reference flows are defined. The functional unit (FU) is a quantified function provided by the product system(s) under study and is used as a reference basis in the LCA. For example, a functional unit could be 1000 hours of light (Guinée et al., 2002).

The type of LCA, either attributional or consequential, is determined during the goal and scope definition phase. Attributional LCA and consequential LCA differ in their approach, as shown in **TABLE 2** This study will focus on attributional LCAs, which means that whenever LCA is mentioned, it refers to attributional LCA unless stated otherwise.

TABLE 2: ATTRIBUTIONAL VS. CONSEQUENTIAL LCA (WEXLER ET AL., 2005)

Attributional LCA	Consequential LCA
Attributional LCA is defined by its focus on describing environmentally relevant physical flows to and from a life cycle and its subsystems.	Consequential LCA is defined by its aims to describe how these flows will change in response to possible decisions.

THE INVENTORY ANALYSIS

During the inventory analysis phase of an LCA, the product system or systems are defined, and system boundaries are established along with the design of flow diagrams. Data is collected for each process, and allocation steps are performed for multifunctional processes, this is explained in more detail in chapter 2.1.2. The result of this phase is an inventory table that quantifies the inputs and outputs to the environment associated with the functional unit. Underlying the scaling of processes is matrix-based calculation, those matrices have to be square, as described and solved in the handbook of LCA (Heijungs & Suh, 2002). Those calculations are typically done by software based on matrix inversion, such as CMLCA, but understanding the background is important for LCA practitioners.

In the inventory phase, a flow diagram is modelled. A flow diagram is a graphic representation of the interlinked unit processes comprising the product system, to support the LCA. This flow diagram contains unit processes and flows. Flows can either be a good or waste. A good is an economic flow with a positive value and a waste is an economic flow with a zero or negative value. Flows are produced in a unit process and serving as an input to another unit process. A unit process is the smallest portion of a product system for which data are collected in an LCA. Functional flows are the flows that constitute the goal of the unit process, which are the product outflows of a production process (good) or the waste inflows (waste) of a waste treatment process (Guinée et al., 2021).

Foreground processes are processes that are modelled by the LCA practitioner themselves, or modified processes from a background database. Within these foreground processes it is important for the LCA practitioner to understand the multifunctionality problem and apply the 4-step approach to solve multifunctionality, if identified.

Background processes are unchanged processes from an LCI database, such as ecoinvent. The impact of the choices made in the background database are important to understand as well, therefore, the background choices of ecoinvent are explained in chapter 2.2.

THE LIFE CYCLE IMPACT ASSESSMENT

The life cycle impact assessment phase (LCIA) is the phase in which the results from the inventory analysis, the inventory table, are used to understand the outcome in terms of environmental impacts. In order to be able to do that, a list of impact categories is defined, with associated models for relating the environmental interventions to suitable category indicators for the impact categories selected. Examples of such categories are climate change or acidification. This step is called characterization (Figure 3).

Characterization means that for a certain impact category, a characterization factor is derived from a characterization model created by researchers. This numerical factor is applied to convert the assigned LCI results to the common unit of the category indicator. This results in a quantifiable representation of an impact category. A selection of those impact categories is called a family. The category indicator results from the impact categories can be compared to each other because they have te same unit. To support understanding and evaluation of the magnitude and significance of the potential environmental impacts of a product system, families are selected, such as the PEF or CML family.

The PEF-family is used for assesments by the European Commission and uses midpoint indicators, these have more certainty than endoint indicators (European Commission et al., 2010). The CML-family contains the characterization factors for all baseline characterization methods (Guinée et al., 2002). An example of the characterization steps of a family can be found in figure 3.

Characterization family	Impact category	Category Indicator	Characterization model	Characterization factor
CML-family	Climate Change	Infrared radiative forcing (W/m2)	IPCC model	Global warming potential for a 100-year time horizon (GWP100) for each greenhouse gas emission to the air (in kg carbon dioxide equivalent/kg emission)
PEF-family	Eutrophication - aquatic	Fresh water: Kg P equivalent Marine: Kg N equivalent	EUTREND model	Eutrophication potential for each emission to the water (in kg P/N equivalent/kg emission)

FIGURE 3: EXAMPLE OF CHARACTERIZATION STEPS, OWN FIGURE, INSPIRED BY GUINÉE ET AL., (2002) AND THE EUROPEAN COMMISSION ET AL. (2010)

At the end, the main result of the impact assessment phase is the environmental profile, the normalised environmental profile and sometimes the weighting profile.

THE INTERPRETATION PHASE

In LCA, the interpretation phase serves to evaluate the soundness and robustness of choices and assumptions made during the earlier phases. The main elements of the interpretation phase are evaluation and analysis of results, with a contribution and sensitivity analysis, and formulation of study conclusions and recommendations.

A contribution analysis analyses what part of the environmental impacts can be attributed to which phases of the product system under study. The contributions are usually expressed as a percentage of the total. A sensitivity analysis analyses how robust the results are when changing variations in process data, model choices and other variables in the LCA model, for example the way of solving multifunctionality.

A critical aspect of the interpretation phase is reducing the potential for multi-interpretability by explicitly outlining choices made and their potential impact on final results.

Doing an LCA also includes making a number of choices that may influence the results of that LCA considerably. The interpretation is a key aspect in order to derive robust conclusions and recommendations (Zampori et al., 2016). Therefore, it is important to clearly explain and understand the decisions made during the study, so results from an LCA are credible, transparent and reproducible. When there is room for interpretation, conclusions could be shaped to emphasize a point in favour of the one using the results, without someone having the means to check if these claims are perceived to be true.

2.1.2 EXPLAINING MULTIFUNCTIONALITY IN LCA

Sometimes unit processes have more than one functional flow and some processes serve more than one product system. This means a process is multifunctional. This multifunctionality should be solved. Behind this multifunctionality problem is a rectangular matrix-based calculation, that cannot be solved before it is made square again. Making this matrix is square again, is essentially solving the multifunctionality, as described and solved in the handbook of LCA (Guinée et al., 2002). Those calculations based on matrix inversion, are typically done by software, but understanding the background is important for LCA practitioners.

When multifunctionality occurs, this should be solved. For solving multifunctionality, allocation is one of the options. Allocation means: partitioning the input or output flows of a process between the product system under study and one or more other product systems. (International Organisation for Standardisation (ISO), 1997). According to ISO, a study should identify the processes shared with other product systems and deal with them. ISO provides a stepwise procedure for dealing with multifunctionality.

The steps to deal with multifunctionality according to ISO are as follows, by quotation:

“Step 1: Wherever possible, allocation should be avoided by: 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or: 2) expanding the product system to include the additional functions related to the co-products.

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them, i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.”

Even though ISO mentions a study should identify the processes shared with other product systems (multifunctionality), how to actually do this identification is unclear. Even though many studies discuss the allocation hierarchy approach from ISO (Moretti et al., 2020; Pelletier et al., 2015; Schrijvers et al., 2016), hardly any explicit attention is paid to the identification of the multifunctionality problem. To structure the identification and solving of multifunctionality more, Guinée proposed to use the 4-step approach (Guinée et al., 2002).

1. Identifying goods and waste flows of the unit processes
2. Identifying the functional flows of the unit processes
3. Identifying the multifunctional processes (those that have more than one functional flow)
4. Solving multifunctionality

Solving multifunctionality is similar to the dealing with multifunctionality according to ISO.

In step 1-3 of the 4-step approach, identifying multifunctionality, the definition of when something is considered waste, when something has negative or zero value, influences the multifunctionality in a system. The article ‘Economic allocation: Examples and derived decision tree’ by Guinée et al. (2004) clearly shows the difference the modelling of flows either as a good or wastes makes. Changing a flow from a waste to a good or the other way around, changes if and which process is multifunctional. When a different unit process is considered multifunctional, this could change the allocation of the impacts divided among the different functional flows. This could influence the outcome of the LCA (Guinée et al., 2004).

When nothing is considered waste, as done within the CE concept, this could influence the identification of multifunctionality within LCA and the outcome of the LCA. The definition of when or if a process is considered multifunctional, mays significantly influence the outcome of the LCA. This makes an LCA multi-interpretable, if the modelling choices are not transparent. It is important to make modelling choices transparent to avoid multi-interpretability of LCA outcomes. Most literature implicitly identifies multifunctionality: they mention a process to be multifunctional and then go on solving the multifunctionality. This is similar to the ISO approach: identify the processes shared with other product systems and deal with them according (Pelletier et al., 2015).

There are different types of multifunctionality (figure 3)

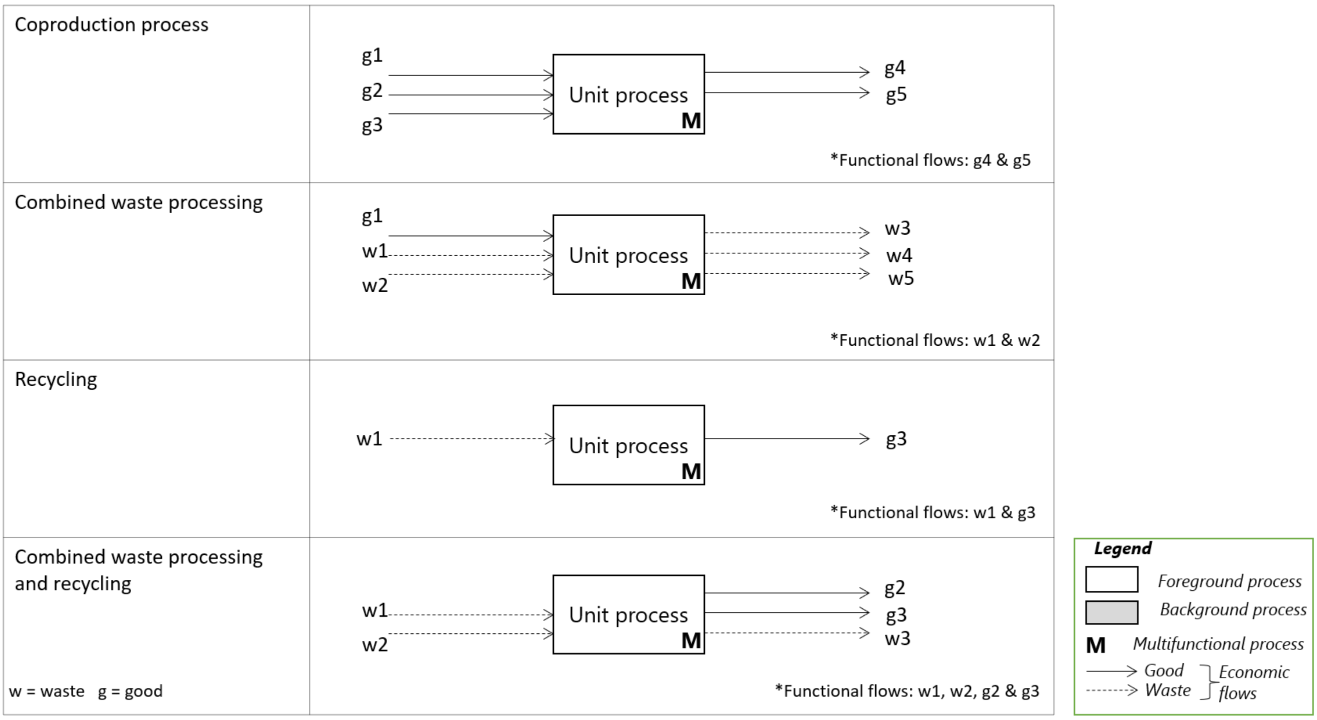


FIGURE 4: TYPES OF MULTIFUNCTIONALITY, ADAPTED FROM GUINÉE ET AL. (2021)

If a process has more than one functional flow, it is considered multifunctional, which can occur in coproduction processes, combined waste processes, recycling processes and combined recycling and waste processes. If there a multifunctionality process in the model, the multifunctionality should be identified and solved.

Within LCA modelling there is a difference between open- and closed-loop recycling. Closed-loop recycling is the recycling of material within one and the same product system. Open-loop recycling is the recycling of one material generated in one product system into a different product system.

When multifunctionality is identified, it can be solved in different ways: System expansion, substitution and partitioning. When applying partitioning, there are different ways to allocate: physical allocation on the basis of mass or volume, economic allocation or energy based allocation (Guinée et al., 2021). Knowing what way of solving multifunctionality is used in the LCA study is important, otherwise, someone using the study, does not know how to interpret the result. E.g., it is relevant for designers to know which assumptions are made: are the results based on an assumption that 80% of the material is recycled and only 20% is virgin material? And are the results then still relevant if a designer can only realise a product with 20% recycled material input? These assumptions probably mean that the environmental impact of the product is very different than modelled. Sometimes, sensitivity analyses are in place to research the effect of such assumptions.

With system expansion, as expected, the system under analysis is expanded. This means that an extra functional unit is defined, so two functions are delivered, and the research question answered is different than the one originally used at the start. In literature, system expansion is often used as a synonym for substitution, but it is not the same (Heijungs, 2014). System expansion is described in

ISO14044 as the inclusion of the additional functions related to the co-products. On the other hand, substitution grants credit to a process system that generates another marketable product or function (Heijungs, 2014). It is important to stay aware of the mixing up of these two terms in literature. In this report, with system expansion, solving multifunctionality by expansion of the functional unit is meant.

As a fictional simplified example, to illustrate the different ways to solve multifunctionality, the unit process ‘production of a combined heat and power (CHP) plant’ is taken (Figure 5). In a CHP plant, both heat and electricity can be manufactured. During the process of producing 2.5 MJ heat and 1 kWh electricity, 10 kg CO_2 is emitted. Multifunctionality solved through system expansion takes as functional units both 2.5 MJ heat and 1 kWh electricity. The production of 2.5 MJ heat and 1 kWh electricity thus emits 10 kg CO_2.

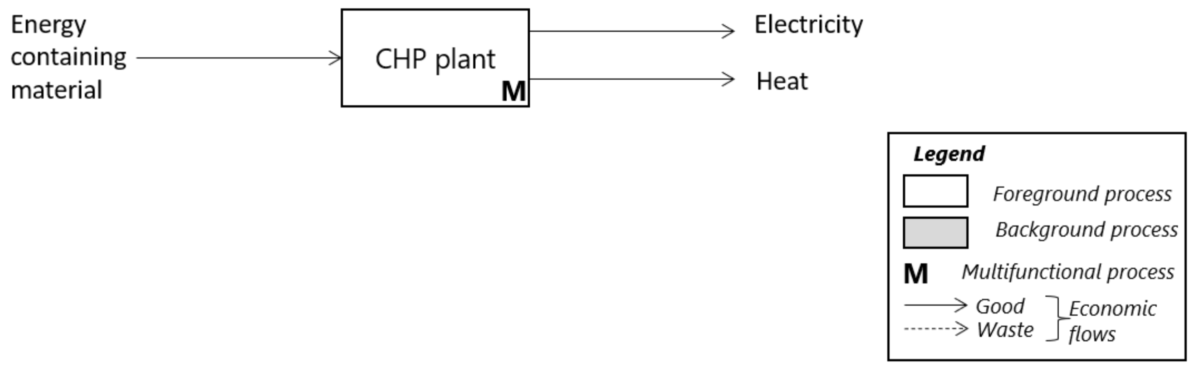


FIGURE 5: FLOW DIAGRAM ILLUSTRATIVE EXAMPLE CHP PLANT

Substitution (or avoided burdens method) gives credit to a process system that is coproducing another saleable product or function. The impacts of an alternative process system, which provides the same quality of a product or function as the output of a mono-functional process, are subtracted from the impact of the system under study. In other words, the burdens of this mono-functional process are assumed to be avoided and subtracted from the impact of the system under study. Substitution is considered a way of solving multifunctionality for consequential LCAs (Schrijvers et al., 2016), and should not be applied in attributional LCAs.

Using the same example as before: Substitution solves multifunctionality by assuming that for every 2.5 MJ, 1 kWh can be produced as well, without having to fulfil the CHP production process again. So, the process of producing 1 kWh does not have to be performed again, and the environmental impact that would happen during this process is subtracted from the impact of producing 1 kWh.

Therefore, the avoided impact that would have to be made to produce 1 kWh, is subtracted from the impact the production of 2.5 MJ has. If producing 1 kWh would emit 2 kg CO_2,the impact of producing 2.5 MJ would be 10-2 = 8 kg CO_2 (3.2 kg CO_2 per MJ), as the avoided impact is 2 kg CO_2 (Figure 6).

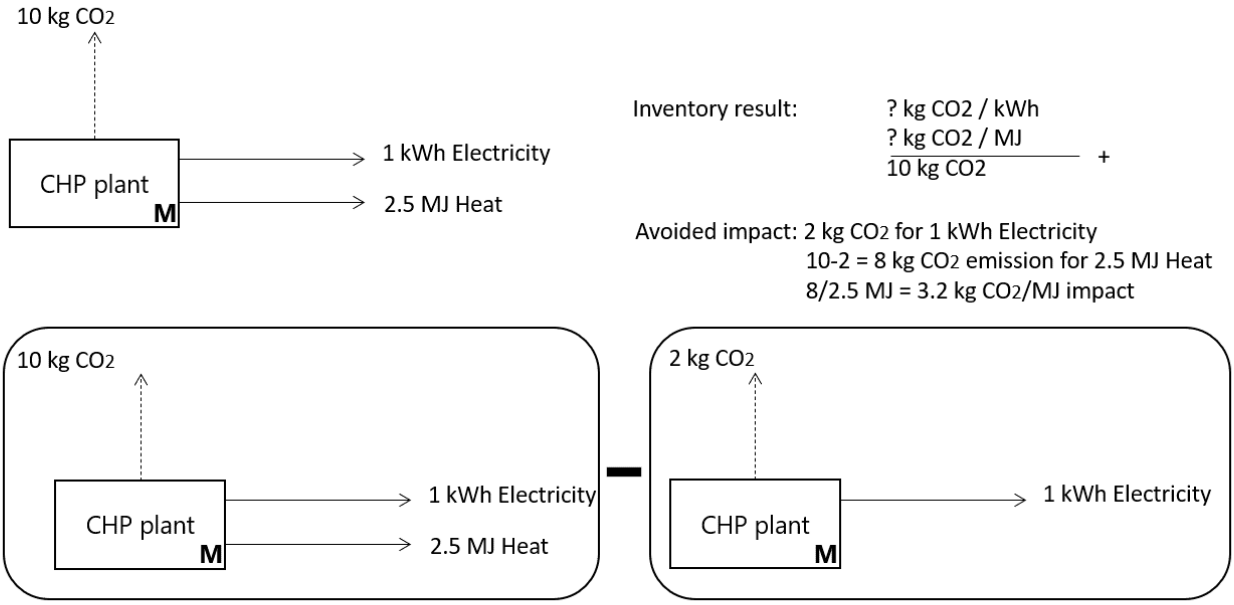


FIGURE 6: VISUALISATION OF MULTIFUNCTIONALITY SOLVED THROUGH SUBSTITUTION

With partitioning a process providing two products or functions, the multifunctional process, is split into two or more (virtual) monofunctional processes. The division of the impacts among those monofunctional processes is referred to as partitioning (or allocation) and can be done in different ways: a general partitioning ratio in percentages, based on energy, mass or price and more. All different ways of partitioning and thus allocation factors could lead to a different outcome of the impact distribution, but the process of solving general procedure them stays the same.

Continuing with the CHP plant production example: partitioning divides the impacts from the CHP production over both product outputs, 2.5 MJ of heat and 1 kWh of electricity. This division is performed according to multiple division based on energy, mass or price, but also a 50/50 division can be possible. If a 50/50 approach is taken, the production of 2.5 MJ is (100/2) 50 kg CO_2 and of 1 kWh is 50 kg CO_2 as well. An example for an energy based partitioning can be seen in Figure 7

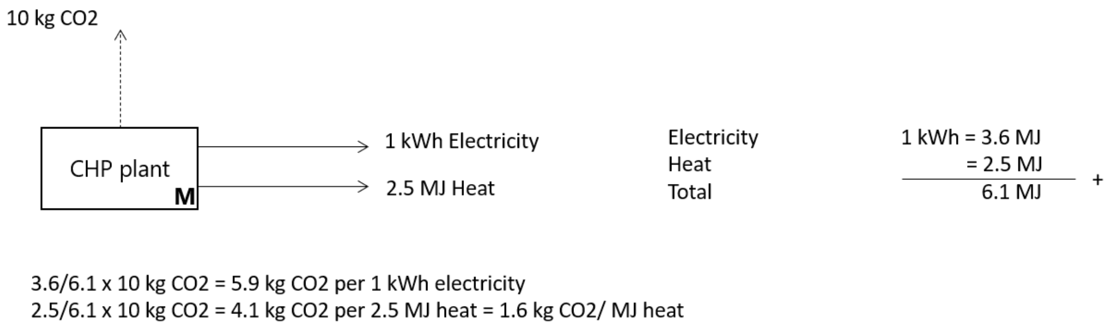


FIGURE 7: ENERGY BASED PARTITIONING

2.2 THE ECOINVENT DATABASE: HOW IS MULTIFUNCTIONALITY HANDLED?

The Swiss ecoinvent database is a worldwide-used life cycle inventory database. The most recent version of this database, version 3.9, contains around 18000 life cycle inventory datasets (ecoinvent Database, 2022).

The data can be used in LCAs by downloading the process data from a database. Getting the information out of their database selecting and deciding which system model they want to use, can be done by selecting a dataset that includes the whole system of linked and allocated processes. The ecoinvent data can be used as an input for LCA tools. Some LCA software programs, like GaBi, already have the ecoinvent data integrated in their LCA software (GaBi, n.d.)

The ecoinvent database comes with different system models that define the methodological rules for linking all individual processes to each other, and solving multifunctional processes, in the database. All the models start from Undefined Unit Processes (UPR) and apply different assumptions to determine how the linking, allocation, and substitution between those processes take place. The undefined database contains unit process data that are not yet linked to other processes and not yet allocated in case the unit process is multifunctional. Undefined unit processes show the data as compiled by the data provider. Undefined UPRs are unlinked multi-product activities, so the suppliers of the inputs are not determined. The undefined unit processes are the starting point on which system model-specific modelling choices are applied. The supply chain is determined (linking), and subdivision and allocation or substitution are applied to produce single-product UPRs through the application of system model (ecoinvent Database, 2022). When a process is selected and it is linked, the process is connected to other processes that are needed for the process to succeed. For example: energy inputs as electricity should be linked to a production process that contains a machine. The location of the process matters, because then it should connect to an energy input from the same geographical location. Not all countries produce energy the same way, and the impact of these processes differs. The system models are a set of distinct rules for linking and allocating the undefined unit process data sets (Wernet et al., 2016).

The following paragraph outlines the various approaches to handling multifunctionality within the ecoinvent database. Table 3 is provided to highlight the similarities and differences between terms used in ecoinvent and those outlined in ISO. The ecoinvent system models are based on three key concepts: Subdivision, Allocation, and Substitution.

Within ecoinvent, different synonyms are used for already known concepts: Processes are called activities. Multifunctional process is the same as a multi-product activity and single-product activity is the same as a monofunctional process. Co-product and by-product are also synonyms.

Subdivision is used across all ecoinvent system models and involves the splitting of processes into multiple processes where possible, without requiring allocation. This enables multiple reference flows to be defined, and inputs and emissions are split based on various physical characteristics, like in the first step of the ISO standard (2.1.1 LCA: the method). Before allocation and substitution are applied, subdivision is used to identify and split all reference flows of a process that could result from that process.

Allocation in ecoinvent refers to the attributional approach of converting multi-product activities into single-product activities. It is included in the system models "Allocation, cut-off by classification" and "Allocation at the point of substitution." The allocation key determines the share of each input and emission assigned to the reference product and to the by-products that have economic value. The ecoinvent database relies primarily on economic allocation, with few exceptions, such as for energy, where allocation is based on exergy (ecoinvent, 2022).

Substitution is the method applied to convert multi-product activities into single-product activities in the consequential system model. By-products that can substitute other productions provide credits to the activity producing them. All by-products are moved to the input side with a negative sign to maintain mass balance (ecoinvent, 2022).

Ecoinvent includes several system models: “Allocation, cut-off by classification”, “Allocation, cut-off, EN15804”, “Allocation at the point of substitution” and “Substitution, consequential, long-term”. These models show similarities with the approaches outlined in the LCA of handbook to solve multifunctionality.

Table 3 provides an overview of the different definitions, key concepts, and system models used in ecoinvent and ISO to address multifunctionality. When concepts are in the same row, they use the same approach to solve multifunctionality.

TABLE 3: SIMILARITIES ECOINVENT (ECOINVENT, 2022), THE LCA METHOD (GUINÉE ET AL., 2021) AND DEFINITIONS FOUND IN LITERATURE (EKVALL ET AL., 2020).

	Solving multifunctionality concepts according to Guinée et al. (2021)	**EcoInvent Key Concepts(ecoinvent, 2022).**	**EcoInvent System Models (ecoinvent, 2022).**	**Alternative definitions for similar concepts (Ekvall et al., 2020)**
Different definitions building on similar concept	Partitioning/Allocation	Allocation (attributional)	Allocation, cut-off by classification: wastes are the producer’s responsibility (“polluter pays”), and there is an incentivisation to use recyclable products, which are available burden free. Allocation, cut-off, EN15804	cut-off approach, 100:0 allocation method zero burden approach 50:50, 0:100 or 100:100 allocation approach
Different definitions building on similar concept	Substitution/ avoided burdens method.	Substitution (consequential)	Substitution, consequential, long term	Avoided burden approach. Energy recovery Crediting System expansion approach*
Different definitions building on similar concept	System expansion	Subdivision	Allocation at the point of substitution	

***** System expansion and substitution are often used interchangeably, but they differ in their approach to accounting for multifunctionality. ISO14044 defines system expansion as the incorporation of additional functions associated with co-products. On the other hand, substitution grants credit to a process system that generates another marketable product or function (Heijungs, 2014); see also discussion in section 2.1.2 'Explaining multifunctionality in LCA'.

Table 4 gives an overview of which method the system models use to solve multifunctionality and how they consider recycling. In Appendix 1 'Explanation system models' a more detailed explanation of all the system models is given. A visualisation of the division of impacts within the different system models can be found in Figure 8.

TABLE 4: DIFFERENT SYSTEM MODELS ECOINVENT (ECOINVENT, 2022)

Allocation, cut-off by classification	**Allocation, cut-off, EN15804**	**Allocation at the point of substitution**	**Substitution, consequential, long term**
Multifunctionality is solved through partitioning. Materials that can be recycled are available burden free: The impact of recycled materials is only from the impacts of the recycling process, and not from the production of the material beforehand. The cut-off is at the end of waste treatment. Waste impact is allocated to the producer of waste.	Multifunctionality is solved through partitioning. Impact is allocated to the first system up to when a product has a market value and fulfils legal requirements. After the materials is not waste anymore (the legal 'end-of-waste-state'), the impact belongs to the secondary system. This system model also provides all Life Cycle Inventory (LCI) indicators required in Environmental Product Declarations. The EN 15804 standard provides the structure for making three different types of EPDs.	Multifunctionality is solved through partitioning. The allocation is between the producers and users benefiting from that process. Exchanges of producing activities and treatment activities are allocated to all valuable by-products	Multifunctionality is solved through the avoided burden approach. If a by-product can substitute something else, credits are given to the process producing it. If a by-product cannot substitute something else, the impacts are allocated to the product system under study. This is a system model that has a focus on consequential LCAs
Examples of different system models: Rubber from a previous product is recycled into the production of new rubber tires for bikes			
When producing rubber tires from recycled rubber, the usage of recycled rubber for the tire production has no impact from the previous product cycle until the waste processing is finished (When the product has a positive market value again), so only processing of the recycled rubber (market value > 0) into a tire has an impact on the production of the new tires, but not the recycling process occurring beforehand.	As soon as processed recycled rubber has a positive market value (> 0) and is not considered waste anymore according to legal requirements, the impacts belong to the production of rubber tires. So, if the used rubber, before waste processing, is bought from the previous user, the production of the rubber tires carries the impact of the waste processing as well.	If the recycled rubber is used to make new tires, the outputs from the treatment activities are divided between the original process producing rubber for the previous product and the new valuable by-product: tires made of recycled rubber.	If, in theory, less virgin rubber has to be produced due to the recycling of rubber into new rubber tires, the impact of the production of virgin rubber can be subtracted from the impact the production of the previous product.

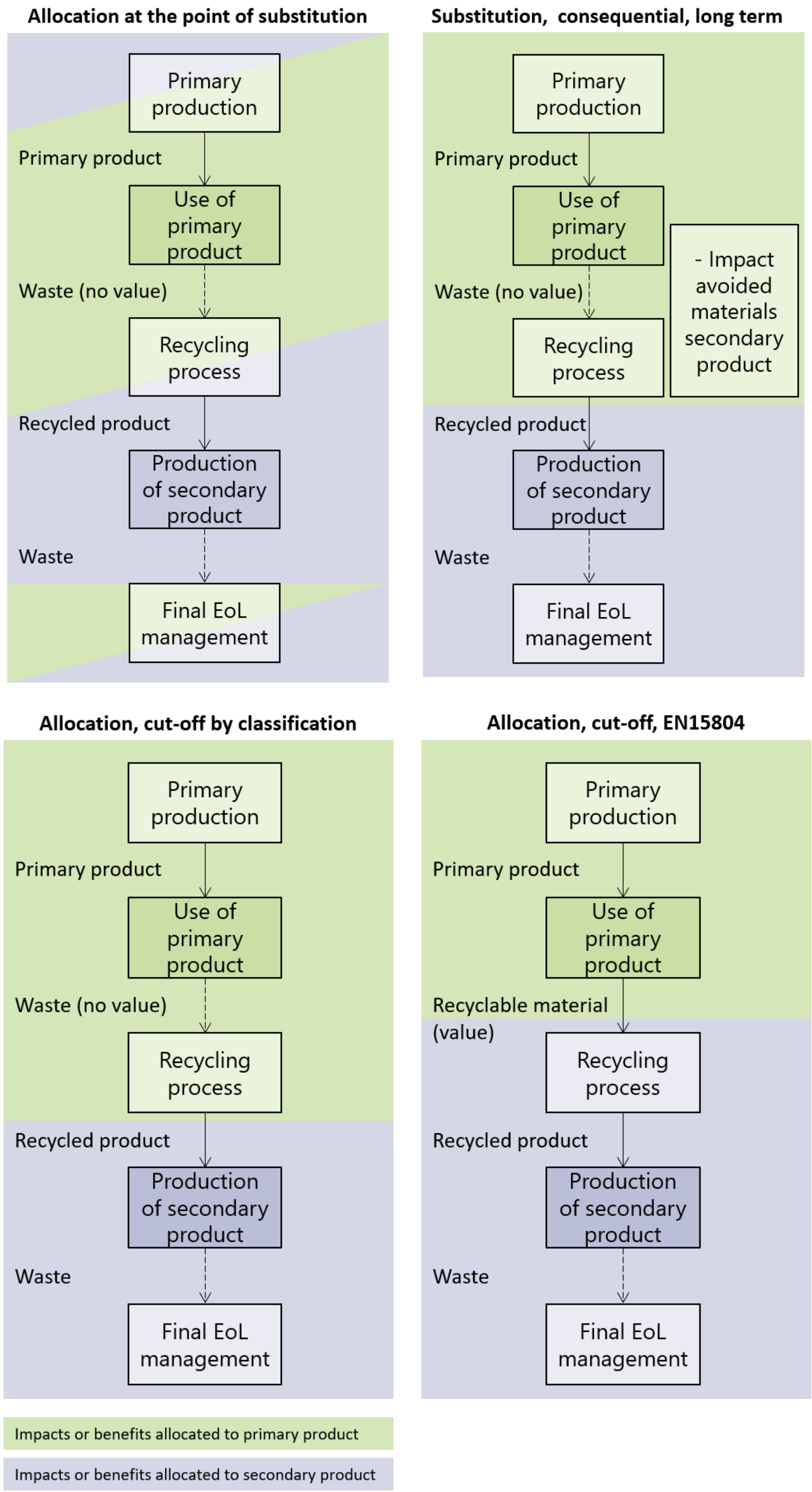


FIGURE 8: VISUALISATION DIFFERENT SYSTEM MODELS (OWN FIGURE, INSPIRED BY ECOINVENT (2022) AND CORONA ET AL., (2019))

In ‘Appendix 1: Explanation system models’ the different system models of ecoinvent and the modelling choices included are explained in detail, based on information is retrieved from the ecoinvent website (ecoinvent, 2022). These system models have different approaches towards the definition of waste, recycling, and allocation of impacts among different functional flows. It is the responsibility of the LCA user to understand and choose the appropriate system model that aligns with their study's goal and scope (ecoinvent, 2022).

In the software program CMLCA, the LCA practitioner can make modelling decisions regarding multifunctionality and recycling waste in the foreground processes. However, the system model selected in ecoinvent also makes decisions regarding waste in the background processes. The selection of the system model and modelling decisions in the foreground should be compatible with the chosen system model.

However, Saade et al. (2019) researched that out of a sample of 137 LCA articles using ecoinvent, only 29 clearly state the selection of the system model. It is stated that ecoinvent users have a lack of understanding of the general concept behind each system model. Practitioners should practice one of the most important actions when performing an LCA: state methodological choices clearly (Saade et al., 2019). This research focuses on the different influences methodological choices and system models have on performing LCAs regarding studies on recycling with a circular economy concept in mind.

This study specifically focuses on attributional LCAs in a product context, using three system models: "Allocation, cut-off by classification," "Allocation, cut-off EN15804," and "Allocation at the point of substitution." The "Substitution, consequential, long-term" system model is reserved for consequential LCAs and is not included in this study.

2.3 CIRCULAR ECONOMY AND CIRCULAR PRODUCT DESIGN

According to Kirrcher et al. (2017) the elaborate definition for circular economy is: “An economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.” (Kirchherr et al., 2017).

The CE concept has a strong focus on closing the product loop in order to minimize negative environmental impacts, meaning that only minimal material and energy is flowing in and out of the material system, while retaining as much product value as possible. A good visual representation of this is provided in the so-called butterfly diagram (Stahel & MacArthur, 2019), depicted in Figure 9. The butterfly diagram shows different value loops of called ‘renewable flow management’ or ‘Bio cycle’ on the left side and ‘stock management’ or ‘Techno cycle’ on the right side, the smaller the loop, the more product value is retained.

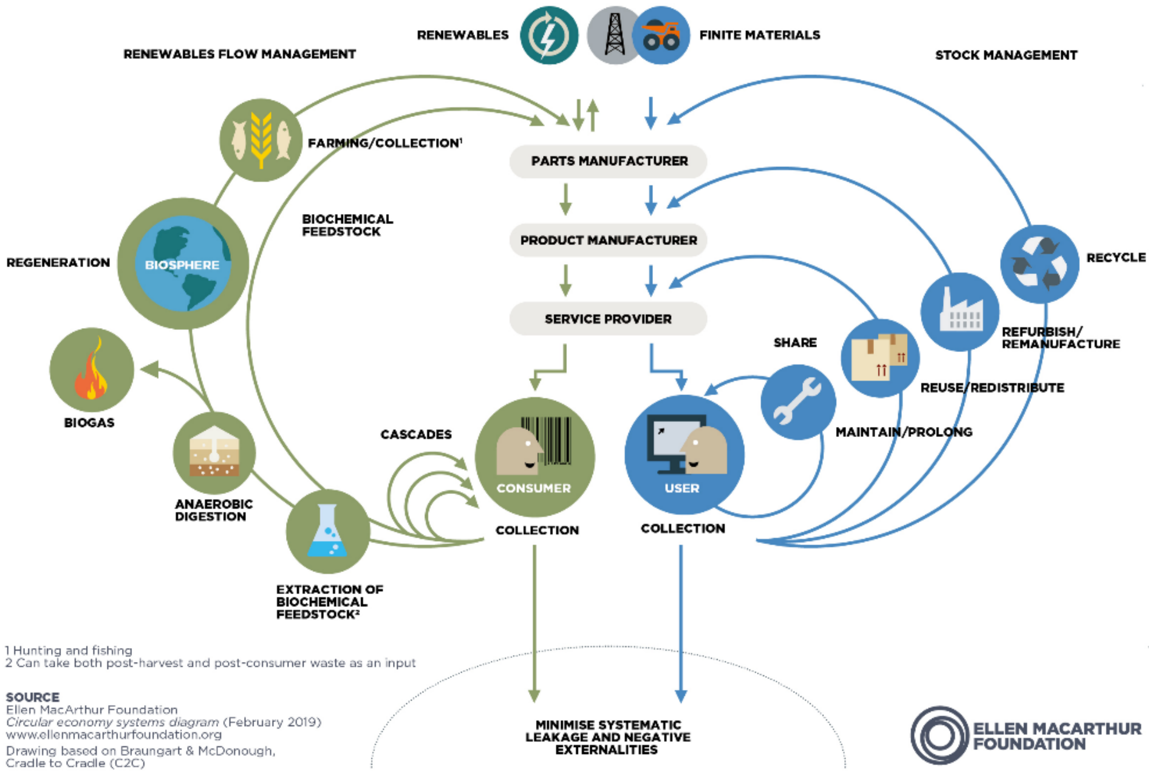


FIGURE 9: THE BUTTERFLY DIAGRAM (STAHEL & MACARTHUR, 2019)

The presented diagram depicts the different pathways to realizing CE by reducing the input of virgin material stocks. This concept is based on the R-framework, which has been documented in various forms in the literature (Kirchherr et al., 2017). Notably, all versions of the R-framework encompass a waste hierarchy, where each R takes precedence over the next. The most elaborate R-framework is the 9R-framework (table 5), including multiple circular strategies in a product production chain, that could be applied by product designers (Potting et al., 2017). A more detailed explanation of the different Rs can be found in appendix 2.

TABLE 5: THE 9R FRAMEWORK ADAPTED FROM POTTING ET AL., (2017)

Strategy focus	R
Focus on smarter product use and manufacture.	R0: Refuse R1: Rethink R2: Reduce
Focus on the extend of lifespan of products and its parts.	R3: Reuse R4: Repair R5: Refurbish R6: Remanufacture R7: Repurpose
Focus on useful application of materials	R8: Recycle R9: Recover

The R-frameworks establish a waste hierarchy, within the retention of value is of great importance. Figure 10 provides an economic perspective on the value retention of products, which can also be considered in terms of function or performance. This figure illustrates that the addition of value occurs at each stage of the product design and production process, including costs, materials, labour, energy, capital, and externalities, such as greenhouse gas emissions, water, and toxic substance (MacArthur, 2013). The linear use of products results in the gradual destruction of this added value after the use phase. The concept of the Circular Economy (CE) emphasizes the preservation of this added value by implementing circular product design and minimizing the disposal of materials, thereby keeping the existing value in the loops as long as possible (Figure 10)(Achterberg et al., 2016).

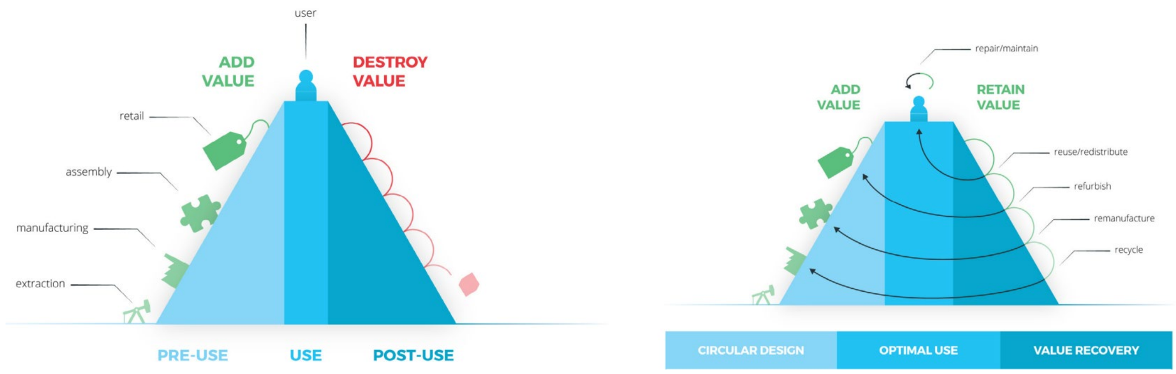


FIGURE 10: THE VALUE HILL OF PRODUCTS IN LINEAR AND CIRCULAR SYSTEMS (ACHTERBERG ET AL., 2016)

The vision of the CE concept is that avoiding material outflow and minimizing virgin material inflow of a system, are means to achieve the goal of sustainable development. Product designers should however not follow this concept blindly. A quantitative method like LCA can be used to compare the environmental impacts of circular design strategies with those of different incumbent alternatives, as well as identify environmental hotspots that require improvement within a system.

Design is defined as 'to conceive the idea for some artifact or system and to express that idea in an embodiable form' (Van Boeijen et al., 2014). To design a product is to conceive the use of the product or service and to find a suitable form for the product and its parts, so that the intended function, or functions, can be fulfilled (Van Boeijen et al., 2014).

According to Roozenburg & Eekels (1995) the design process consists of the following phases:

- **Analysing** which design criteria are needed in order to reach achieve an earlier defined design function.
- **Synthesising** the needed design criteria into a provisional design, created through the ideation phase, the concept phase and comparison of different concepts.
- **Simulating** the provisional design into a final concept phase and test the expected properties
- **Evaluating** the final concept and design iterations take place to finalize the design and it is decided if the design it meets the design requirements and is approved.

A more detailed version in Figure 11 shows the phases of a basic design cycle according to Roozenburg & Eekels (1995).

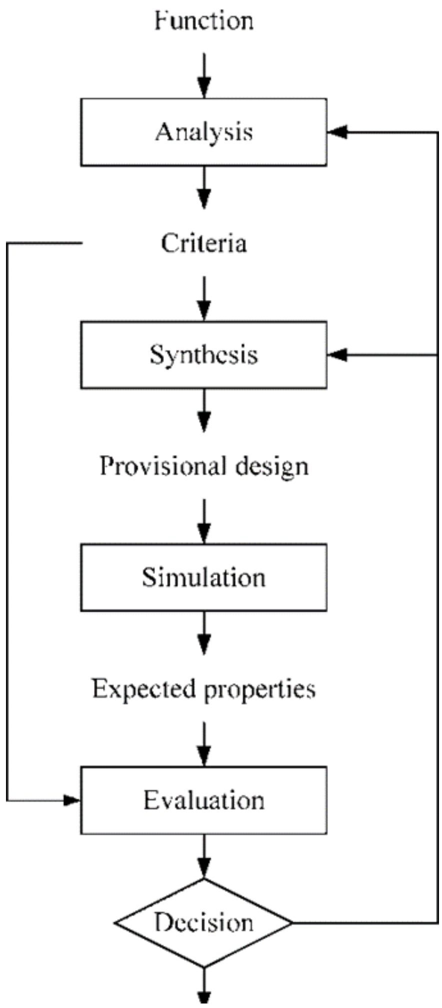


FIGURE 11: THE BASIC DESIGN CYCLE (ROOZENBURG & EEKELS, 1995)

Designing a product contains many iterations, through these iterations, design choices are made with the end requirements in mind. When designing with the aim of reducing environmental impact, decisions must be made in accordance with this goal.

Eco-design focuses on the integration of environmental considerations into product development (Karlsson & Luttropp, 2006). Designers should integrate environmental impacts of a product from the earliest stage of the design (Bovea & Pérez-Belis, 2012).

There are several eco-design methodologies that could be used for assessment of the environmental impact of the design product through the design process. The three key factors that should be included are: early integration of environmental aspects into the product design and development process; the life cycle approach, which takes into account how the product can affect the environment in its different stages; and a multi-criteria approach: the design has to meet certain criteria in order to be approved. One of the methods that includes these key factors is LCA, which requires data and time for application (Bovea & Pérez-Belis, 2012).

LCA results can be used at different points in the design process. During the design process, to guide decisions and for improving existing designs. E.g., As guidance for material selection before embodiment design and as basis for improvement of existing design, after the embodiment design. A designer should keep in mind that with improvement of existing design one cannot simply replace one material with another, because it has less environmental impact. The designer should keep in mind that material properties also change, and perhaps more material of another material is needed, changing the environmental impact. Assessments should guide the users towards the most environmental desirable option. LCA results can also be used to assess the environmental impact of the use phase of the design.

Eco-design is the systematic integration of environmental aspects into product design with the aim to improve the environmental performance of the product throughout its whole life cycle and circular product design strives for achieving an ideal state and designing the entire system surrounding a product (Den Hollander et al., 2017). Circular product design builds on the CE concept.

In section 2.1.2, it is described that within the LCA method, products that have a negative value, are considered waste. Waste in LCA (an economic flow with a value of zero or negative value produced in a unit process and serving as an input to another unit process), also influences the identification of multifunctional processes according to the 4-step approach. However, with retaining the value of the circular products designed, no material should have a negative value. Waste in the CE (obsolete material), or the perception of, is designed out of the system (Den Hollander et al., 2017). The disappearance of waste could influence the outcome of LCAs on circular products that include recycling.

If a designer is following the CE concept and is aiming for sustainable development, it is important to use LCA results that they understand and that transparently quantify and analyse possible environmental impacts. This ensures that design improvements are not only made on a concept vision and assumptions of what is assumed to be environmentally sustainable, but also on quantified and reproducible results of environmental sustainability assessments such as LCA. LCA results help establish the environmental effects of the design and identify areas for improvement. It is important to understand the assumptions underlying these LCA outcomes to comprehend the parameters influencing their interpretation of the conclusion.

3 APPROACH

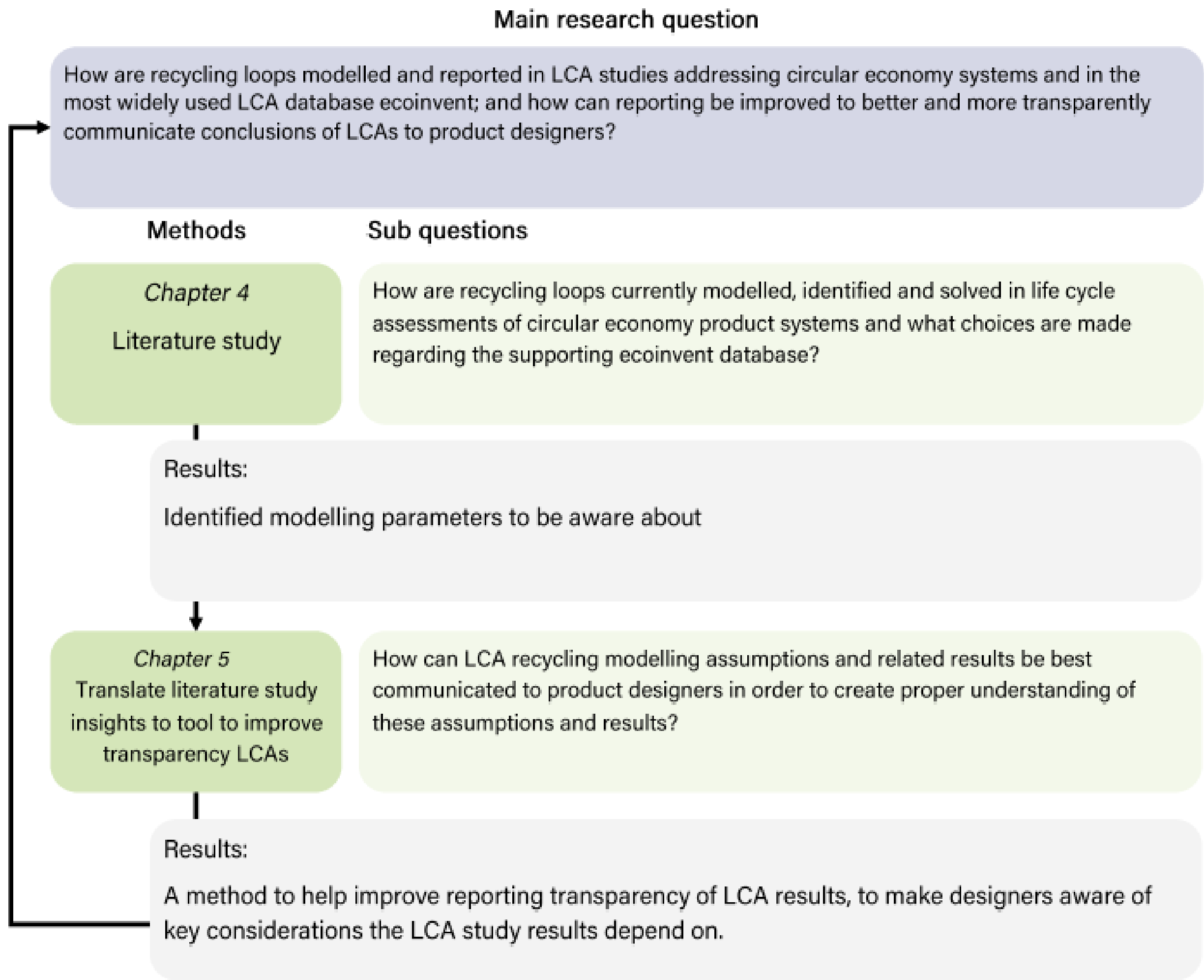


FIGURE 12: A RESEARCH DIAGRAM OF THE THESIS PROJECT

In order to answer the main research question two supporting sub questions were defined in chapter 1. These are answered through different methods (Figure 12).

Sub question 1: (1) '*How are recycling loops currently modelled, identified and solved in life cycle assessments of circular economy product systems and what choices are made regarding the supporting ecoinvent database?'* is answered by performing two separate, targeted literature reviews in chapter '4 The state of the art of CE-LCAs: Two literature studies' . The first literature review focuses on the case studies including recycling with a circular economy mindset. The second review focuses on methodological literature about multifunctionality in LCAs. The literature reviews took place between September and December 2022, literature published after this timespan, is not included in the scope.

The PRISMA method is used to select literature systematically (Appendix 3: PRISMA). The outcome of PRISMA is a selection of articles applicable for the literature review (Page et al., 2021). The databases Web Of Science (WoS) and Scopus are used for the search. The search used different variations of the terms "LCA", "Circular Economy" and "Multifunctionality". After literature selection, articles are systematically reviewed according to review criteria.

Sub question 2: (2) *'How can LCA recycling modelling assumptions and related results be best communicated to product designers in order to create proper understanding of these assumptions and results?'* is answered by development of a tool.

The parameters identified in the literature review are used to construct a tool that helps LCA practitioners assess the transparency of their LCA study. It helps them understand that the LCA conclusion might guide design decisions for designers, and this also helps LCA practitioners to improve the reporting transparency of their LCAs including recycling regarding the CE. This reporting should help make designers aware of key considerations the LCA study results depend on.

In chapter '5 Transparent LCA communication to designers' the goal of the tool is given, following by the explanation of the tool and a first evaluation to iterate on the first design of the tool. At last, application and implementation of the tool is discussed.

4 THE STATE OF THE ART OF CE-LCAs: TWO LITERATURE STUDIES

To be able to understand the reporting and treatment of multifunctionality within LCAs that include recycling and how the system model selection in the ecoinvent database influences the LCA outcome, it is important to first understand the state of the art of treatment of multifunctionality and system model selection in existing CE-LCA studies. The understanding of the state-of-the-art treatment of multifunctionality can help identify where possible caveats and room for improvement of reporting and communication might lay. Therefore, the sub question '*How are recycling loops currently modelled, identified and solved in life cycle assessments of circular economy product systems and what choices are made regarding the supporting ecoinvent database?'* is addressed via two separate literature reviews of CE-LCAs. The first review concentrates on case studies of recycling within a circular economy context, while the second review focuses on methodological literature that discusses the handling of multifunctionality in LCAs generally. See Figure 13 for a visual representation of the structure.

Both literature reviews consist of a literature search, followed by the literature review.

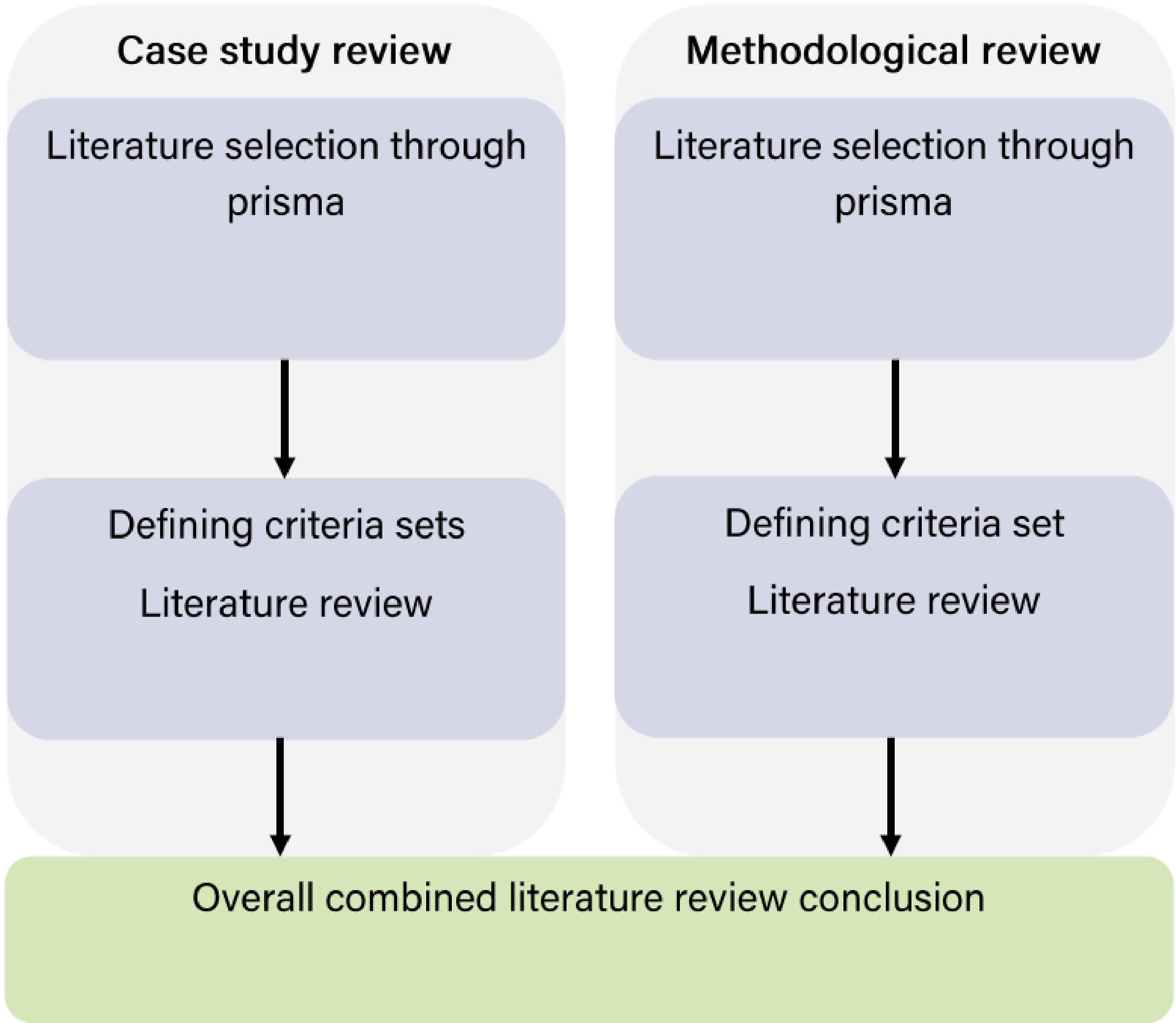


FIGURE 13: THE TWO SEPARATE LITERATURE REVIEWS ADOPTED FOR ANSWERING SUB QUESTION 1

4.1 CASE STUDY REVIEWS: LITERATURE SELECTION

To structure the literature search, the PRISMA method is used to select literature systematically. The outcome of PRISMA is a selection of articles applicable for the literature review (Page et al., 2021). The databases Web Of Science (WoS) and Scopus are used for the search and the review is limited to international scientific articles only.

The complete literature selection can be found in the digital excel 'Appendix A: Literature review', more specifically A1 and A2. Below, the steps and decisions made during the selection are explained.

The search terms should not miss out on relevant articles reporting an LCA with a CE perspective, while not exactly matching the search terms. Therefore, search terms are not limited to the title only, but the topic (Title, abstract, keywords).

The search terms contain various equivalents of the words for LCA and CE, based on different concepts related to the CE concept (Kirchherr et al., 2017). The words 'recycle', 'product', 'case study' and equivalents of 'LCA of' are included to already scope the search towards the research focus: designed products.

No equivalents of, and the terms 'multifunctionality', 'allocation', 'database' or 'ecoinvent' are used as search term. These words could be mentioned in many LCA studies, but not always in the abstract, when this is often not the main focus of the article. Including these terms in the search terms, thus including them as prerequisite in the abstract or title, the result could exclude relevant articles from the search results. Articles not explicitly focussing on these terms in the title or abstract are important to review in order to understand the state of the art of CE-LCAs.

Articles that explicitly mention allocation or multifunctionality in abstract are searched for in the second literature review.

After the search, articles are filtered due to double results found both in Scopus and WoS. The title and abstract of the articles resulting from the search are screened. Some articles are excluded as they are classified as 'no article', but as book chapter or review paper. These are excluded, because the focus is on LCA case studies and these are not expected within these classifications.

The remaining articles are scanned for eligibility through the title and abstract. Articles not meeting the following requirements are excluded in the literature review:

The study presented in the article.

- Performs an attributional LCA;
- has a circular economy perspective and focuses on the 'Recycling-loop';
- Includes recycling in the LCA performed as part of the product system under assessment (and not just mentions it as an end-of-life option without including it in the assessment or comparison of different recycling options);
- includes an LCA on (design) product systems.

Studies meeting all criteria were further reviewed. Appendix A1 and A2, summarize why articles have been excluded.

TABLE 6: LITERATURE SEARCH LCA CASE STUDIES

Search words	**# Of hits**	**Excluded**	**Reviewed**
Title: LCA or Life cycle assessment OR life cycle analysis OR Life-cycle assessment OR Life-cycle analysis *Subject, title, abstract: AND Circular AND Economy AND Case AND Study.*	271	263	8
Topic: *"LCA" OR "life cycle assessment" OR "life cycle analysis" OR "Life-cycle assessment" OR "Life-cycle analysis"* *AND "circular economy" OR "cradle to cradle" OR "cradle-to-cradle" OR "4R framework" OR "3R framework" OR "6R framework" OR "9R framework" OR cascad** *AND recycl** *AND "product" OR "products"* *AND "case study" OR "life cycle assessment of" OR "Life cycle analysis of" OR "Life-cycle assessment of" OR "Life-cycle analysis of"*	199	173	23
Total			30

4.2 CASE STUDIES REVIEW: LITERATURE REVIEW

Two criteria sets are defined and all the included articles are reviewed against these criteria to better understand how and if recycling and multifunctionality is handled within the LCA study and which decision is made regarding the supporting database.

As described in section 2.1, the modelling, identification and solving of multifunctionality happens in the Inventory analysis phase of the ISO 14040 LCA framework (International Organisation for Standardisation (ISO), 1997). Criteria set 1 is defined in order to identify how multifunctionality of recycling processes is treated in a given article. A second criteria set is created to check if there is awareness of the possible influences that the selected background database can have on the results of the LCA.

1. **Criteria regarding multifunctionality in the inventory analysis**

a. Is a flow diagram modelled? If so, how does it represent recycling?

b. Is multifunctionality identified?
   The multifunctionality is considered identified if the article shows awareness that recycling represents a multifunctional process, and is adressing multifunctionality accordingly.

c. Is multifunctionality explicitly adressed and how?
   Multifunctionality is considered adressed when impacts are distributed over different product systems according to one of the possible methods of solving multifunctionality, this can occur without the multifunctionality being identified, so mentioning of the awareness that a multifunctional process is represented is not necesarry.
   Which method is used to distribute the impacts over the different product systems?

d. How is recycling modelled? Is there one single recycling process modelled or multiple unit processes considering the recycling process and is the data used in the modelling of the recycling process retrieved from a dataset or modelled by the practitioner themselves with results based on a performed data study?

e. Is recycling modelled representing open-loop, closed-loop or semi-closed loop recycling?

2. **Criteria regarding the database for data collection**
    a. Is the ecoinvent database used for the LCA?
    b. If ecoinvent is used, do the authors report which system model is selected and why?

Below, it is discussed how the 30 articles identified scored on these two sets of criteria (Table 7). The detailed literature review can be found in digital appendix A4. The relevant conclusion of this literature review can be found below

FLOW DIAGRAM MODELLING

Out of the 30 articles, 21 have modelled a flow diagram to accompany the performed LCA. The flow diagrams appear in various qualities and differ in amount of detail recycling is displayed, as later elaborated on is this paragraph. Some of the flow diagrams are more clear than others. 9 of the articles reviewed thus do not display a flow diagram of the product system under study (Ford & Fisher, 2019; Galve et al., 2022; Kooduvalli et al., 2020; Lucchetti et al., 2019; Martínez-Cámara et al., 2021a; Monteiro et al., 2022a; Remic et al., 2022; Ros-Dosdá et al., 2019; Tamoor et al., 2022).

MULTIFUNCTIONALITY: IDENTIFICATION

5 of the 30 articles have modelled a flow diagram and identified the multifunctionality (Abejón et al., 2020; Ferreira et al., 2001; Moraga et al., 2022; van Straten et al., 2021; Wilson et al., 2021). Those articles do not follow a step by step method to identify the multifunctionality, but do show clear awareness that some processes analysed within their system have more than one functional flow. For that reason they apply a method in order to distribute the impacts over different product systems according to one of the possible methods of solving multifunctionality. Those are the only articles that display the modelling, identification and solving of the multifunctionality transparently, corresponding with only 17% of the articles included in the literature review. Moreover, this shows that 83% of the CE-LCA articles reviewed do not show identification of multifunctional processes in the product system under study (Table 8).

MULTIFUNCTIONALITY: ADRESSING AND METHODS FOR SOLVING

20 out of 30 articles adress the multifunctionality witin their system (Table 7): they use a method of solving multifunctionality in order to distribute impacts over the different product systems. 12 of the articles that adress multifunctionality, do so without mentioning the identification of the multifunctional processes that might have occurred beforehand (Braun et al., 2021; Civancik-Uslu, Puig, Ferrer, et al., 2019; Garcia et al., 2020; Gu et al., 2019; Huysman et al., 2015; Khan et al., 2021; Kooduvalli et al., 2020; Lonca et al., 2020; Maga et al., 2019; Ros-Dosdá et al., 2019; Stotz et al., 2017; Willskytt & Tillman, 2019). The other 5 articles that are also mentioned for identifying multifunctionality and presenting a flow diagram: the articles show clear awareness of the relevance to report these modelling choices transparently. (Abejón et al., 2020; Ferreira et al., 2001; Moraga et al., 2022; van Straten et al., 2021; Wilson et al., 2021).

Different variations of names for the methods used to solve multifunctionality are used throughout different LCA articles, but all definitions build on the allocation principles of either partitioning or substitution. Eventhough all studies are attributional LCA studies, some also use the subsitution method to solve multifunctionality which is a way of solving multifunctionality that has a consequential nature. Those LCAs however, do not work with scenarios of how flows will change in response to possible decisions like consequential LCAs are expected to do, but still use the substitution method to solve multifunctionality. Out of the 20 articles solving multifunctionality, 3 articles use both a partitioning and a substitution method to solve multifunctionality (Abejón et al., 2020; Kooduvalli et al., 2020; Kouloumpis et al., 2020), 9 articles use only partitioning (Braun et al., 2021; Civancik-Uslu, Puig, Voigt, et al., 2019; Ferreira et al., 2001; Gandhi et al., 2021; Garcia et al., 2020; Monteiro et al., 2022b; Moraga et al., 2022; van Straten et al., 2021; Wilson et al., 2021). 8 of those articles use a way of substitution (Garcia et al., 2020; Gu et al., 2019; Huysman et al., 2015; Lonca et al., 2020; Maga et al., 2019; Ros-Dosdá et al., 2019; Stotz et al., 2017; Willskytt & Tillman, 2019).

Interestingly, one article (Khan et al., 2021) uses both a cut-off approach and an avoided burden approach. This an inconsistent use of system boundaries. The study models recycled materials as being impact-free, but at the same time also substracts the impact from avoided energy production from the product impact, by mentioning possible energy recovery. This means taking double 'credits' for using the left over materials from another product system without accounting for the impact and burn them to reclaim the energy recovery. It could be argued that instead of doing this, the materials could be used as input for a new product system for free as well. The producer of the virgin material could have modelled/claimed the benefits of the energy recovery process as well and appearlingly have optimised the LCA outcome. This implies that they view the system boundaries different in other product systems and use them in their advantage by modelling in such a way the lowest environmental impact is seemingly achieved within the product system under study. Depending on the focus of the study, the system boundary should be either be on benefits for recycling waste as input of the recycling process or on producing the recyclable material output, but not on both.

ECOINVENT DATA USAGE

19 out of 30 articles use ecoinvent as background database (Table 7), but only 3 of those mention the system model selected: all 3 of those mention to have used the cut-off by classification system model, but no motivation for the selection of this system model is given (Braun et al., 2021; Kooduvalli et al., 2020; Moraga et al., 2022). The other database that is used in the literature 4 times is the GaBi database, which builds on ecoinvent data (GaBi, n.d.). The found information matches with the conclusion of Saade (2019); that ecoinvent users have a lack of understanding of the general concept behind each system model (Saade et al., 2019).

MODELLING RECYCLING

There is a huge variation in how recycling is modelled, 15 articles use recycling dataset retrieved from databases, the other articles either use own data to define the recycling process or it is unclear which data they use as input (Table 7). Stotz et al. (2017) retreives recycling data from a database but warns for the lack of transparency of the assumptions behind the available datasets. Therefore, this is justly mentioned by Stotz et al. (2017) as a key aspect that needs to be improved in order to be able to provide reliable results.

To understand the difference in details of the modelled recycling processes, it is checked in literature if single or multiple processes are modelled within the system model. In 17 articles, multiple processes involved in the recycling process are modelled (Table 7), in another 10 articles the amount of unit processes involved is single. In the remaining 3 articles it is unclear how many unit processes are part of the recycling process (Ford & Fisher, 2019; Kooduvalli et al., 2020; Vujanović et al., 2022)

OPEN-LOOP, CLOSED-LOOP OR SEMI-CLOSED LOOP

To understand the kind of recycling loops that are modelled in the literature, the literature is reviewed whether recycling in the LCAs is modelled as an open-loop, closed-loop or semi-closed loop. Open-loop recycling occurs 9 times in the articles (Table 7). Semi-closed loop recycling, meaning that recycling in in reality is partly recycled in a different system model (open-loop), but is now modelled as being recycled within the same system model (closed-loop), occurs 5 times (Abejón et al., 2020; Kouloumpis et al., 2020; Moraga et al., 2022; Willskytt & Tillman, 2019; Wilson et al., 2021). Recycling is modelled as a closed-loop in 7 articles (Table 7). 4 articles model both open and closed-loop recycling, to compare the different scenarios. (Huysman et al., 2015; Lonca et al., 2020; Maga et al., 2019; Niero &

Olsen, 2016). In 5 out of 30 articles it is unclear how the recycling loops are modelled (Ford & Fisher, 2019; Lozano-Miralles et al., 2019; Monteiro et al., 2022a; Remic et al., 2022; Vujanović et al., 2022). In the articles of Civancik-Uslu, Luchetti and Galve, the open-loop recycling goes hand in hand with the cut-off, or burden-free allocation approach that they use. Assumed is that recycable material can be used, but as the origin is not precicely determined the impacts that accompany this material are unknown either. Therefore, the recycled material comes from an open-loop and the use of this recyclable material is modelled without impact, before leaving the system boundary as recycable material again. (Civancik-Uslu, Puig, Voigt, et al., 2019; Galve et al., 2022; Lucchetti et al., 2019).

Interesting is that for most recycling processes it is unclear if recycling more products leads to a decrease of virgin material input in the processes. In 2 articles, it is clear that the possible reduction of virgin materials is not taken into account. This is because the substitution method is used to take credit for producing recycable material, but how the material will actually come to be recycled is not explained and the processes needed to achieve this are not taken into account. It is thus more stating the fact that the material is recycable, but does not include the pathway of the recycling process and the actually realisation of decreasing virgin material inputs (Ros-Dosdá et al., 2019; Willskytt & Tillman, 2019). 3 out of 30 articles clearly mention the decrease of virgin material input in the starting process (Maga et al., 2019; Martínez-Cámara et al., 2021b; Moraga et al., 2022). This means in 25 out of 30 articles, it is unclear if the apparent impact of the recyling process is seamingly reduced, when not explicitlty stating and being aware of the impact recycling has. The article by Ferreira focuses on an illustrative example to compare different allocation methods, so only one singular process is modelled to not make the illustration unneccesarily complicated. The impact of the recycling processes is thus seamingly reduced, but clearly argued for(Ferreira et al., 2001).

TABLE 7: LITERATURE REVIEW CASE STUDIES

Reference	Flow diagram?	MF Identified?	MF solved?	How?	Ecoinvent?	System model?	How is the recycling modelled?	Open-loop, closed-loop or semi-closed loop?
(Kouloumpis et al., 2020)	Yes	No	Yes	Mass allocation, avoided burden approach	Yes	No	Multiple, dataset	Semi-closed
(Monteiro et al., 2022b)	No	No	Yes	Cut-off recycled content approach	Yes	No	Single process, data based on study	Unclear
(Khan et al., 2021)	Yes	No	Yes	Avoided burden approach and zero burden approach	Yes	No	Multiple, dataset	Closed-loop
(Abejón et al., 2020)	Yes	Yes	Yes	system expansion, partitioning and substitution, allocation hierarchy from ISO 14044	GaBi	n/a	Multiple, unclear	semi-closed loop
(Civancik-Uslu, Puig, Voigt, et al., 2019)	Yes	No	Yes	the 100:0 allocation method (also known as cut-off approach)	GaBi	n/a	Multiple, dataset	Open-loop
(Lucchetti et al., 2019)	No	No	No		Yes	No	Multiple, dataset and data based on study	Open-loop
(Willskytt & Tillman, 2019)	Yes	No	Yes	"System expansion (avoided burden approach) and energy recovery	Yes	No	Single, unclear,	semi-closed loop
(Kooduvalli et al., 2020)	No	No	Yes	Allocation and crediting	Yes	specifically, the allocation, cut-off by classification – unit)	Unclear, unclear	Open-loop
(Vujanović et al., 2022)	Yes	No	No		Yes	No	Unclear, unclear	Unclear
(Wiprächtiger et al., 2022)	No	No	No		Yes	No		
(Galve et al., 2022)	No	No	No		Yes	No	Single, dataset	Open-loop
(Tamoor et al., 2022)	Yes	Yes	Yes	partitioning, mass allocation	Yes	cut-off model	Multiple, dataset and data based on study	Open-loop
(Moraga et al., 2022)	No	No	No		No	n/a	Multiple, data based on study	Semi-closed loop
(Remic et al., 2022)	Yes	Yes	Yes	partitioning, mass allocation	No	n/a		
(van Straten et al., 2021)	No	No	No		Yes	No	Multiple, dataset and data collected from measurements	Closed-loop
(Martínez-Cámara et al., 2021b)	Yes	No	Yes	50/50 partitioning	Yes	recycled-content system model	Multiple, datasets	Closed-loop
(Braun et al., 2021)	Yes	No	No		No	n/a	Single, data based on study	Closed-loop
(Gandhi et al., 2021)	Yes	No	Yes	5 ways of EoL partitioning	Yes	No	Multiple, unclear	Open-loop
(Garcia et al., 2020)	Yes	No	Yes	Substitution	Yes	No	Multiple, unclear	Closed-loop
(Lonca et al., 2020)	Yes	No	No		Yes	No	Single, dataset,	Open-loop and closed-loop
(Lozano-Miralles et al., 2019)	No	No	Yes	Avoided burden approach	GaBi	n/a	Single, dataset	Unclear
(Ros-Dosdá et al., 2019)	No	No	No		No	n/a	Single, datasets	Closed-loop
(Ford & Fisher, 2019)	yes	No	Yes	Substitution	GaBi	n/a	Unclear, unclear	Unclear
(Maga et al., 2019)	Yes	No	No		No	n/a	Single, unclear	Open-loop and closed-loop
(Xiao et al., 2018)	Yes	No	No		Yes	No	Multiple, datasets and data based on study	Closed-loop
(Niero & Olsen, 2016)	Yes	No	Yes	Substitution	No	n/a	Multiple, data based on study	Open-loop and closed-loop
(Gu et al., 2019)	Yes	Yes	Yes	partitioning	Yes	No	Multiple, unclear	Open-loop
(Wilson et al., 2021)	Yes	Yes	Yes	partitioning	No	n/a	Multiple, dataset	Semi-closed loop
(Ferreira et al., 2001)	Yes	No	Yes	Substitution	Yes	No	Single, dataset	Open-loop
(Huysman et al., 2015)	Yes	No	Yes	Substitution	Yes	No	Single, datasets and data based on study measurements	Open-loop and closed-loop
(Stotz et al., 2017)	Yes	No	Yes	Mass allocation, avoided burden approach	Yes	No	Multiple, dataset	Open-loop

CASE STUDY REVIEW CONCLUSION

The existing literature on LCAs of products including recycling with a circular economy mindset has a lack of awareness regarding the potential impact of various methods used to address multifunctionality, the selection of background data, and the recycling modelling approach have on LCA outcomes. The overall reporting transparency fluctuates. Additionally, transparency and reporting quality vary among articles, with some failing to provide adequate information about the flow diagrams used to model the LCA. Furthermore, obtaining the exact data used within the LCA model is challenging due to data confidentiality issues. While some articles attempt to disclose the assumptions made and their possible influence on the results, this information is often difficult to locate amidst a vast amount of numerical and textual data. Gaining a thorough understanding of these assumptions and their impacts on communicating concluding LCA results requires significant effort and motivation.

Overall, the reporting, modelling and identification of multifunctionality within the system models under study are lacking. There is no systematic approach used to identify and solve multifunctionality. This lack of consistency may lead to multiple interpretations of the LCA results. In Table 8, the different criteria sets and the percentage of the articles answering these criteria are given in an overview.

TABLE 8: REVIEW CASE STUDIES SUMMARY

Total of articles reviewed	30	30

Flow diagram modelled?		%
Yes	21	70
No	9	30

Multifunctionality identified?		%
Yes	5	16.67
No	25	83.33

Multifunctionality solved?		%
Yes	20	66.67
No	10	33.33

Way of solving		%
Total	20	
Partitioning	9	45.00
Substitution	8	40.00
Both	3	15.00

Background database use, ecoinvent?		%
Yes	19	63.33
GaBi	4	13.33
No	7	23.33

System model selection		%
Total	19	
Cut-off by classification	3	15.79
Unclear	16	84.21

How is the recycling modelled?		%
Dataset	15	50
Own selected data	15	50

Unit processes recycling number		%
Single	10	33.33
Multiple	17	56.67
Unclear	3	10

Type of 'loop' recycling		%
Open	9	30
Closed	7	23.33
Semi	5	16.67
Open and closed	4	13.33
Unclear	5	16.67

Reduction in virgin material mention		%
Not taken into account	2	6.67
Taken into account	3	10
Unclear	25	83.33

4.3 METHODOLOGICAL REVIEW: LITERATURE SELECTION

As shown in the previous literature review little awareness or transparent reporting is present regarding the way of solving multifunctionality in LCAs that analyse product systems that include recycling with a CE view. However, this does not mean there is absolutely no awareness of possible multifunctionality problems among LCA practitioners. Articles that explicitly mention the methodological issues considering allocation or multifunctionality in the title or abstract of the report - instead of only discussing it as part of a case study - are included in this literature review, in order to get a complete picture of the state of the art of multifunctionality solving in LCA.

Another literature search according to the PRISMA method (Page et al., 2021) is done detailed search results can be found in digital appendix A6 and summarized search results in Table 9 .The focus is on literature mentioning and solving multifunctionality issues. The detailed literature review can be found in appendix A8. There is only one search requirement: articles are considered relevant if the title indicates active discussion about solving multifunctionality and allocation considering recycling or the CE. Articles meeting these criteria were further reviewed.

TABLE 9: LITERATURE SEARCH METHODOLOGICAL LITERATURE ON MULTIFUNCTIONALITY IN LCAS

Search terms	**# Of hits**	**Relevant**
(TITLE-ABS-KEY ("LCA" OR "life cycle assessment" OR "life cycle analysis" OR "Life-cycle assessment" OR "Life-cycle analysis") AND TITLE-ABS-KEY ("circular economy") AND TITLE (multifunctional OR allocat))*	9	8
(TITLE-ABS-KEY ("LCA" OR "life cycle assessment" OR "life cycle analysis" OR "Life-cycle assessment" OR "Life-cycle analysis") AND TITLE-ABS-KEY ("circular economy") AND TITLE-ABS-KEY (multifunctionality OR allocat))*	65	15
(TITLE-ABS-KEY (allocation) AND TITLE-ABS-KEY (circular AND economy AND lca))	48	6
(TITLE-ABS-KEY ("LCA" OR "life cycle assessment" OR "life cycle analysis" OR "Life-cycle assessment" OR "Life-cycle analysis") AND TITLE (multifunc OR alloc*) AND TITLE-ABS-KEY (recycl*))*	58	5
Snowballing	0	4
Sum		57
Review sample after removing double hits literature searches		21
Review sample after excluding extra literature after reading for review, seeming less relevant		19

4.4 METHODOLOGICAL REVIEW: LITERATURE REVIEW

The articles are reviewed on two criteria:

1. **Criteria regarding multifunctionality in the inventory analysis**
   a. Does the article argue for the identification of multifunctionality?
   b. What methods used to solve multifunctionality are discussed?

2. **Criteria regarding the database for data collection**
   a. Is the influence of the (ecoinvent) background database mentioned?

Below, it is discussed to what extent the 19 articles of the review discuss the treatment of multifunctionality and mention explicit realisation of the influences of background data on the assessment results. A summary of this literature review can be found in Table 9 and the complete, detailed results can be found in digital Appendix A7.

MULTIFUNCTIONALITY: SOLVING AND IDENTIFICATION.

All of the 19 articles do discuss the solving of the multifunctionality occurring, but none of the articles mention the identification of multifunctionality beforehand. The articles all take the fact that there is a multifunctional process as a starting point and discuss how to solve this multifunctionality.

3 out 19 articles focus on a caveat for solving multifunctionality in the built environment, when contributions should be divided between different life cycles of different parts of buildings, but this is difficult not being able to estimate the life spans of different parts of the system under study (Malabi Eberhardt et al., 2020; van Stijn et al., 2021). Van Gulck et al. (2022), focus on how the EN15804 standard is applied in the built environment and LCA. Van Gulck et al. (2022) shows no awareness about the different system models that can be selected in ecoinvent, and thus include different ways pre-allocation in the background data. In this article, there is also no awareness that and how the EN15804 standard is applied in one of the system models that can be selected in ecoinvent and the possible influence this might have on the outcome of the LCA (Van Gulck et al., 2022).

Overall, 10 out of 19 articles compare different (and new) ways of partitioning and research the influence on the results when using either a 50:50, 100:0, 0:100 or 100:100 as partitioning distribution. The influence of these decisions is discussed, and which option might be most suitable. It is important to realise the effect of the different partitioning distributions and the effect it has on the LCA outcome. 2 out of 19 articles include a focus on a partitioning division based on decreasing material quality in the methods to solve the multifunctionality (Kim et al., 1997; Nicholson et al., 2009). Ekvall et al. (2020) elaborately discusses twelve different ways of partitioning. This article shows insight in how the different ways of partitioning might influence the results and the incentives gives from these LCA studies (Ekvall et al., 2020).

9 out of 19 articles include solving multifunctionality through a method that builds on the substitution principle (Table 9). The article by Lewandowska (2019) contains a detailed description of solving multifunctionality through the application of the complex circular footprint formula, which allocates the impacts and the avoided burdens due to substitution among multiple cycles in a linearly decreasing formula (Lewandowska, 2019).

According to Ekvall (2020) it is important to help decisionmakers better understand the results of an LCA and in order to do that, the LCA report should also explain what views the allocation methods reflect (Ekvall et al., 2020). Houssard et al. (2021) also shows interesting insight in the different incentives that different methods of solving multifunctionality might bring along. They show that when multifunctionality is solved according to substitution principles. E.g., in this study: the process for which the multifunctionality is solved, incentivises decreasing of milk production, as the remaining whey from yoghurt production can be used in cream production, instead of coming from milk production. Whereas partitioning would not motivate to facilitate this recycling process (Houssard et al., 2021a).

The confusing terminology around system expansion and substitution, as mentioned in the theoretical background is highlighted as a problem as well (Schrijvers et al., 2020).

INFLUENCE BACKGROUND DATABASE

Out of 19 articles, 5 articles mention ecoinvent, these 5 also mention which ecoinvent system model they select for their LCA (Bijleveld, 2022; Lewandowska, 2019; Malabi Eberhardt et al., 2020; San-Francisco et al., 2020; van Stijn et al., 2021).

Several articles show insight in the possible influences of the background database on the result of LCA (Brogaard et al., 2014; Lewandowska, 2019; Malabi Eberhardt et al., 2020; San-Francisco et al., 2020; Schaubroeck et al., 2021). Brogaard et al. (2014) does focus in detail on the possible differences between selection of different datasets considering recycling that can be used as LCA background data. However, no research is done yet into what these influences actually entail.

Brogaard mentions that great care should be taken with data selection and a high degree of transparency when selecting datasets is mandatory for clear and transparent LCA results, but advice on which datasets are best to use to achieve this is not provided by (Brogaard et al., 2014). The article does not discuss the influence of solving multifunctionality in the background data. Further research should be done on what the effect of different types of background data have on the results of the LCA

TABLE 10: LIST OF STUDIES REVIEWED FOR THE METHODOLOGICAL REVIEW, SUMMARY OF LITERATURE REVIEW

Reference	*Multifunctionality identified?*	*Method of solving multifunctionality applied/discussed*	*Mention influence background data*
(van Stijn et al., 2021)	No	CE-LCA: approach allocates impacts between cycles: the largest share of initial production and disposal impacts is allocated to the cycle where they occur, namely the first and last, respectively. The share of impacts allocated to following or previous cycles reduces linearly.	Yes
(Bijleveld, 2022)	No	mLCA (multicycle LCA): Substitution (vermeden impact)	Yes
(Allacker et al., 2017)	No	EC EF: credits for avoided virgin production a ratio of R2/2.	No
(Malabi Eberhardt et al., 2020)	No	CE-LD approach: Substitution & allocation (according to the ISO 14044 hierarchy)	Yes
(San-Francisco et al., 2020)	No	not mentioned	Yes
(Lewandowska, 2019)	No	Circular Footprint Formula: Substitution & allocation: "The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure presented	Yes
(Tanguay et al., 2021)	No	Partitioning	No
(Houssard et al., 2021b)	No	Partitioning and substitution	No
(Corona et al., 2019)	No	0:100, 100:00, 50:50	No
(Ilic et al., 2018)	No	Partitioning and substitution	No
(Nicholson et al., 2009)	No	Cut-off, loss of quality method, closed loop method, 50/50 method, substitution method	No
(Schaubroeck et al., 2021)	No	Cut-off, partitioning, system expansion and co-function effect/avoided burden approach:	Yes
(Sfez et al., 2019)	No	Three common categories of allocation methods are identified as follows: the cut-off (100:0), recyclability (0:100), and distributed (50:50) allocation methods and CFF	No
(Kim et al., 1997)	No	new method, 50/50, material pool method	No
(D. Schrijvers et al., 2020)	No	system expansion and substitution, the cut-off approach and other partitioning methods	No
(Toniolo et al., 2017)	No	Partitioning (cut-off) and substitution	No
(Van Gulck et al., 2022).	No	Cut-off allocation approach (100:0) and system expansion/substitution	No
(Brogaard et al., 2014).	No	Substitution	Yes
(Ekvall et al., 2020).	No	12 different ways of allocation	No

METHODOLOGICAL REVIEW OVERALL CONCLUSION

In section ‘2.1.1 LCA: the method’ the 4-step method by Guinée et al. (2002), is noted as a relevant approach for identifying multifunctionality in LCA studies. However, it is observed that the first three steps of this method are not commonly applied in the methodological literature on multifunctional LCAs. Instead, studies generally assume the presence of multifunctionality and focus on addressing and resolving it, without clearly outlining how it was determined. While some literature acknowledges that the choice of the ecoinvent database system models in LCA studies can impact the resulting data, there is a lack of information regarding how these modelling decisions actually influence study outcomes. Consequently, it remains uncertain whether different modelling approaches and methods for resolving multifunctionality have a significant impact on LCA results, and whether the reporting of such outcomes may lead to varying interpretations.

4.5 COMBINED LITERATURE DISCUSSION AND CONCLUSION: STATE OF THE ART LITERATURE REVIEW CE-LCAS

In the state-of-the-art CE-LCAs containing case studies, flow diagrams have been used in 70% of the reviewed articles to model the product system under study. However, only five articles discuss the identification of multifunctionality within these systems. Various approaches to solving multifunctionality have been discussed, but there is no consensus on how to allocate burdens between different systems that involve recycling. The focus is on which partitioning division is most appropriate for a given modelling scenario. Literature considering case studies and methodological literature about multifunctionality in LCA all start from the same starting point: there is a multifunctional problem, and needs to be solved. But unclear is how the articles ended up at this starting point in the first place, and identified the multifunctionality.

The methodological literature on multifunctionality in LCA, shows awareness discusses some knowledge about the different system models of ecoinvent and how the pre-allocation in these datasets could influence results of an LCA. However, it remains unspecified what the influence of the ecoinvent database system model choice on the results of an LCA can be. Resulting from this, it is unclear what different modelling decisions and methods of solving multifunctionality have for influence on the results of the LCA and how these results are interpreted. This is similar to the conclusion of Saade et al. (2019) that ecoinvent users have a lack of understanding of the general concept behind each system model and should practice stating methodological choices clearly (Saade et al., 2019).

The modelling of the recycling process varies in detail between articles, with some recycling processes are modelled as multiple unit processes while others use only a single unit process to display it. Data used for recycling modelling is obtained from either the researchers themselves or from downloaded datasets. Brogaard et al. (2014) found that the choice of dataset used to represent the environmental load of a material recycling process is crucial for the outcome of an LCA on waste management. Great care and a high degree of transparency are mandatory for a reproducible and understandable LCA, but the article Brogaard et al. could not give advice on which datasets to as the influences of different choices made in the modelling of the LCA are untransparent (Brogaard et al., 2014). The little context given for the selection of open-loop or closed-loop recycling and the little awareness of the effects this has on minimizing material inputs makes it is unclear if the impact of the overall recyling process is seamingly reduced in the modelling process by not explicitlty stating and realising the impact recycling has.

To answer the question: '*How are recycling loops currently modelled, identified and solved in life cycle assessments of circular economy systems and what choices are made regarding the supporting EcoInvent database?*'

In conclusion, recycling is not always modelled as loops in LCAs. and no multifunctionality identification takes place in LCAs that contain recycling with a CE mindset. Solving multifunctionality occurs through partitioning and substitution principles mostly. There is almost no mention of selection of ecoinvent system models, only articles specifically focussing on multifunctionality within LCA show insight that different system models might influence results of an LCA.

It is crucial to gain a better understanding of the various modelling, identification, and solving multifunctionality choices and their effects on LCA results to improve reporting clarity and facilitate the correct communication of LCA results to non-experts, for example, designers. Greater transparency in reporting LCA studies and explaining the differences in ecoinvent background data, the effects of foreground data modelling, and the identification and solving of multifunctionality, can support accurate interpretation and application of LCA results in circular economy systems by these non-experts.

The different criteria that are used for the literature study seem to be important key considerations that have different modelling and reporting variations and accompanying assumptions that possibly influence the results of the LCA, and thus need proper communication, are given:

1. Modelling of the flow diagram
- Yes or No?
2. Identification of multifunctionality
- No, Yes, Yes and the decision is substantiated.
3. Way of solving of the multifunctionality
- No, Yes: Partitioning (different ways) or substitution
4. Background database use
- Not specified, Own data use, database use, database use and realisation of pre-allocation is showed
5. The modelling of foreground recycling (dataset and number of recycling processes)
- Specified which data set is used: yes or no.
- Specified if: multiple, single or unclear how many recycling processes are included.
6. Type of loop recycling
- Unclear, open-loop, closed-loop and semi-closed loop.
7. Reductions in virgin material inputs are mentioned.
- The reduction of virgin materials is unclear, it is mentioned it is taken or not taken into account, the impact and the effects are supported and explained.

The outcomes of LCAs, and the assumptions it depends on, should be understood by the product designers using the LCA, therefore LCA reporting should be transparent. If a designer is performing eco-design and aims to design for sustainable development, and thus as little environmental impact as possible, it is important to understand which underlying assumptions are taken to achieve the LCA result and what parameters the results of the LCA depend on. In the following chapter these parameters will be referred to as 'key considerations'.

5 TRANSPARENT LCA COMMUNICATION TO DESIGNERS – MAKING LCAS MORE ACCESSIBLE TO DESIGNERS

The current state of LCAs presents a range of transparency, as evidenced in various reporting quality and modelling choices for recycling processes and multifunctionality solutions within product systems. This can create friction between the LCA results and designers, who may not fully understand the complex assumptions made during the assessment and the key considerations that should be taken into account for the overall interpretation of the results.

Furthermore, many LCAs may not be written with the assumption that the results will be communicated to, and used for interpretation by designers, which can further complicate the process. The way in which recycling loops are currently reported, modelled, identified, and solved in LCAs of circular economy systems can strongly differ between studies, see section 4.5 'Combined literature Discussion and conclusion: State of the art literature review CE-LCAs'. There is often little clarity around the choices made regarding the supporting ecoinvent database. Even though most LCAs provide a conclusion, the impact of the different assumptions made during the LCA considering recycling is not always clear nor mentioned. It is important for a designer to have good understanding what they have to keep in mind if certain modelling choices are made within the LCAs. This communication could influence their interpretation. The conclusion of the LCA should be communicated by LCA practitioners to designers conditionally: If X then, keep in mind that Y, also referred to as the 'what ifs.

There is a lack of transparency in existing LCA reports regarding recycling, with important considerations for the outcome of the assessments often left unclear: Recycling is not always modelled as loops in LCAs. No multifunctionality identification takes place in LCAs that contain recycling with a CE mindset, even though multifunctionality does occur. Solving of multifunctionality occurs through partitioning and substitution principles mostly. Moreover, there is almost no mention of selection of ecoinvent system models, only articles specifically focussing on multifunctionality within LCA show insight that different system models might influence results of an LCA.

As mentioned in chapter 2.3 'Circular Economy and Circular Product Design' it is important for designers to understand the different assumptions made in LCA context, and how they can influence the LCA results they are using. Practitioners should communicate the conclusion of the LCA to designers conditionally, stating that certain considerations should be kept in mind depending on the modelling choices regarding recycling made. The literature review shows that there is a need for greater transparency and standardization in LCA reporting to better inform decision-making processes.

In this section, the second sub question is answered:

'*How can LCA recycling modelling assumptions and related results be best communicated to product designers in order to create proper understanding of these assumptions and results?'*

In the rest of this chapter a tool to assess and improve transparency of LCAs is given: The 'LCA Transparency wheel' tool. The tool is explained, drafted and tested and evaluated.

5.1 “LCA TRANSPARENCY WHEEL” TOOL: GOAL AND APPLICATION

To improve the communication of LCA results, the key considerations underlying of different results should be reported to ensure the transparency of the LCA. The literature should report conditionally on the outcome and the factors on which the outcome depends. The lack of transparency and clarity in reporting the parameters regarding recycling on which the LCA outcome depends make it difficult for non-experts to comprehend the conclusion. To ease the reporting for LCA practitioners, in order to be clearer about the assumptions the conclusion depends on for designers, the LCA transparency wheel tool is suggested.

The tool is primarily for LCA practitioners, so they can improve the transparency of their LCA report regarding the choices made considering the ‘key considerations’, so the communication of the conclusions of the LCAs can be made more transparent. LCA practitioners can also use the tool to assess the transparency of LCA reports that are made by other LCA practitioners, however this limits the ability to adjust the transparency after the assessment of the transparency. The improved LCA conclusions is for designers, using the LCA conclusions, which could influence their decision making.

Resulting from the literature review in chapter 4 the ‘key considerations’ in LCA transparency regarding recycling are identified and the underlying assumptions behind these parameters are explained. When given more explanation of the choices taken behind these key considerations, the designer should be able to create proper understanding of which modelling assumptions regarding recycling are key for considering in a design by reading the conclusion of the LCA and how the related LCA results could be translated in the design.

Secondly, the tool could also be used by designers, who have enough LCA expertise to understand the complex context decisions made in the LCA background, to assess the transparency of the LCA they want to use.

The main expertise for understanding the modelling choices and transparency is not with the designers, but with the LCA practitioners. It is the responsibility of the LCA practitioners to report their LCA results as transparent as possible in order to make the results usable, in this case for designers. However, if aware of the importance of the key considerations made within an LCA study and comprehending the LCA method enough to do so, a designer could take some steps to check the transparency of the LCA themselves.

As the ISO steps do not cover the influence of choices made regarding recycling in the CE, the extra transparency check with the LCA transparency wheel is proposed. Together with following ISO, using the ‘LCA transparency wheel’ tool is suggested for LCA practitioners. This is in order to guide the LCA practitioners with what criteria the LCA report should meet, in order for the results to be usable by designers.

The conclusion of an LCA is always uncertain, as the conclusion is mostly: … It depends. For designers using these outcomes it is important to know what the outcome depends on, so they can deal with these uncertainties. What are the key considerations in the LCA conclusions? And are these considerations understandable when making design decisions for the design of a product existing in a system model. When being aware of this, designers can ask themselves the question: What do the results depend on and what can I do with this knowledge?

The outcome of an LCA is not necessarily right or wrong, but the LCA context is important to communicate. In order to comprehend the modelling and allocation choices, a high level of transparency is needed.

In the literature review in chapter 4 it is found that 7 different parameters influence the interpretation and the outcome of LCAs that include recycling in a CE context. If the parameters are transparently reported, designers using the LCA can more easily assess the applicability of the LCA outcome for their goal and understand its dependency.

These 7 identified key considerations are:

1. Modelling of the flow diagram
2. Identification of multifunctionality (MF)
3. Way of solving of the multifunctionality
4. Background database use
5. The modelling of recycling (dataset and number of recycling processes)
6. Type of loop recycling
7. Reduction in virgin material inputs

The 'LCA Transparency wheel' is a novel tool that LCA practitioners can use to improve the transparency of their reports. By structuring the reporting of the LCA study using this tool, designers can have access to results, that are accessible and useable and of which they understand the key considerations. This could lead to a reduction in the environmental impacts of designs, as designers can better understand the results and make informed decisions.

The way the LCA practitioners could communicate the transparency of their LCA better is by providing a section or perhaps an extra ISO step to complete: the ‘LCA transparency wheel’ tool. This step could be implemented when assessing a system model in which the assumptions regarding the recycling process on the subjects multifunctionality, allocation, data selection and the modelling of recycling loops are influencing the results. When LCA practitioners report these choices clearly, people using the LCA can easily get an overall overview on these perspectives and thus understand the parameters that influence the outcome.

It is very important to realise that the ‘transparency wheel’ does not test the quality of the LCA itself, merely the transparency. Having a low transparency doesn’t mean the outcome of the LCA is not correct, it is only harder to validate the outcome and be aware of the assumptions behind the conclusion. The other way around, a very transparent LCA is not necessarily a good LCA. When the assumptions are made very clear, the assumptions could still be incorrect or build on faulty data. But by clearly communicating all key considerations to the designer, it helps them judge if the results are useful for them, themselves.

The preconditions to this tool are that LCA practitioners perform an LCA in order to improve or map expected environmental impacts to the best of their ability. At the same time it is assumed that designers are interested in substantiating their design decisions by referring to LCA results and already doing this. Basic LCA education for designers is thus a prerequisite in the further development of this tool. LCA practitioners and designers are referred to as individuals, could also be teams with the same expertise. Almost no interdisciplinary design-LCA teams are expected in the context of this tool. Another assumption is that most LCAs assessed with the tool, can still be adjusted to improve transparency. In paragraph 5.2 the first version of the ‘LCA transparency wheel’ tool is explained.

5.2 'LCA TRANSPARENCY WHEEL' TOOL: DRAFT

The goal of the tool is to help assessing what the different modelling choices and reporting choices regarding recycling mean for the conclusion of the LCA used by designers. The tool guides the reporting of the key considerations of an LCA study done by LCA practitioners.

The LCA practitioner should maintain a consistent and transparent recycling-allocation perspective throughout the entire LCA study. By doing so, the assumptions made can be easily translated to those who use the outcome of the LCA, allowing the users of the LCA conclusion to recognize which key considerations the results depend on and should be considered when making design decisions. The LCA reports checked with the 'transparency wheel' should be transparent and clear enough to have results that are usable in in any step in the basic design cycle (Figure 11) according to Roozenburg & Eekels (1995) in the event that designers require guidance on uncertain environmental impact issues.

The LCA practitioner should follow the four steps of the tool to evaluate and improve the transparency of the LCA as shown in Figure 14:

1. Score transparency
2. Understand missing transparency through interpretation tab in the electronic appendix
3. Check if key considerations in the LCA study are compliant with the system model under study, and what possible influences of key considerations are.
4. If missing, clearly report the (missing) key considerations important to know when using the results of this study.

The tool exists of a visual representation (Figure 13) and an accompanying excel sheet, with in depth explanation of the definitions used in the visual. This excel sheet can been found in digital appendix 'Appendix B: LCA Transparency wheel'. The current shape of the tool is inspired by the 'Doughnut Economy' model (Raworth, 2017), but no research is done if another shape would be more fitting.

In the following sections, the actions for each step of the tool are explained into detail, in order to better understand what the steps entail.

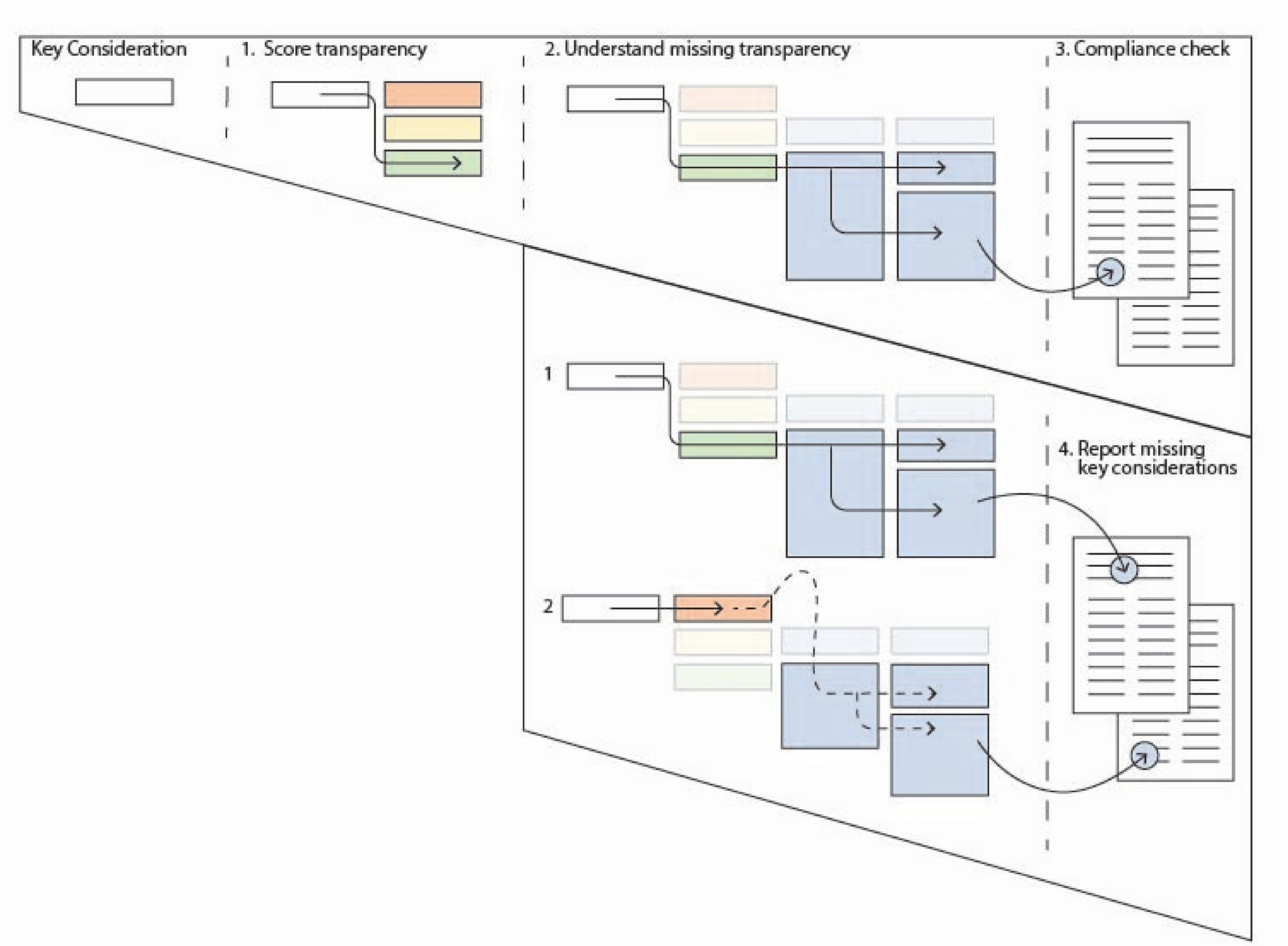


FIGURE 14: FLOWCHART: STEPS WHEN USING THE TRANSPARENCY WHEEL TOOL

5.1.2 STEP 1: SCORE TRANSPARENCY

When an LCA practitioner wants to assess the transparency of the LCA they are reporting considering the recycling assumptions the LCA builds on, in a visual way, one can assess the model in different wedges of a circle. The order of assessing the wedges does not matter, but clockwise is most logical as the different themes of key considerations are following each other (Figure 14).

All the wedges show three levels of transparency: not transparent (red) – medium transparent (orange) – transparent (green). The individual wedges show, how transparent the study is considered on that specific key consideration (Figure 13).

Below, the three transparency levels are explained for each key consideration:

1. **Modelling of the flow diagram**
- *Not transparent*: No flow diagram is given
- *Medium transparent*: A flow diagram is given, but it is missing a distinction between different unit processes and is not displaying clear flows between processes
- *Transparent:* A flow diagram is given and it included a distinction between different unit processes and flows from one unit process to another.

2. **Identification of multifunctionality (MF)**
- *Not transparent:* Multifunctionality is not mentioned at all
- *Medium transparent:* The process(es) for which multifunctionality should be solved are mentioned, but no argumentation why these processes are multifunctional is given.
- *Transparent:* Multifunctionality is identified and argumentation why the process(es) are multifunctional is given.

3. **Way of solving of the multifunctionality**
- *Not transparent:* the multifunctionality is not solved
- *Medium transparent:* the multifunctionality is solved, but the exact mention how is missing. The argumentation for the choice of solving multifunctionality is also lacking.
- *Transparent:* The way multifunctionality is solved is mentioned and argumentation why this choice is made is given. Two possible options for ways of solving multifunctionality are also in this level of the pie displayed.

4. **Background database use**
- *Not transparent:* it is unclear which database is used for background data
- *Medium transparent:* The database used, ecoinvent or another, or the specific mention of not using a database is given. Insight in pre-allocation of specifically the ecoinvent database, or missing insight in possible database influences is missing in the report.
- *Transparent:* The usage of the ecoinvent database (or different) is specified and insight of the pre-allocation and its possible influences and selection of system model is given and reasoned.

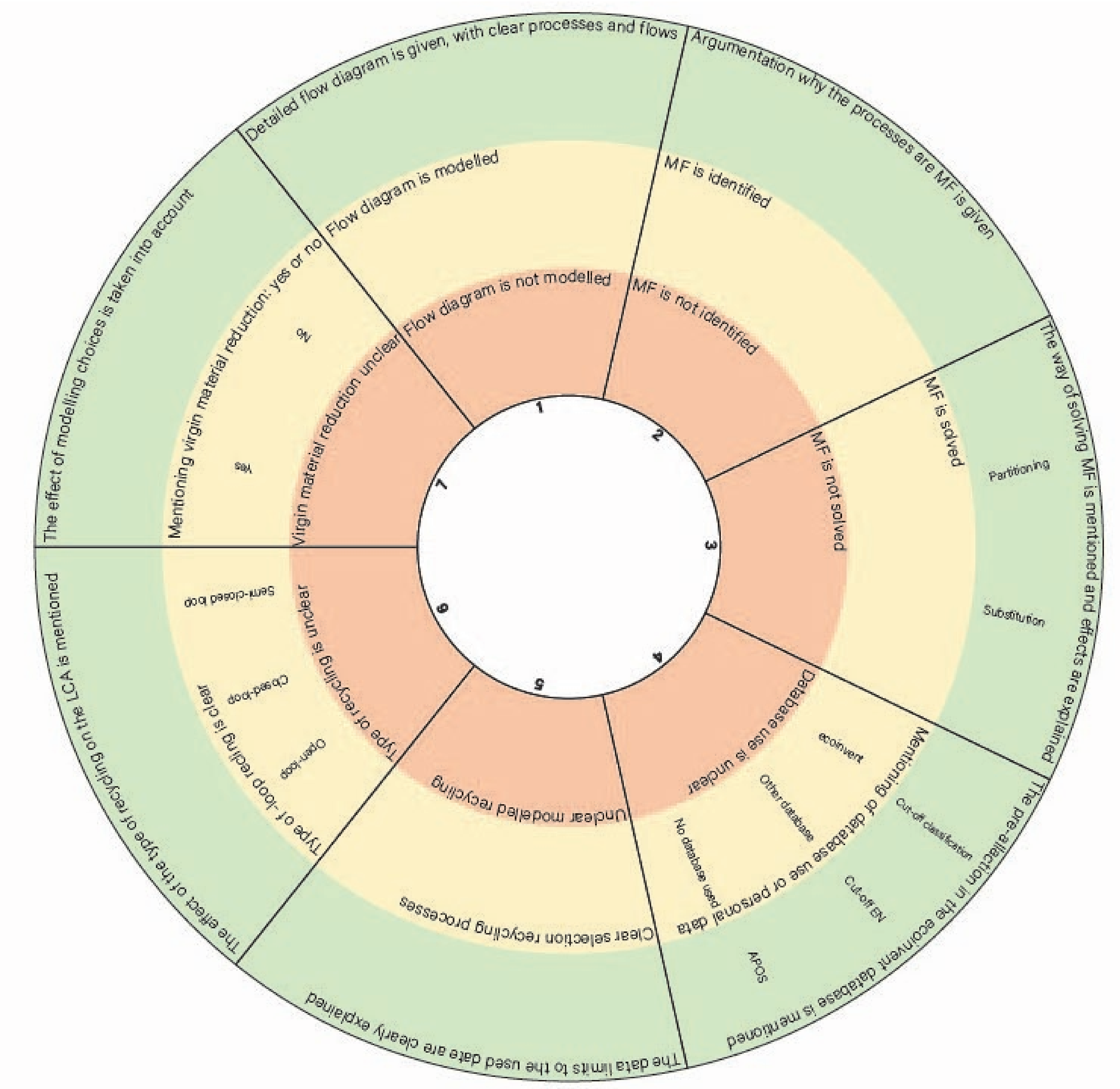
5. **The modelling of recycling (dataset and number of recycling processes)**
- *Not transparent:* It is unclear which recycling processes are modelled within the system model under study.
- *Medium transparent:* It is mentioned which datasets are selected for the modelling of recycling or if the recycling process is created from data that is not retrieved from a dataset. What is missing is an explanation of the data limits to using the selected data.
- *Transparent:* It is mentioned which datasets are selected for the modelling of recycling or if the recycling process is created from data that is not retrieved from a dataset. The report also includes an explanation of the data limits to using the selected data.

6. **Type of loop recycling**
- *Not transparent*: It is unclear what type of recycling is modelled.

- *Medium transparent*: Information is given what type of recycling is modelled: Open-loop, closed-loop or semi-closed loop. No insight of the possible effects this might have is given.
- *Transparent:* Information is given what type of recycling is modelled: Open-loop, closed-loop or semi-closed loop. The effect of this the type of recycling on the rest of the LCA outcome is mentioned.

7. Reduction in virgin material inputs

- *Not transparent:* It is unclear if reduction in virgin materials because of recycling is taken into account
- *Medium transparent:* It is mentioned if reduction of virgin materials due to recycling is taken into account or not. What is missing is the explanation and argumentation of the effect of this modelling choice.
- *Transparent:* It is mentioned if reduction of virgin materials due to recycling is taken into account or not, including the explanation and argumentation of the effect of this modelling choice.



Legend

1 - Modelling of the flow diagram

2 - Identification of multifunctionality

3 - Solving of the multifunctionality

4 - Background database use

5 - The modelling of recycling
(dataset and amount of recycling processes)

6 - Type of loop recycling

7 - Reduction in virgin material inputs are mentioned

FIGURE 15: THE TRANSPARENCY WHEEL

After assessing the transparency of the different key considerations, the scores corresponding to the level of transparency the LCA currently has, should be filled in in the digital appendix . When rated red (not transparent) the score is zero, rated orange (medium transparent) the score is 1 and when rated green (transparent) the score is two.

Key considerations	Scoring of transparency	Score
1. Modelling of the flow diagram	No, flow diagram is not modelled	0
In compliance with designed product system?	Yes, flow diagram is modelled	1
	A very detailed flow diagram is given, with clear processes and flows	2
		1

FIGURE 16: DETAILED PREVIEW OF EXCEL FILE CONTAINING TRANSPARENCY WHEEL SCORING

The tab B2 in the excel can be used to score the LCA on transparency: 0 – not transparent, 1- medium transparent and 2 – transparent. The total LCA transparency score also shows the transparency level: Not transparent 0-5, medium transparent 5-10 and transparent 10-14. 14 means perfect transparency in the determined set of key considerations. Currently, there is no hierarchy in the order of parameters assessed, and all key considerations weigh equal in calculating the overall transparency score. The score form (Figure 16) can be used in order to see where the LCA is lacking transparency and if there is room for improvement of transparency of the LCA reporting regarding recycling modelling choices and assumptions.

The score of all separate parameters is summed. When having finished this scoring for all seven key considerations, currently a radar diagram is given as an overview outcome in the digital appendix. With further development of the tool, this radar diagram should be translated to the more visual representation of the wheel automatically. This transformation should thus happen without the manual transformation, that is currently done (Figure 17).

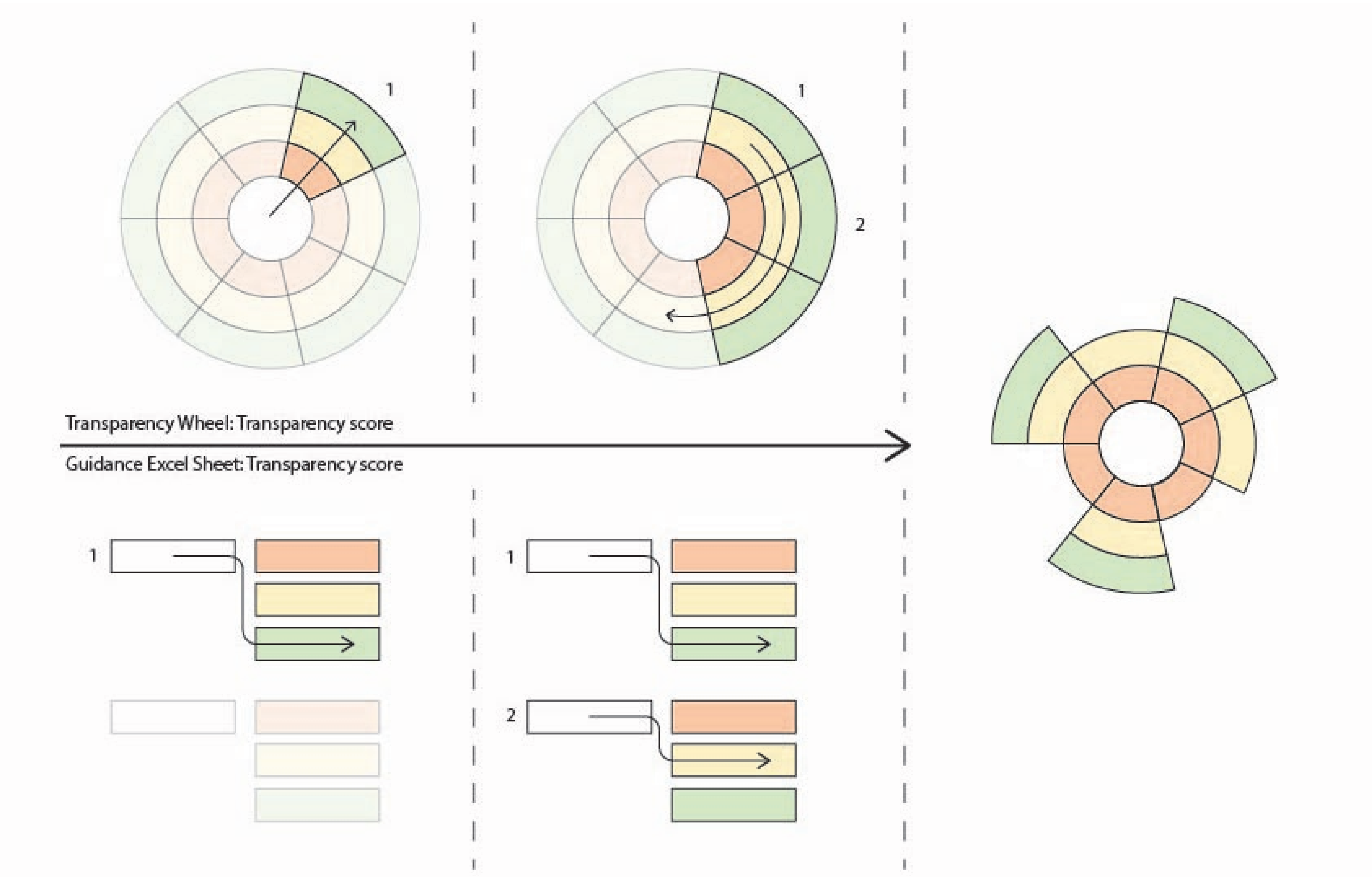


FIGURE 17: COMPARISON TRANSPARENCY TOOL: VISUAL WHEEL AND RADAR DIAGRAM

The transparency wheel shows on which parameters the LCA is very transparent and on which parameters a lack of transparency is found. No certain number of green wedges is required, but it is preferred to have an as transparent report (green pie) as possible.

5.1.3 Step 2: Interpreting transparency

Based on the knowledge after step 1, the LCA practitioner should use the interpretation table (Appendix B1) in cases where the assessed life cycle assessment (LCA) lacks transparency. The table serves as a guidance sheet for identifying possible corresponding underlying assumptions that are linked to the choices made with regard to the key considerations (Figure 18).

The detailed table (appendix B1) is an assessment form that helps fill in the scoring and offers valuable information for the LCA practitioner to include in the report, so the designer knows what influences key considerations made by the LCA practitioner have on the conclusion. The insights from the table can be used to understand the possible LCA context influences that are within the LCA. Even when modelling decisions are untransparent, the tool helps to create understanding of the possible underlying assumptions of LCA results, after the report is finalized.

This table should be used as a reference table as basis for possible communication of take-aways resulting from decisions taken considering the seven parameters. The interpretation table works as follows (Figure 18):

Column A: Shows the 7 key considerations.

- E.g., Key consideration 4: Background database use

Column B: Shows the different levels of transparency: Not transparent, medium transparent and transparent.

- E.g., it is selected if it is unclear which database is used, clear or even mentioned which system model with pre-allocation from the ecoinvent database is selected.

Column C-D: Shows the modelling decision + take-away message, related to the adjacent transparency level in column B. The LCA practitioner could also look at these columns to understand what assumption could lie behind key considerations, even if the reporting is not transparent, and then include relevant missing information in the improved version of the LCA reporting.

- E.g., the different possibilities of pre-allocation in the ecoinvent database are mentioned and specified and the important information to keep in mind is given in the rows next to the 'transparent' B column. The rows have the different underlying assumptions to keep in mind corresponding to the key consideration made, or to get an understanding what the different underlying assumption of choices that are not transparently reported, could be.

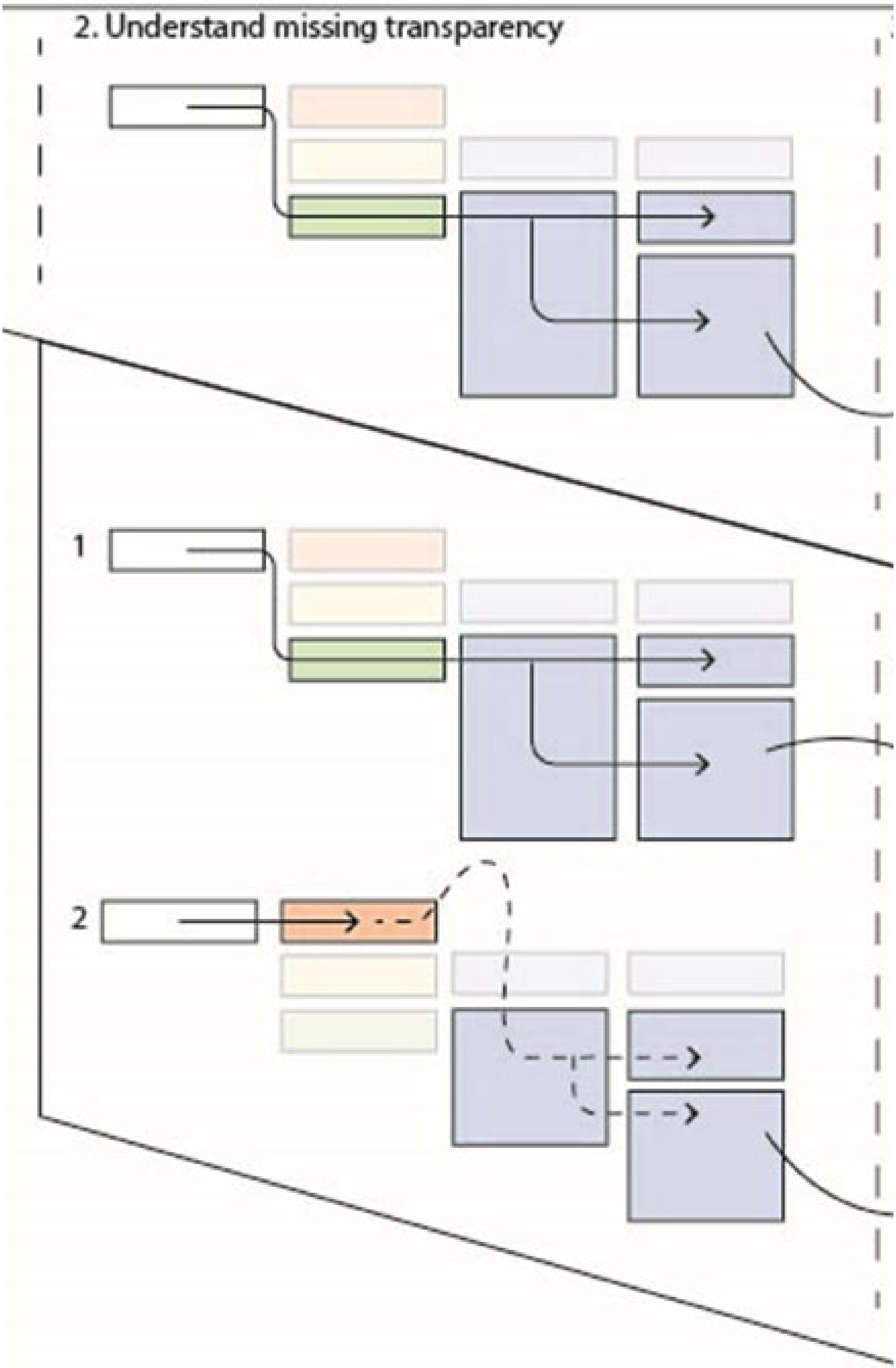


FIGURE 18: STEP 2, UNDERSTAND THE MISSING TRANSPARENCY

4. Background database use	It is unclear if or which database is used.		
In compliance with designed product system?	Ecoinvent data base is used	Be aware the pre allocation that might occur in the background	
	A different database is used	Impacts from the pre-allocation in other database are not within the scope of this framework, but should be kept in mind by the designer	
	Researched data is used, not retrieved from a LCA database	Own personal data is less transparent, but pre-allocation in the background rarely occurs.	
	The pre-allocation in the ecoinvent database is mentioned and specified	Cut-off by classification	In the background data multifunctionality is solved through partitioning. Materials that can be recycled are available burden free: The impact of recycled materials is only from the impacts of the recycling process, and not from the production of the material beforehand. The cut-off is at the end of waste treatment. Waste impact is allocated to the producer of waste so it makes sense to use this assumption te rest of the LCA too.
		Cut-off EN	In the background data multifunctionality is solved through partitioning. Impact is allocated to the first system up to when a product has a market value and fulfils legal requirements. After the materials is not waste anymore (the legal 'end-of-waste-state'), the impact belongs to the secondary system This system model also provides all Life Cycle Inventory (LCI) indicators required in Environmental Product Declarations. The EN 15804 standard provides the structure for making three different types of EPDs.
		APOS	In the background data multifunctionality is solved through partitioning. The allocation is between the producers and users benefiting from that process. Exchanges of producing activities and treatment activities are allocated to all valuable by-products.

FIGURE 19: EXAMPLE OF WEDGE TRANSPARENCY WHEEL IN TABLE FORM

5.1.4 Step 3: Compliance with system model under study

The next step for the LCA practitioner involves assessing the alignment of decisions made in the LCA with those made in the system model. This analysis aims to identify similarities and differences between the assumptions made in both the LCA and system design under study. The results of this evaluation can highlight the key considerations that impact the LCA outcomes, and the LCA practitioner should check if the reported assumptions are similar to actual assumptions in the study (Figure 20). For example, an LCA practitioner could become aware that for key consideration 6 'Type of loop recycling', closed-loop recycling is used as modelling choice. By using the corresponding excel sheet of the tool, the LCA practitioner is then aware that the assumption behind this key consideration is different than with open-loop or semi-closed loop recycling.

Reading the information considering the key considerations in the excel helps identifying what the outcome of the LCA depends on. The LCA practitioner should examine the assumptions made in the LCA and in the system design under study to identify any discrepancies. E.g., if the LCA practitioner realizes through the key considerations that even though currently modelled as a closed-loop recycling process, in reality this recycling is actually open-loop, this modelling choice could either be changed or it could be reported on transparently what the modelling choice implies, but how it differs from reality. This information gap analysis is useful when providing LCA conclusions and requires transparent reporting to facilitate designers' understanding of the LCA study, as mentioned in chapter 2.3.

Transparent reporting of these considerations enables designers to make more informed and environmentally sustainable decisions. This is either to confirm their expectations or guide decision making when in doubt. By understanding the uncertainties underpinning the LCA conclusion, designers can better address any potential gaps in the information presented. E.g., the designer using the LCA conclusion can then keep in mind that the LCA conclusion is made for a system model that assumes closed-loop recycling, and if that is not a design choice that is possible in reality, the LCA conclusion might be less applicable for their purpose and this dependency should be kept in mind.

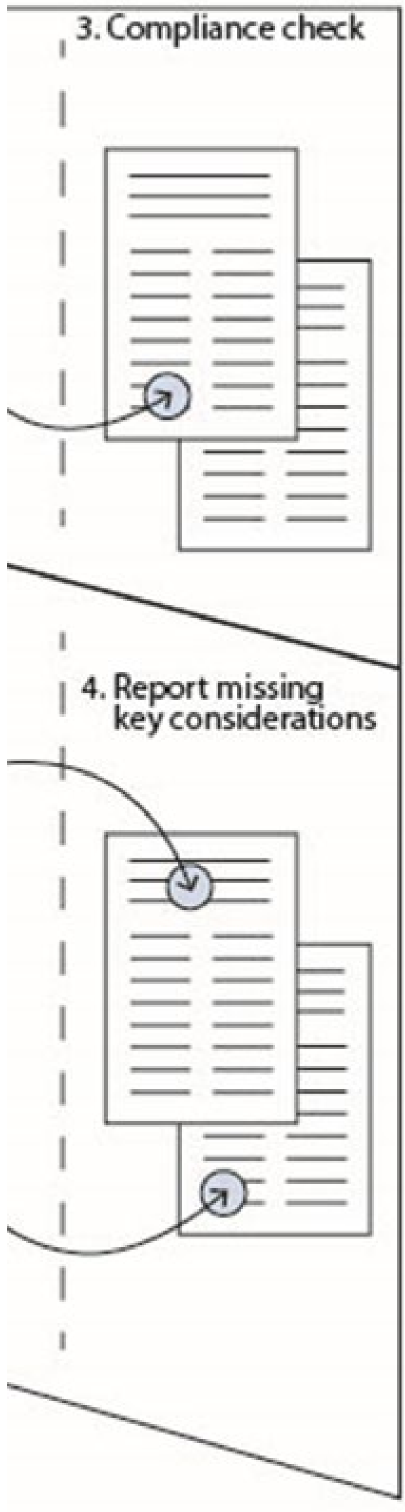


FIGURE 20: STEP 3 AND 4 OF THE 'LCA TRANSPARENCY WHEEL' TOOL

5.1.5 Step 4: Report clearly

After assessing the transparency of the key considerations of the LCA, it is time improve the lack of transparency.

In an LCA conclusion it should be clear 'what ifs' the LCA builds on, as these can have a significant impact on the validity and usefulness of the results. If these influences are not clearly reported, it is the responsibility of the LCA practitioner to take these learnings into account and improve the reporting of the LCA (Figure 20). The reported conclusion of the LCA, including the what ifs, can be used in design development. Hopefully, using the tool gives the

LCA practitioner insight in the transparency of the own LCA study because inconsistencies in reasoning are highlighted more. Resulting from this the transparency of the LCA conclusion should be improved.

When assessing the transparency of already published reports, in case of missing transparency, it is important to be aware that even though not mentioned, key considerations in the LCA context might influence the conclusion of the LCA results. The LCA practitioner assessing this report can search for answers within the report or request more information with the reporter of the LCA study. This is time-consuming, so the LCA practitioner could also keep in mind the possible underlying assumptions, and be aware of this when using the results for further research or reporting.

It is important that when the designer is using the conclusion of the LCA, the information reported in an LCA conclusion is used as a take away message from LCA practitioners to designers. The assumptions and parameters used in the conclusion of the LCA should be clear and the designer using LCA results should take these assumptions into consideration. A designer should be aware that the LCA outcome depends on a certain LCA context. When using the results, the designer should thus also be aware that the context of the design should be similar to the LCA context and it is possible to achieve this context in reality. E.g., If in the LCA closed-loop recycling is modelled, the designer should keep in mind the results are more best applicable for products that are closed-loop recycled too, and less applicable if the design has the possibility of closed-loop recycling while in reality this infrastructure is not in place for the product that is designed (yet). While designers do not have to follow the assumptions of the LCA in their design, it is important that they are aware of these assumptions and can judge for themselves whether they influence the usability of the results.

It is important to judge if it is needed for designers to fill certain information gaps by researching into the topic some more, until they feel they have enough information to deal with the uncertainties considering their design choices. It could even be needed that a different LCA study is needed for the designer in order to get more transparent or compliant results depending on the intended application purpose of the LCA results for the design. It could also be possible for the designer to judge that the LCA serves the intended purpose as it is in its current form and keep the transparently reported take-aways in mind for further development. A draft flowchart is given to illustrate the decisions a designer could make depending on the goal they use the LCA results for (Figure 19). It is recommended to further study and develop such a decision flowchart for designers using LCA. This more developed flowchart should be more quantitative than qualitative, as currently it is not clear when transparency is 'negligible'. E.g., it could be said the transparency is negligible if the transparency score is at least 10 out of 14, but this requires further research.

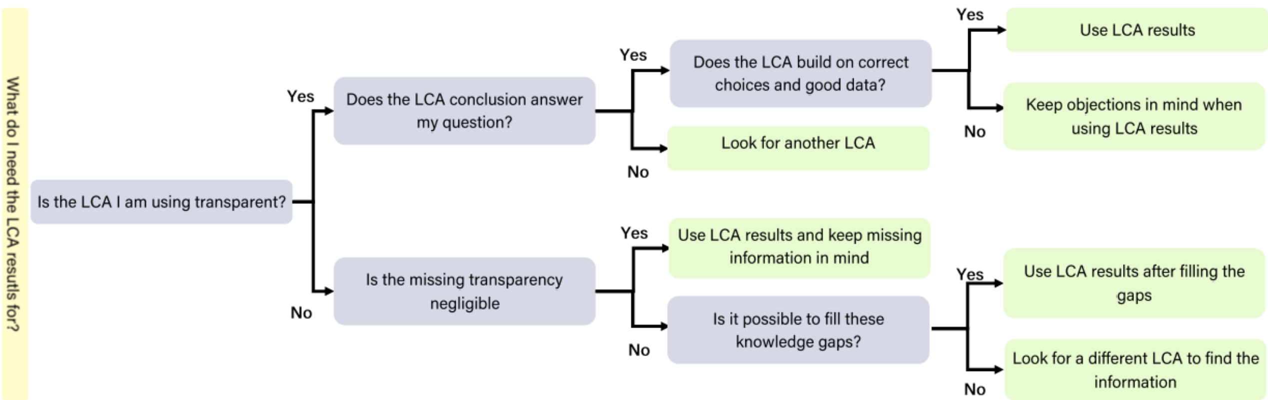


FIGURE 21: FLOWCHART FOR DESIGNERS ABOUT USEFULNESS LCA

5.3 “LCA TRANSPARENCY WHEEL” TOOL: EVALUATION

The present study evaluates the first version of the tool the 'LCA transparency wheel' and investigates potential gaps and improvements for the tool by examining five LCA studies included in the literature review (see Table 11 and Figure 22). The elaborate analysis of these studies using the ‘LCA transparency wheel’ tool can be found in ‘Appendix 4: Testing the transparency wheel’ and in electronic Appendix B2-7, the reasoning for the exact scoring is given. It should be noted that the transparency of these papers has been evaluated by an LCA expert who is well-versed with the LCA methodology. However, future research should consider testing the tool with individuals of varying LCA expertise. It is also worth noting that the LCA studies used for assessment were conducted independently without any design team involvement or known design perspective. Nevertheless, these studies were evaluated based on their transparency regarding recycling modeling decisions and reporting and how they can be improved to provide more useful results for designers.

TABLE 11: ARTICLES USED TO EVALUATE TRANSPARENCY WHEEL METHOD

Articles used for evaluation	Transparency score
(Kouloumpis et al., 2020)	*11 - transparent*
(Monteiro et al., 2022)	*4 – not transparent*
(Galve et al., 2022)	*5 – medium transparent*
(Kooduvalli et al., 2020)	*5 – medium transparent*
(Stotz et al., 2017)	*8 – medium transparent*

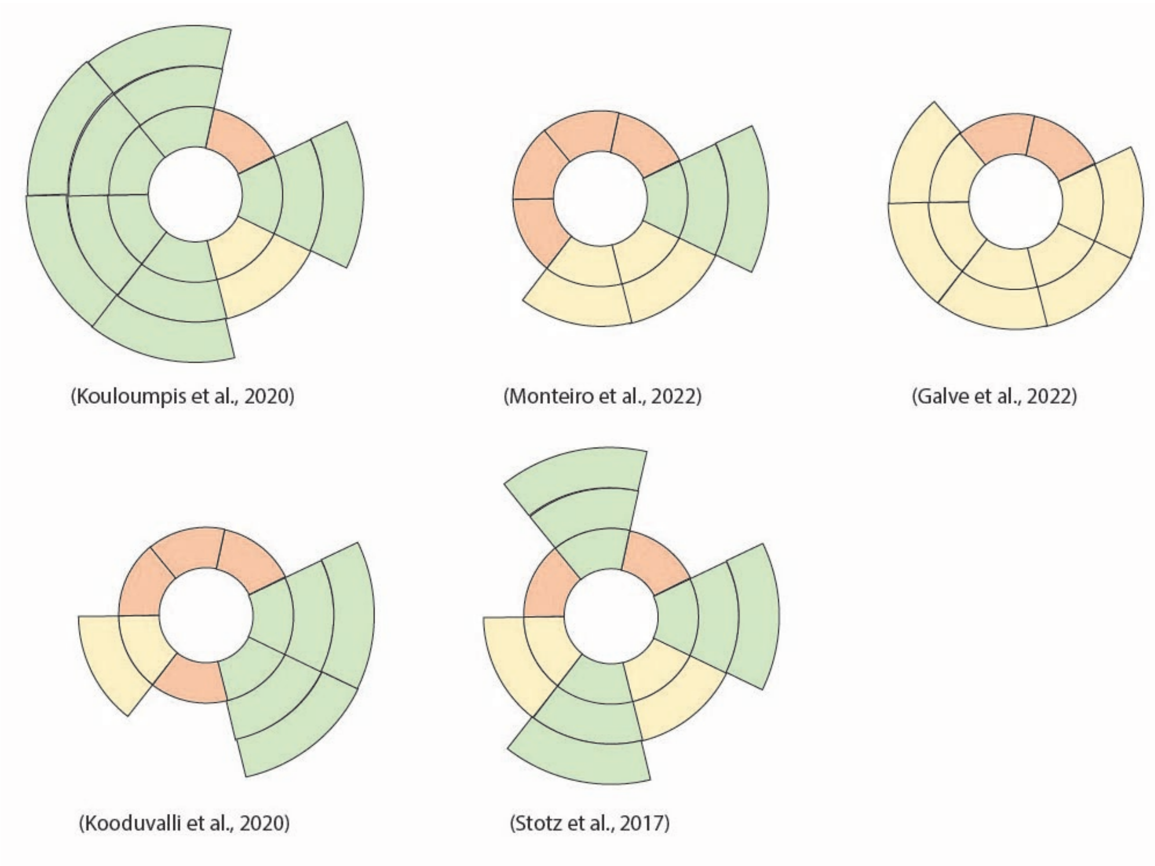


FIGURE 22: ARTICLES EVALUATION, TEST TOOL

After testing the tool with the five articles, it was observed that the tool has potential to be an effective tool for analyzing and identifying recycling related areas where transparency is lacking in an LCA study. This can be particularly beneficial for LCA practitioners to use in order to evaluate their own transparency and assumptions, and ultimately improve LCA reporting for the purpose of generating useful results for designers.

Moreover, the tool can also be useful for designers who possess an advanced understanding of LCA, as it can assist in identifying information gaps related to assumptions and modeling choices. This enables designers to approach the reporting of an LCA in a more critical manner, and determine whether the outcomes of the study can be applied to their own product design or if additional information is needed to account for assumptions made in the LCA. The tool also aids designers in considering potential modeling influences, allowing them to determine if any lacking information is negligible and if the study outcome is still suitable for their design.

However, it should be noted that the primary responsibility for transparent reporting about the key parameters lies with the LCA practitioners, and for designers with LCA expertise the tool may only serve as a secondary check, if desired. For designers without such expertise, additional detailed information about how to spot multifunctionality and clear communication of different effects that different ways of solving multifunctionality have, may be helpful.

In this chapter, two key insights regarding the future development of the tool specific are discussed. Additional considerations are presented in chapter '6 Discussion and limitations '.

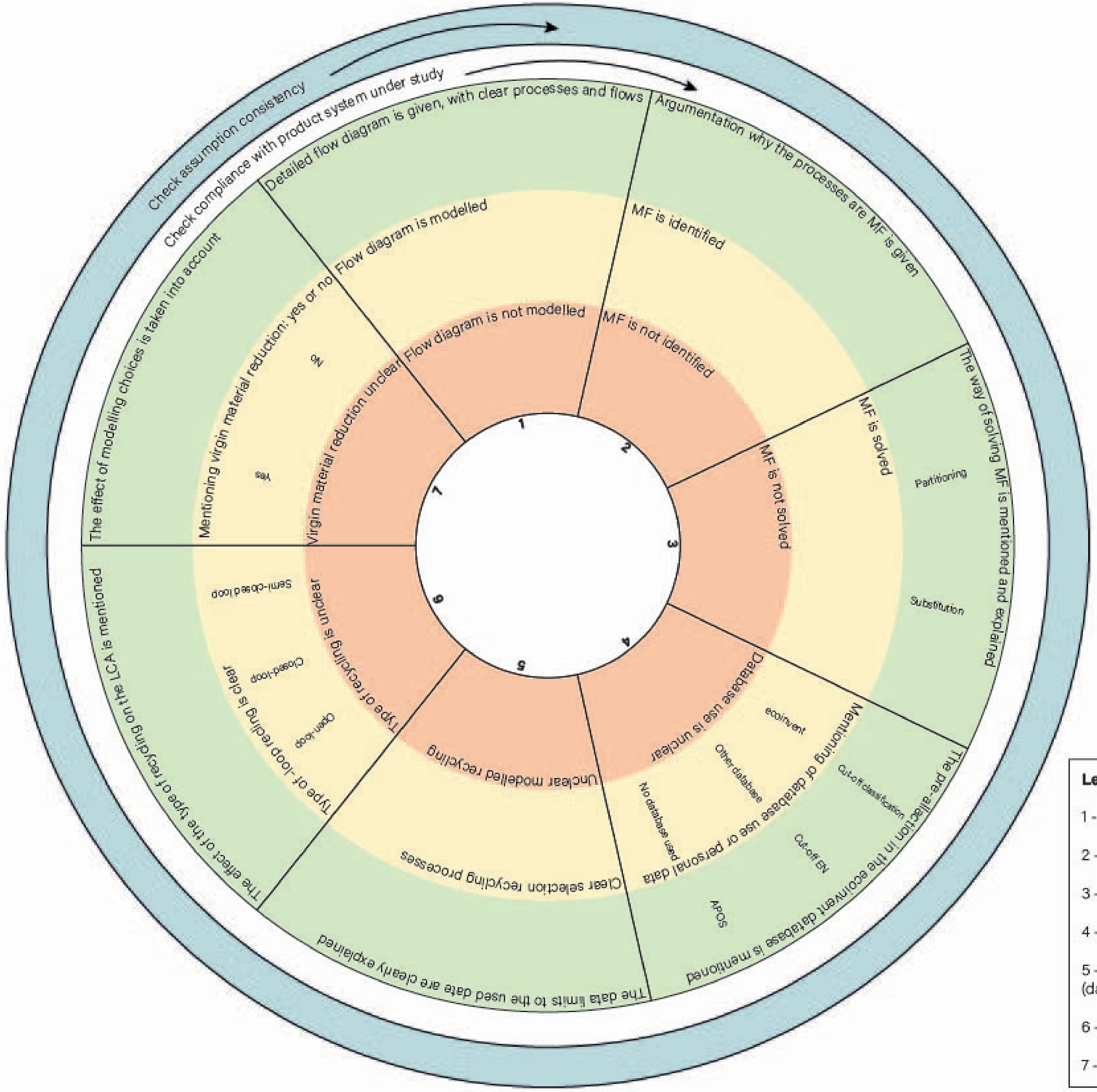
At first it should be considered if the transparency score in itself (e.g. 5 out of 14 possible) says enough about the transparency of the report regarding recycling the key considerations. Is there a difference if an article scores 5 because it scores two times 2, onetime 1 and 0 in the other categories, compared to an article scoring 1 in 5 separate parameter categories. In other words: Is there a difference in transparency when literature is medium transparent in all categories compared to an article being completely transparent in a few categories, and not at all transparent in the other. The transparency wheel provides a visual representation of the different transparency levels for different wedges, but the transparency score itself does not reflect this variation (Table 11 and Figure 22). Therefore, the transparency score should be reevaluated. Filling in the wheel as in Figure 17 would immediately show where transparency fails for the evaluated LCA study.

For the visual display and the scoring, in the further development of the tool, the possibility of a hierarchy of transparency parameters should be explored: are some parameters more important to be transparent on than other parameters? If in further development of the tool, this seems relevant to implement, extra development on the scoring of transparency should be done.

Testing the tool also shows that the LCA articles that are assessed through the transparency wheel, differ on how they model recycled material and recyclable material, and thus how the multifunctionality is solved. Multifunctionality could be solved for the use of recycled materials by e.g., using the cut-off approach for recycled material use. However, multifunctionality may not be solved or may be approached differently at the end-of-life phase in the same LCA. Hence, for future development, both could be developed as different key considerations, and thus different wedges, in future development of the tool. The tool should then also include a step during which the consistency in multifunctionality solving in use of recyclable material versus producing recyclable material is checked. Are similar and consistent assumptions made in all places of the circular system?

One potential approach for integrating this aspect into the tool involves the addition of an additional ring/step surrounding the individual wedges that contain key considerations. This ring/step could be dedicated to comparing the impacts of various parameters to one another, with a particular emphasis on identifying noteworthy combinations: such as the impact that energy recovery might have (allocation parameter), and how this differs when a different process location is selected (data selection) and visualisation of these situations in diagrams might be confusing. It might be the case that it seems that energy recovery in areas where more fossil fuels are used as energy source, is more effectful than in areas where renewable energy is the main energy source, when the impact of energy recovery is actually be the same.

To ensure that all relevant steps are incorporated into the tool when using the visual wheel version as a guide, it is necessary to add an additional ring focused on assessing the consistency of the LCA study with the system model under study too (Step 3). This step should not only be the check-box in the excel document, as it currently is, but should also be integrated in the visual transparency wheel. An example of a potential future development of the transparency wheel can be seen in Figure 23, which represents a first iteration of the transparency wheel method.



Legend

1 - Modelling of the flow diagram

2 - Identification of multifunctionality

3 - Solving of the multifunctionality

4 - Background database use

5 - The modelling of recycling
(dataset and amount of recycling processes)

6 - Type of loop recycling

7 - Reduction in virgin material inputs are mentioned

FIGURE 23: LCA TRANSPARENCY WHEEL TOOL - ITERATION

5.4 'LCA TRANSPARENCY WHEEL' TOOL: APPLICATION, IMPLEMENTATION AND RECOMMENDATIONS

To answer the second sub question: '*How can LCA recycling modelling assumptions and related results be best communicated to product designers in order to create a proper understanding of these assumptions and results?'* the 'LCA transparency wheel' tool is developed.

In conclusion, the 'LCA transparency wheel' helps LCA practitioners for enhancing the transparent communication of the results delivered by the LCA method and assessing the transparency of an LCA study performed. LCA practitioners can use the 'LCA transparency wheel' scoring to evaluate the transparency of their own LCA studies, by identifying areas where transparency regarding recycling can be improved or conclusions need further development.

The LCA transparency wheel helps designers, as it makes LCA practitioners more informed about the goals of designers for LCA and the necessity of transparent reporting and which criteria an LCA has to meet in order to be useful for designers. Combined with this, designers should integrate using LCA results into their standard design process. In this way the LCA expertise and the design expertise can develop both parallel and hand-in-hand. When aiming to make more environmentally sustainable design decisions, LCA conclusions should be used by designers. This study assumes an ongoing trend of LCA integration into design practice, which the LCA transparency wheel can help to further enable. By using the transparency tool on top of the LCA study outcomes, the assumptions taken can easily be translated to the designer using the outcome of the LCA and realising which key considerations the outcome of the LCA depends on and should be kept into mind when making design decisions.

The way the LCA practitioners could communicate the transparency of their LCA better by providing a section or perhaps an extra ISO step to complete; the 'LCA transparency wheel'. This step could be implemented when assessing a system model with a CE-recycling focus including key considerations regarding the recycling process on the subjects multifunctionality, allocation, data selection and the modelling of recycling loops. When these choices are displayed clearly, people using the LCA can easily get an overall overview on these key considerations and thus understand the key considerations that influence their outcome. Increasing transparency and awareness of these considerations made in a study can also improve the quality of the LCA, but this is not researched within this report and development of the tool and is thus a research recommendation.

It is recommended to keep developing the 'LCA transparency wheel' tool and test the method with both designers as well as LCA practitioners. When testing it in practice, valuable new insights could be gained on how the tool can be developed in a way everything is understandable and clear for the ones using the tool. The user friendliness of the tool can be developed.

Additionally, it is important to raise awareness about the significance of transparency in LCA studies and the 'LCA Transparency Wheel' for increasing transparency in terms of assumptions made regarding the recycling process, like explained in section 1.2 'Problem definition & knowledge gap'. In this way, the whole LCA method can keep improving, when LCA practitioners report more for the usability of their results for designers. LCAs and its reporting transparency should be part of both design and LCA education, thereby creating a stronger connection between both areas of expertise.

Ultimately, the 'LCA Transparency Wheel' tool aims to facilitate communication between LCA practitioners and product designers, and can help ensure that recycling modelling assumptions and related results are properly understood.

6 DISCUSSION

Design decisions should be based on credible, transparent and reproducible assessments of environmental impacts, and not on assumptions. While the CE concept, when implemented in practice by designing products, often leads to reductions in environmental impacts throughout product life cycles, this is not always the case. Therefore, it is relevant to understand how recycling loops are modelled and reported in LCA studies addressing circular economy systems and in the most widely used LCA database ecoinvent; and how reporting can be improved to better and more transparently communicate conclusions of LCAs to product designers. Improving the reporting transparency in terms of recycling can improve the usability of the LCA conclusions for designers, because designers can be aware if the key considerations the conclusion depends on, are applicable for their design and can be kept in mind.

Since many databases and software programs used to perform LCAs, don't include ways and data to solve multifunctionality explicitly and transparently, it is generally unknown how current LCA practice handles multifunctionality in CE systems and which underlying assumptions are included in the analysis performed. It is important that multifunctionality in CE systems is modelled, identified and solved explicitly and transparently. This is important, because if untransparent assessments are used as a basis for decision-making in product innovations or regulations, decisions could be made on distorted information. This is possibly leading to different effects than expected or desired and non-optimal circular strategies might be selected. Therefore, it is important that a systematic approach for solving and identifying multifunctionality within CE-LCA is used and that the influences different modelling decisions have, are transparently reported.

FOCUS OF STUDY

The primary objective of this study was to investigate the modelling and reporting of recycling loops in LCA studies that address CE systems, with a particular focus on the ecoinvent database. This report provides the results of a literature research on the status-quo of modelling and reporting in LCA studies that include recycling loops in the CE-context. The literature research follows the PRISMA-method.

This literature study specifically focuses on LCAs done on products and products systems that include the recycling of material back into the product system, in a CE context, the study is looking into the multifunctionality issues arising with recycling processes. The literature study also focuses on LCA studies using the ecoinvent database to research the way multifunctionality is currently handled. It is not ruled out that the research is also applicable to some other databases, but this is not analysed.

Following from the literature research seven key considerations/issues were identified for which different choices can be made during the modelling and reporting of those LCAs: modelling of the flow diagram, identification of multifunctionality, solving of the multifunctionality, background database use, modelling of recycling, type of loop recycling, and reduction in virgin material inputs. The lack of transparent reporting of these choices for these seven key considerations found in literature is used as a basis to develop a tool for LCA practitioners to improve transparent reporting for LCAs that include recycling loops, addressing CE systems: the 'LCA Transparency Wheel'.

In this report the focus is not on increasing overall transparency in LCAs, which is always relevant in itself, but this relevance is discussed in existing literature and the ISO standard already. The focus in this report is on transparent reporting regarding identification and solving of multifunctionality, background data base selection and modelling related to recycling. As the ISO guidelines already focus on overall reporting transparency but misses out on transparency regarding those key considerations about recycling modelling choices, a tool is created that aims to help LCA practitioners and designers.

By assessing and improving the reporting transparency of different modelling and reporting choices regarding recycling, the LCA conclusion made by the LCA practitioner is more usable for the designer. The reporting of the LCA conclusion should be written more with the use of non-LCA experts in mind. The conclusion should enable designers to check whether the results of studies are applicable to their (circular) product design and help them guide their design decisions.

While the 'LCA transparency wheel' tool appears promising, it remains to be seen whether it will work in practice. This chapter discusses the limitations of this report.

LIMITATIONS TO LITERATURE REVIEW.

- **Literature review scope:** To be able to understand the current status of LCA reporting, a literature review is done according to the PRISMA method. The whole literature review of 49 articles is done with the goal of getting a most complete overview about the modelling choices made in current LCA literature containing recycling with a CE perspective. Additionally, the study used search terms such as 'recycle', 'product', 'case study' and equivalents of 'LCA of' to scope the search towards the research focus of designed products that include recycling. The literature review conducted in this report focuses on LCAs with a CE perspective, and the data is limited to that found between September and December 2022. The focus of this study is on attributional LCAs. Review papers were excluded from the literature study, as the focus was on finding case studies. Using the same search terms, and including review articles, 5 additional articles are found, but these 5 do not meet the criteria set for the literature review, such as 'performs an attributional LCA' and 'includes an LCA on (design) product systems'.

  This scope was selected to make the amount of relevant literature to be found more manageable. However, it is important to consider that by using these search terms, possibly relevant articles may have been excluded from the search results. By broadening the scope and erasing the criteria: 'LCA on (design) product systems', more articles considering LCAs in the building environment can be found. Although these are current excluded due to the criteria setting, including this might result in interesting insights. A first scan already shows 15 of the excluded literature articles are LCAs done on circularity in the building industry and modularity of buildings. Buildings could be seen as large products, with a function as living or working, the recycling of the components and how this is done in LCAs could give interesting new insights on how transparency is reported in LCAs of which conclusions are used for building design and construction. At the same time, the LCAs on the building environment seem precursors on focussing on circular LCAs, as the methodological literature focussing on multifunctionality problems, mostly come from this sector. When making LCAs made for design product systems, lessons could be learned from the insights from LCAs for the built environment. Case studies with this scope could be more developed in terms of new allocation strategies and the reporting of it and this could be insightful to learn from in the product design environment.

  The current conclusion for the current scope is still applicable. The vast majority of the relevant literature for the current scope is still considered and this literature shows a lack of transparency in terms of recycling modelling decisions, background database use and identification of multifunctionality.

  It should be kept in mind that similar questions, issues, or new insights might arise when also including consequential LCAs in the literature review. The influence of the change of flows and the response to possible decisions in the system model under study, related to recycling decisions, would be an interesting future research perspective, but is currently considered out of scope in this study.

- **Insights literature review:** In the literature review it is found that when modelling for open-loop recycling, negative impacts might disappear with certain choices of modelling and solving multifunctionality. At the same time, benefits are double counted for LCAs that include the same recycling process, when this is in the LCA practitioner, and the research initiating stakeholder's, favour. Modelling and solving multifunctionality that gives environmental benefits to using recycled materials, but not the negative impacts of waste processing, leads to distorted conclusions and it should be discussed if certain 'rules' for achieving consistency among key consideration choices should be set in place.

The study presented a tool for improving the transparency and conditional communication of conclusions of LCA studies that incorporate recycling and a CE perspective. The goal of the tool is to help LCA practitioners best communicate LCA recycling modelling assumptions and related results to product designers in order to create a proper understanding of these assumptions and results. However, the current status of the tool has room for improvements. The current shape of the tool is inspired by the 'Doughnut Economy' model (Raworth, 2017), but no research is done if another shape would be more fitting, due to time limits.

LIMITATIONS TO TOOL.

- **Preconditions tool**: To start with, the preconditions to this tool are that LCA practitioners perform an LCA in order to improve or map expected environmental impacts to the best of their ability. At the same time it is assumed that designers are interested in substantiating their design decisions by referring to LCA results and already doing this. Basic LCA education for designers is thus a prerequisite in the further development of this tool. LCA practitioners and designers are referred to as individuals through the study, but could also be teams with the same expertise. Almost no interdisciplinary design-LCA teams are expected in the context of the development of this tool. Another assumption is that most LCAs assessed with the tool, can still be adjusted to improve transparency.

- **Testing the tool:** The tool is currently tested once and is tested with reports from the literature review. Testing with literature that is also used for the identification of the key considerations, the tool builds on, could lead to an self-fulling bias when assessing the tool on its applicability. This is because the gaps in this reporting transparency are clearly apparent in the literature review, and the tool points out the exact level of transparency on these seven key considerations. New insights considering other missing key considerations in terms of transparency, within the tool will be harder to find through this way of testing.

  It should also be noted that test of the tool: testing the transparency of 5 literature reports, has been evaluated by an LCA expert who is both well-versed with the LCA methodology and the one that came up with the tool. The test might thus be biased. As for now, it is unknown how other LCA practitioners that have a varying level of LCA expertise understand how to use this tool and what valuable insights they might have to improve the tool for applicability in the LCA-method.

  Currently, there has been no tests at all to see if improving the reporting transparency of dependency on the key considerations positively influences the communication of LCA conclusions to designers. A research limitation is the unclear and inconsistent connection between the LCA expertise and the design expertise. In this report assumptions are made regarding the cooperation and connection between both expertise. Although designers are somewhat educated about LCAs, they are rarely experts. The other way around, although LCA practitioners should be aware of the possibility conclusions being used as guidance in design decisions, this awareness is not always the case.

It is important to note that the LCA literature used for the test of the tool, taken from the literature review sample, were done independently, without a known (or reported) design perspective. However, the reports were still assessed on their transparency and how the reporting the conclusion and the dependency on the key considerations can be improved. If this analysis would be implemented on these LCAs, by the LCA practitioners who reported the LCAs, and the reporting transparency of the modelling decision regarding recycling become clearer, it is assumed that the improved conclusion leads to design decisions based on credible, transparent and reproducible assessments of environmental impacts, and not on assumptions. For LCA practitioners, the insights gained about an LCA by using the tool, creates awareness about the reporting quality of the current LCA, and for future LCAs they are making, they might be more aware of the dependencies within their own LCA as well and of how the reporting quality of their LCAs influences design decisions. It is important to recognize that confusion about LCA results is not only an issue for designers, but also for LCA practitioners who could take the first step towards displaying results more clearly.

- **LCA and Design interaction**: This study assumes an ongoing trend of LCA results integration into design practice, which the 'LCA transparency wheel' can help to further enable. The report assumes that designers have a basic understanding of LCA, assuming that relevant conclusions of LCAs can be used correctly by designers. However, this ability is probably not feasible for all designers, only for a small subset. A limitation is that designers might not even refer to LCA conclusions at all. LCA education for designers might lack in quantity and quality of the education to make them skilled enough to use LCA conclusions as guidance by themselves.

  If designers do use LCA conclusions, a discussion point is if they have to check the LCA they are using on transparency, or should be able to trust the LCA practitioner to do proper communication of the uncertainties the study results depend on. This LCA practitioner-designer interaction remains a critical factor and is a relevant point up for discussion. Should designers become LCA experts or should the LCA method improve its communication? Is the main responsibility to facilitate clear communication of LCA conclusions for the LCA discipline or is it up to designers to check the LCA transparency and their interpretation those conclusions, depending on certain assumptions? Even though this remains a discussion point: in this study it is assumed that the LCA discipline should certainly develop to communicate credible, transparent and reproducible assessments of environmental impacts that could directly be used by designers. It could be argued that this development should be the other way around, by improving LCA education among designers to give them the tools to assess this transparency of an LCA by themselves. The truth probably lays somewhere in between. This is because good communication of results and what the outcome depends on, does not equal correct interpretation. When developing the quality of communication and transparency of LCA conclusions, improvements should also be made on the receiving side of the line, by empowering designers to interpret and implement the conclusions in a correct way to help with decision-making to design for sustainable development.

As I am both educated as an Industrial product design and as LCA specialist, I believe both expertise would benefit from the development of interdisciplinary design teams, where both the LCA expert and the designer can actively learn from each other and thus facilitate the best communication of the influences and dependencies within an LCA conclusion. In this way the LCA practitioner can learn how the reporting quality of their LCAs influences design decisions. The LCA practitioner can learn from checking if the message of the LCA conclusion did not get lost in translation when interpretated by the designer. When understanding the interpretation by designers better, communication by LCA practitioners to designers can be improved. The other way around, by learning from LCA practitioners, designers can learn to understand the way LCA conclusions are reported more.

- **Point of implementation tool**: The best point of implementation of the tool, into the LCA method, is still unknown. Currently, with the test of the tool, this is done at the end of the LCA, in order to find the room for improvement in the conclusions of the already existing LCAs. However, the flexibility and possibility of changing modelling choices in LCA, is decreasing towards the end, when developing the conclusion of the LCA. It might be relevant to be aware of the key considerations earlier in the doing of the LCA study, so data changes and influences can be done more easily. In the current state of the tool, it is not yet known where it is best to be implemented, when performing an LCA study. The implementation could even be considered at multiple points in the LCA process: keeping the key considerations in mind during the LCA, and assessing the transparency of the conclusion regarding recycling at the end, additionally to performing the ISO steps.

- **Quality versus transparency:** It is important to recognize that the 'LCA transparency wheel' tool does not test the quality of the LCA itself, only its transparency in terms of the modelling choices related to the mentioned key considerations. Having a low transparency doesn't mean the outcome of the LCA is not correct, it is only harder to validate the outcome and be aware of the assumptions behind the conclusion. The other way around, a very transparent LCA is not necessarily a good LCA. When the assumptions are made very clear, the assumptions could still be incorrect or build on faulty data. By clearly communicating all key considerations to the designer, it helps them judge if the results are useful for them. It is important for designers to understand the difference between the transparency and the quality of LCA results, and how improved transparency increases their ability to check for quality. Possible data confidentiality issues should be taken into consideration for assessing transparency as well. As sharing the exact data used within the LCA model appears to be challenging sometimes, due to competition. However, it should then be clearly mentioned which data cannot be shared due to confidentiality and for what reason. A small set-up of a decision flowchart for designers is given in this report, to provide guidance on how to use LCA results effectively and ensure the transparency. However, this set-up is still very limited, and is missing inputs from further research about effective communication and education about assessing LCA transparency and if the results serve the purpose designers have in mind.

- **Research magnitude impact background data:** Currently an important limitation to the development of the tool is lack in research on what the exact impacts of the background ecoinvent database system model selection on the LCA results and their implications for the tool are. It is relevant to test these actual modelling influences in an exact and numerical way to gain more understanding about the magnitude of these influences for the outcome of the LCA, instead of assuming this impact to be relevant, like this report currently does. Doing so could provide valuable new insights about the magnitude of the impact, and the tool could be further refined. Additionally, this information could be used to develop the tool further in terms of hierarchy and importance of the different key consideration scores and their effects on the LCA outcome, which is currently still limited in the testing and reiteration of the tool. Missing this research is a current limitation to the fundamental set-up of the tool.

- **Research interdependencies key considerations:** The literature review and the testing of the tool created awareness that LCA studies differ on how they model recycled material and recyclable material, and thus how the multifunctionality is solved and the impacts are distributed between different product systems. It might be important for the tool to include a step where the consistency in multifunctionality solving in use of recycled material versus producing recyclable material is checked. Are similar and consistent assumptions made in all places of the circular system? This step should be dedicated to comparing the impacts of various parameters on one another, with a particular emphasis on identifying noteworthy combinations: such as the impact that energy recovery might have (allocation parameter), and how this differs when a different process location is selected (data selection). However, this study is lacking research on how this inconsistencies in modelling recycling, or solving multifunctionality could be reported more transparently.

- **Best improvements tool development:** As mentioned, the tool is still in the early stage of its development and this should be kept in mind. As the application of the 'LCA transparency wheel' has not yet been tested by different LCA practitioners than the researcher, and the improvement of transparent reporting regarding recycling is not tested yet with designers, it can be assumed that many relevant iterations in terms of ease of usability and of the tool can still be done. Some of these could be fundamental iterations, like discussed above, but additionally many iterations could be done in the (visual) design development or automatic programming of the tool in order to be more intuitive to work with. For instance, currently, when having finished the scoring for all seven parameters in the digital appendix, a transparency radar diagram is given as an overview outcome, which is now manually transferred to the transparency wheel outcome. Providing a computer codes that provides the visual wheel with colouring of the pies immediately, instead of showing the radar diagram after filling in the excel sheet, could be a first step in the right direction. However, other relevant developments are certainly up for discussion.

GENERALIZABILITY OF STUDY

The current focus of the tool is that the tool should be used by LCA practitioners. By using the tool LCA practitioners increase the usability of the LCA conclusion for designers. As this tool builds on key considerations, derived from a literature study that specifically focuses on LCAs done on products and products systems that include the recycling of material back into the product system, this is also the scope the tool is applicable on. At the same time, the thorough understanding of what product design means and the background as industrial product designer by the researcher, makes the whole tool scoped towards applicability for design purposes. The scope is currently focussed on the recycling loop of the CE, but generalizability to other CE-loops, where the multifunctional processes in the system model change due to 'waste' keeping value, is possible. This is because the identified key considerations are applicable to other modelling choices and processes that include multifunctionality as well even though being a different loop, and transparent reporting for modelling this is considered relevant too. For the same reason, the results of the improved transparency in the LCA conclusion is applicable for all LCA reports that use recycling and designs that include recycling. The CE makes the key considerations regarding recycling more visible, but recycling does not occur in eco-design and circular product design only.

What remains unresearched within the report, is generalizability of this research, and applicability of the tool by LCA practitioners, when the LCA conclusion is not necessarily improved for design purposes. Because the research scope and my design background the LCA transparency wheel is more design oriented. The question is, if the improved transparency of LCA conclusions, is also beneficial for other professions than design. As not only design decisions, but all decisions benefit from being based on credible, transparent and reproducible assessments of environmental impacts, and not on assumptions, the increased transparency of LCA conclusions regarding modelling choices are probably generalizable and beneficial for other decision-makers, such as policy makers, too. However, no research is done on what is exactly required for other decision makers in order to make these choices. This is combined with less familiarity with other areas of application of LCAs conclusions than the aforementioned design background. This means, overall information might be lacking about what is needed to apply the tool in a different scope and other important key considerations might need to be included in the tool when future research would focus on applicability for different, or more general purposes.

Part of this research, specifically focuses on the modelling choices made in the system model choices in the used database of ecoinvent, as no research is done on pre-allocation influences in other existing databases, this tool is not generalizable to the influence of different databases. However, the other key considerations in the tool are still relevant to check on transparency and the tool can still be used, as a clear option is given that the database used is not ecoinvent, and transparent mentioning about the unknown effect of the database that is not ecoinvent can then be reported.

In summary, this study consists first of a literature review to assess the status quo of recycling loops currently modelled, identified and solved in life cycle assessments of circular economy product systems and what choices are made regarding the supporting ecoinvent database. Secondly, it includes the development of the so-called ‘LCA transparency wheel’ tool. The literature review identified a lack of transparent modelling and reporting of the choices in important key considerations, in LCA studies that include recycling loops and that address circular economy systems. The ' LCA transparency wheel' tool, developed building on these key considerations, is a tool for LCA practitioners and LCA community in general, aiming to enable them to improve the transparency in LCA reporting regarding recycling for usability in design decision making. This improved reporting is relevant for designers, so they can base their decisions on transparent LCA conclusions of environmental impacts, and not on assumptions. Developing the LCA transparency wheel aims to accommodate a better cooperation and communication between the LCA and design communities. However, only a first draft version of the LCA transparency wheel was developed in this report with constraints and limitations as discussed above. Further research and testing are needed to refine and improve its effectiveness. The limitations presented in this chapter provide insights into the areas that require further attention to ensure the tool's applicability and usefulness to LCA practitioners, designers and the academic world and will be further elaborated on in chapter 8 'Recommendations’.

7 CONCLUSIONS

The primary objective of this study was to investigate the modelling and reporting of recycling loops in life cycle assessment studies that address circular economy systems, with a particular focus on those adopting the ecoinvent database for background processes. The study aimed answering the following research question:

‘ How are recycling loops modelled and reported in LCA studies addressing circular economy systems and in the most widely used LCA database ecoinvent; and how can reporting be improved to better and more transparently communicate conclusions of LCAs to product designers?’

The study also aimed to identify opportunities to improve the current modelling and reporting practices to enable more transparent and accurate simulations of recycling loops in LCAs. Two sub-questions were formulated to guide the research: (1) How are recycling loops currently modelled, identified, and solved in LCAs of circular economy product systems, and what choices are made regarding the supporting ecoinvent database? (2) How can LCA recycling modelling assumptions and related results be best communicated to product designers to create proper understanding of these assumptions and results?

The first sub-question was addressed through a literature review using the PRISMA method, which revealed a wide variation in the transparency of current LCAs that contain recycling with a circular economy perspective. The findings suggest that recycling is not modelled as loops in 47% of the LCAs included in literature review. Multifunctionality identification is only undertaken in 17% of the reports. Multifunctionality is typically addressed through partitioning and substitution principles. The solving of multifunctionality is not always consistent in the same system model for the use of recyclable material and the production of recyclable material. The selection of ecoinvent system models is mentioned in 15% of the reports. Only reports specifically focusing on multifunctionality within LCA show insight that different system models might influence results of an LCA.

To address the second sub-question, the study proposed the ‘LCA transparency wheel’ tool to help LCA practitioners assess the transparency of their studies and communicate assumptions and results related to the seven key considerations, based on the literature review results: modelling of the flow diagram, identification of multifunctionality, solving of the multifunctionality, background database use, modelling of recycling, type of loop recycling, and reduction in virgin material inputs.

Using the LCA transparency wheel can help LCA practitioners identify transparency gaps within their LCA and improve the transparency by being aware of the different influences that the different key considerations have on the outcome of their LCA. This evaluation of the transparency of their LCA helps them realize where data is missing and what opportunities there are to improve the modelling and reporting of the LCA. By applying the LCA transparency wheel tool, practitioners can increase the reporting transparency of the dependencies in a conclusion regarding these key considerations. Following from this, design decisions could be based on credible, transparent and reproducible assessments of environmental impacts, and not on assumptions.

In conclusion, this study aimed to investigate how recycling loops are modelled and reported in LCA studies related to circular economy systems, and how current modelling and reporting can be improved to better and more transparently simulate recycling loops in LCAs. The study found that only 17% of the researched literature report complete transparency in current LCAs containing recycling with a circular economy perspective, only 16% mentions the system model selection in ecoinvent and that recycling is not modelled as loops in 17% of the researched LCAs. Resulting from the literature review, the study identified seven key considerations that impact the conclusion of an LCA, that include the modelling of the flow diagram, identification of multifunctionality, and background database use. To address these issues, the study proposed a ‘LCA transparency wheel’ tool. By using the tool, LCA practitioners can identify information in gaps the conclusions and improve the transparency of their studies. Improving the transparent communication of the dependencies in the LCA conclusion, helps designers understand the underlying assumptions that influence the outcomes of the LCAs. Using the tool can ultimately lead to more informed decision-making, which in its turn could results in better environmental decisions in product design and implementation of circular economy systems. How designers exactly use the conclusions of an LCA in their designs is out of scope for this report. While the tool has the potential to improve the modelling and reporting of recycling loops in LCAs, further testing and development are necessary to ensure its effectiveness in real-world settings. Overall, the study highlights the importance of transparent reporting and modelling regarding recycling in LCAs addressing circular economy systems to improve communication of results to decision-makers.

8 RECOMMENDATIONS

The purpose of this chapter is to provide recommendations for future research on how recycling loops are modelled and reported in LCA studies addressing circular economy systems and in the most widely used LCA database ecoinvent; and how reporting can be improved to better and more transparently communicate conclusions of LCAs to product designers. The study presented a tool for improving the transparency and usefulness for designers of LCA studies that incorporate recycling and a CE perspective. This chapter builds on the Discussion chapter of this report and provides recommendations for future research to improve the effectiveness of the ' LCA transparency wheel' tool.

The most important recommendation for future development of the tool is to test the tool in different ways, so these insights can be used to improve it. To ensure its applicability in real-world scenarios, it is important to test the tool. Tests are recommended on several points:

- **Test tool with other existing and new literature:** It should be considered that other LCA studies not included in literature review that the tool builds on, should be included in the testing and further development of the tool in order to remove the possible bias when assessing the tool with the same studies of the review.
- **Test tool with several LCA practitioners and designers**: The tool should be evaluated by individuals who have a variety of LCA expertise, not just by LCA experts familiar with the method.
  The tool should be also be tested with designers and LCA practitioners to evaluate its effectiveness. This testing will be necessary for improving the quality of the proposed tool and its application and valuable lessons can be learned from both expertise
- **Test influence of 'improved in transparency' conclusions for designers and their interpretation:** No tests of the tool have be done at all to see if improving the reporting transparency of dependency on the key considerations positively influences the communication of LCA conclusions to designers, and this should be done.

A research limitation is the unclear and inconsistent connection between the LCA expertise and the design expertise, therefore several recommendations are done in terms of LCA education for different expertise. In this report assumptions are made regarding the cooperation and connection between both fields of expertise, but these assumptions should be validated through further research.

Although designers are somewhat educated about LCAs, they are rarely experts. The other way around, LCA practitioners should be more aware of the possibility that their conclusions might be used as guidance in design decisions. Therefore, the further development of the tool should be done together with designers and LCA-practitioners to make the tool as applicable in reality as possible, resulting in the following education-related recommendations:

- **Educate designers in LCA**: In this way, relevant conclusions of LCAs can be used correctly by designers, making it feasible for all designers, not just a small subset. It is also recommended to further develop a decision set-up for designers to provide guidance on how to use LCA results effectively and ensure their transparency and quality.
- **How to educate LCA practitioners about the 'LCA transparency wheel':** Research should be done on how to make LCA practitioners aware of the LCA transparency wheel tool to improve transparency of their reports. Research should show how LCA practitioners could best be educated on how to use the tool.

Additionality, more applicability of the 4-step approach by Guinée et al. (2002) is recommended in LCA courses, as this is considered a useful approach to identify multifunctional processes and this is an important key consideration mentioned in the 'LCA transparency wheel' tool, that influences the conclusion of an LCA.

- **Develop more connection between LCA practitioners and designers**: It is recommended to educate for more interdisciplinary LCA-design teams. It is much more effective to share knowledge with each other, than to all individually try to be an expert in the field of LCA and design. It is recommended to explore how LCA expertise and design expertise can work together to improve the reporting quality and transparency of the LCA results.

At the same time, there is a research recommendations considering the implementation and development of the tool:

- **Research the best point of implementation for the tool**: Research should be done on what is the best timing to intervene in LCA reporting, by using the tool. What is the best point to implement the tool, and at what point in the LCA process is there enough flexibility to assess the transparency of the LCA and still be able to implement the relevant changes.

The following recommendations are already identified as possible areas of improvements of the tool, and are recommended to research.

- **Research the exact impacts of the background ecoinvent database system model selection on LCA results**: Especially in the case of the influences of the background ecoinvent database system model selection, it is relevant to test actual modelling influences to gain more understanding about the magnitude of these influences for the outcome of the LCA. This information could also be used to develop the tool further in terms of hierarchy and importance of the different key consideration scores and their effects on the LCA outcome.
- **Research the application of a step focussed on being aware of inconsistencies between modelling choices, for the key considerations in the tool:** It might be important for the tool to include a step where the consistency in multifunctionality solving and modelling of recycling is checked. This step should be dedicated to comparing the impacts of various parameters on one another.
- **Improve the (visual) design development and programming of the tool:** The development of the tool is important, in order for the tool to be more intuitive to work with. The tool presented following from the literature review is intended to make LCA outcomes more understandable for designers, and therefore in itself should be designed to be as understandable as possible.

The tool presented in this literature review is based on certain assumptions and generalizations. The last recommendations are therefore regarding research that could lead to generalizability of the study:

- **The whole research application could be done on a broader scope**. The literature review and tool development is now done for LCA practitioners, who write a conclusion used by designers. It could be researched if the tool can be generalizable for a broader scope, to other disciplines or different users than the current target group.

In conclusion, this chapter provides valuable recommendations for future research to improve the reporting transparency of recycling loops in LCAs for circular economy systems. The proposed tool should be tested in different ways to remove biases and ensure its applicability in real-world scenarios. The education of designers and LCA practitioners about the LCA methodology, transparency, and the proposed tool is essential for its successful implementation. Research should be done to develop a more user-friendly 'LCA transparency wheel' tool to provide more transparent results to non LCA-experts. It is recommended to explore how LCA expertise and design expertise can work together to overall improve the transparency of LCA results. The implementation of the tool and other ways to improve LCA communication should be researched further to provide valuable insights for LCA practitioners and designers alike.

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APPENDIX

APPENDIX 1: EXPLANATION SYSTEM MODELS

Allocation, cut-off by classification

Waste is the producer's responsibility, meaning that there is an incentivisation to use recyclable products; they are available burden free (cut-off) and recycled materials bear only the impacts of the recycling process. The cut-off takes place at the end of the waste treatment.

All intermediate exchanges are classified at product level in three categories:

- Allocatable: ordinary by-products with economic value.
- Recyclable: materials with no or little economic value but can serve as input or as source for a recycling activity. There is an interest in collecting the material.
- Waste: Materials with no economic value are considered waste, there is no interest in collection, and one has to pay to dispose it. Wastes are linked as a negative input in ecoinvent, resulting in 'waste as a service'.

Allocation, cut-off EN15804

The key differences to cut-off by classification are the cut-off points are between the primary (producer) and the secondary (consumer) system. A product reaches its end-of-waste state when there is a market for the recovered product and when the recovered product fulfils the technical requirements for the specific purposes and meets the legislation and standards applicable to the product. The cut-off point in some supply chains has been adjusted to align with the end-of-waste criteria. Further processing that may be required after the material has reached its end-of-waste state belongs to the secondary system.

This system model also provides all Life Cycle Inventory (LCI) indicators required in Environmental Product Declarations. The EN 15804 standard provides the structure for making three different types of EPDs: Cradle-to-gate, Cradle-to-grave, and Cradle-to-gate with options (Ecomatters, 2022). This is a norm focussing on regulations considering the built environment.

Allocation at the point of substitution

The responsibility over waste is shared between producers and subsequent users benefitting of the treatment processes by using valuable product generated in these.

This system uses expansion of product systems, to avoid allocation within treatment systems.

Products are classified in two ways: material for treatment (mft) and material not for treatment (non-mft). Mft requires treatment in general or treatment to become valuable. Non-mft does not require any treatment prior to being used.

In an activity where all reference products and by-products are non-mft, inputs and emissions are allocated based on the allocation factors.

In this approach, allocation within end-of-life, i.e., within treatment activities, should be avoided. To do so, each activity that produces a product that requires further treatment before becoming valuable (e.g., waste) is considered together with all treatment activities required for that product in a single system. The exchanges of the producing activity and those of the treatment activities are allocated to all the different valuable by-products in the system (from both producing and treatment activities).

The point of substitution is at the first activity in the downstream supply chain after a treatment (or recycling) activity that produces a valuable product. This activity now carries many different exchanges from different activities, which is particularly relevant for waste produced in many different industries.

The impacts of the production and treatment process are allocated to various non-mfts, the treatment is delivered as a service so it can be used within multiple processes with the same waste treatment. It contains multiple activities merged into one.

Substitution, consequential, long-term

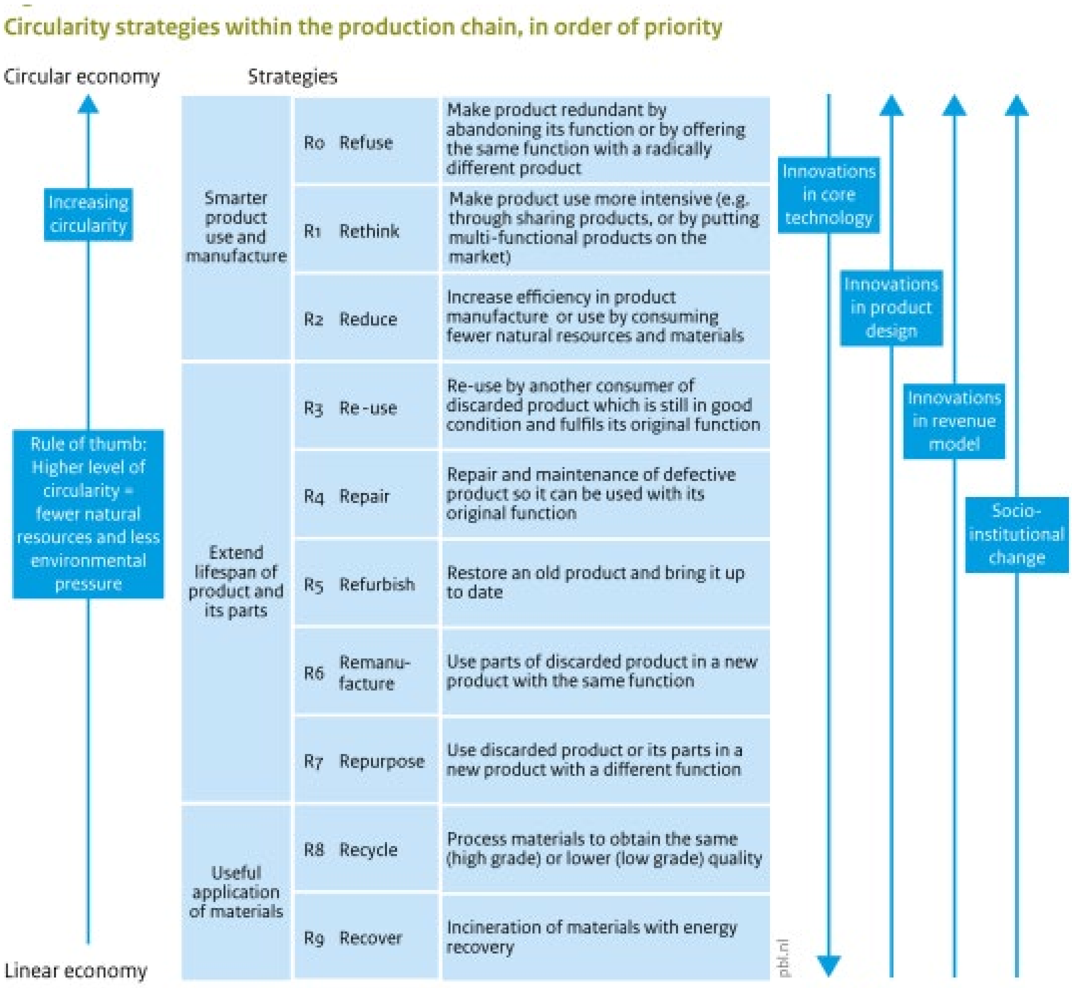
This system model is used to assess the consequences of a change in an existing system and is used for prospective studies and prediction of future changes.

No allocation is applied, but the burden is on the activity. If by-products can substitute something they can bring credits to the activity producing them. The system works with marginal supply and the burdens are allocated to the one triggering demand.

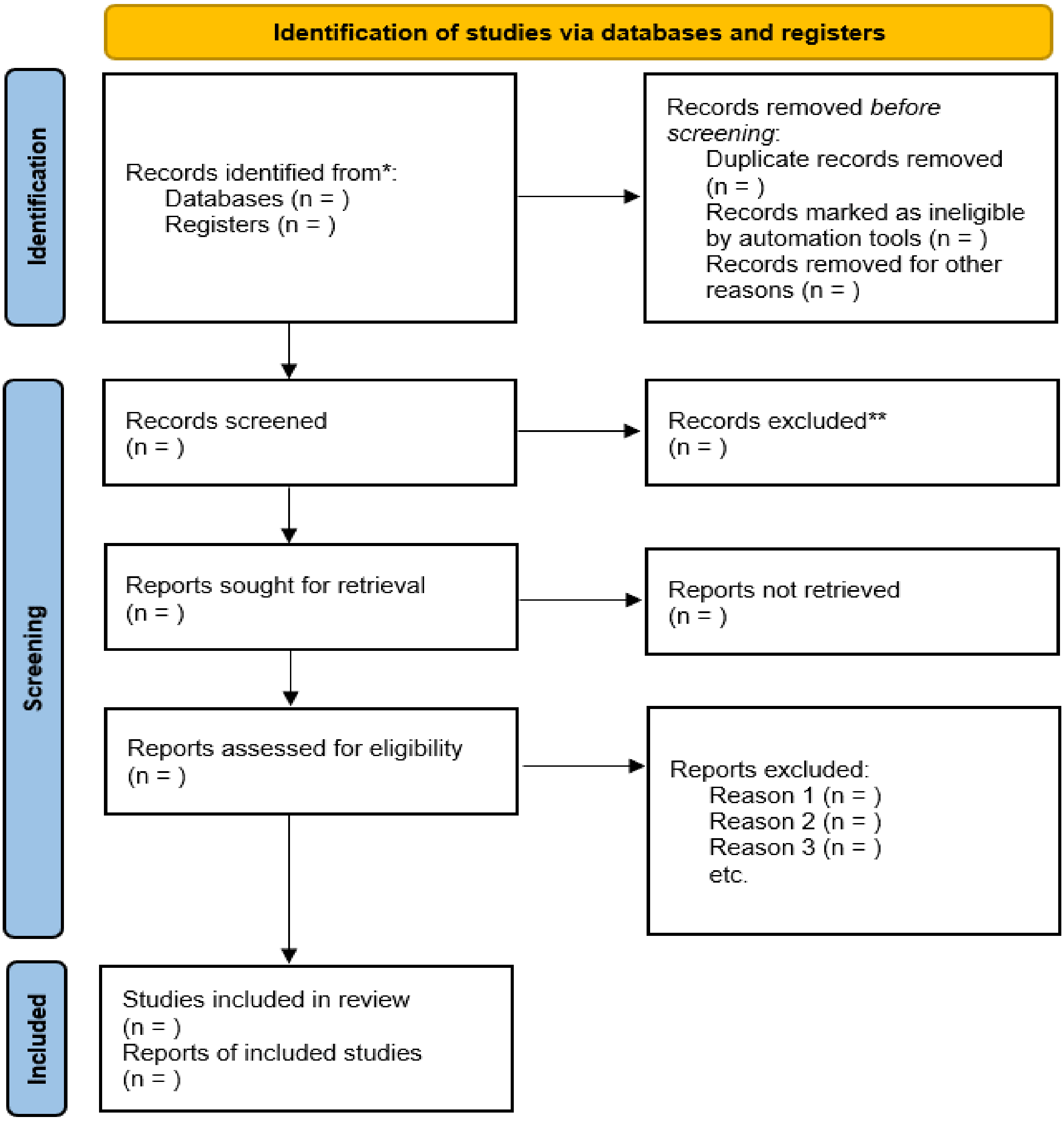
As the focus of this study is on attributional LCAs, future perspectives within LCAs are not included.

APPENDIX 2: DIFFERENT CIRCULARITY (R) STRATEGIES

The different R strategies according to (Potting et al., 2017)

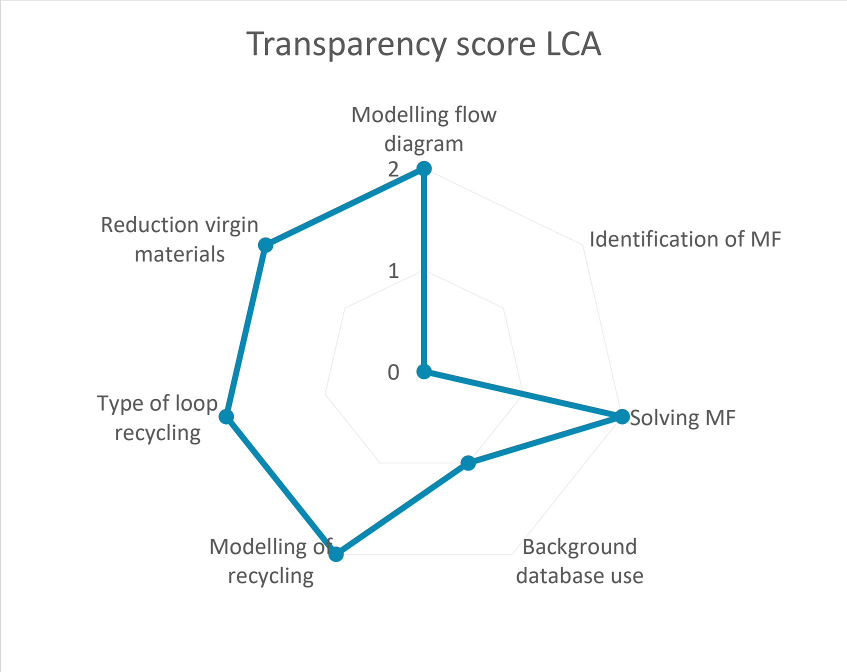


APPENDIX 3: PRISMA



APPENDIX 4: TESTING THE LCA TRANSPARENCY WHEEL

TEST (KOULOUMPIS ET AL., 2020)

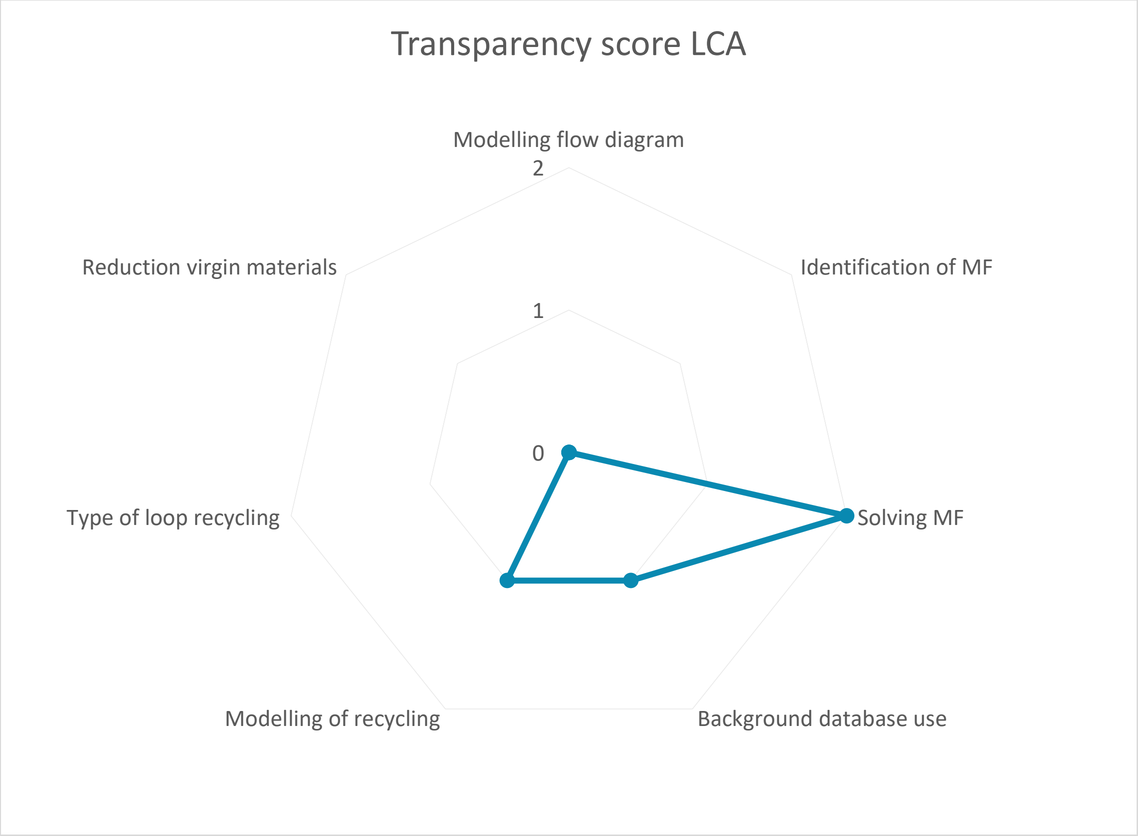


When analyzing the report of Kouloumpis (2020) through the eye of the ‘LCA transparency wheel” it becomes clear that the report is already quite transparent. The only two points where the report lacks transparency are the identification of multifunctionality and the possible background influences through the ecoinvent system model.

The lack of identification of multifunctionality makes it unclear which perception on material values are taken for materials and how they influence recycling: If this is clear for the user of the LCA , an estimation can be done if the same value of materials (waste/good) can be realised and if the processes evaluated occur in the designed product system as wsell. In this part the vision on the CE principles will also be clear: Does everything have value?

As the location of the processes are clearly mentioned and the mention of open-loop recycling as well, the designer using the outcome of the LCA can know if this LCA product is in in line with designed product system. If the LCA practitioner is aware of the transparency gaps, the LCA practitioner can start with making the results more transparent.

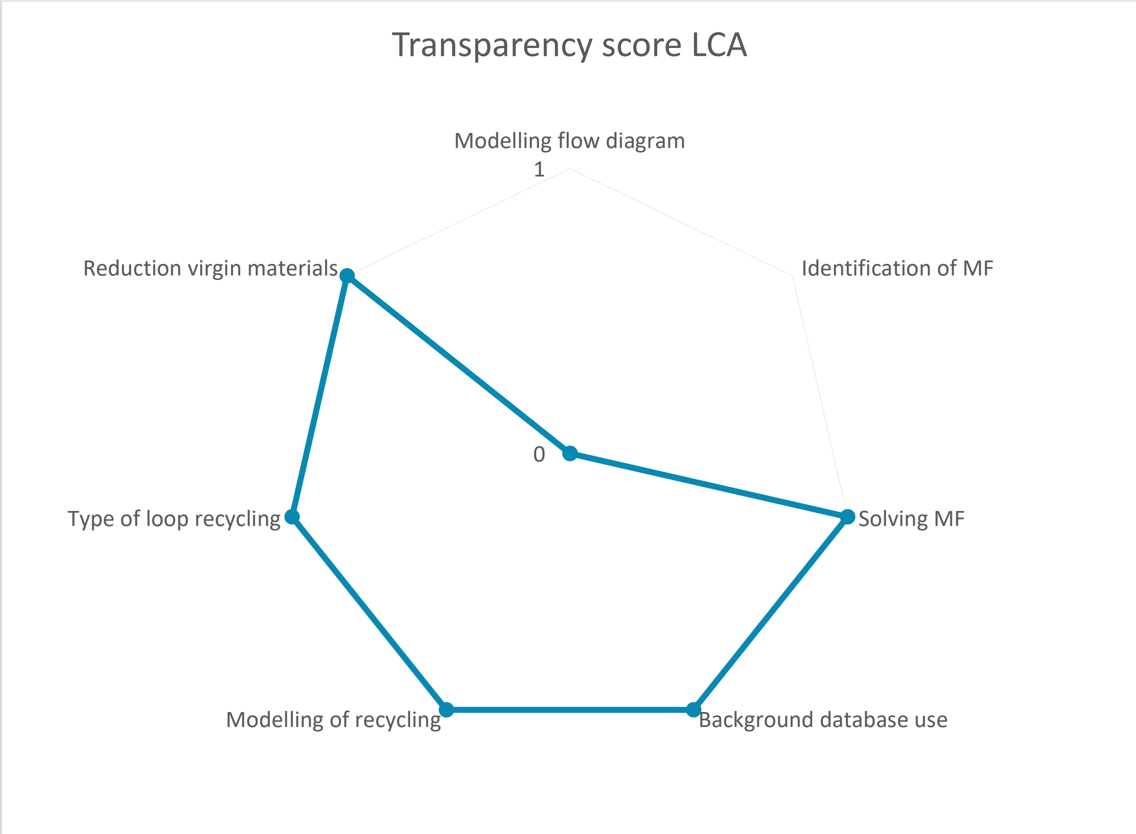
Test: (Monteiro et al., 2022)



Analyzing the report by Monteiro et al. (2022) there are a lot of unknowns, so it would be hard to fully comprehend the assumptions that lay behind the interpretation of the outcome. There is very little transparency and this is where room for improvement can be found for the LCA practitioner.

Another insight is that the cut-off approach for use of recycled materials is used. It is good that this choice is made transparent. As it means that the product made of recycled material scores a lot higher than the other product. This vision is important for designers using the LCA results to take into consideration, and to double check if this vision is matching with own principles, when assuming one choice is better than the others.

TEST: (GALVE ET AL., 2022)

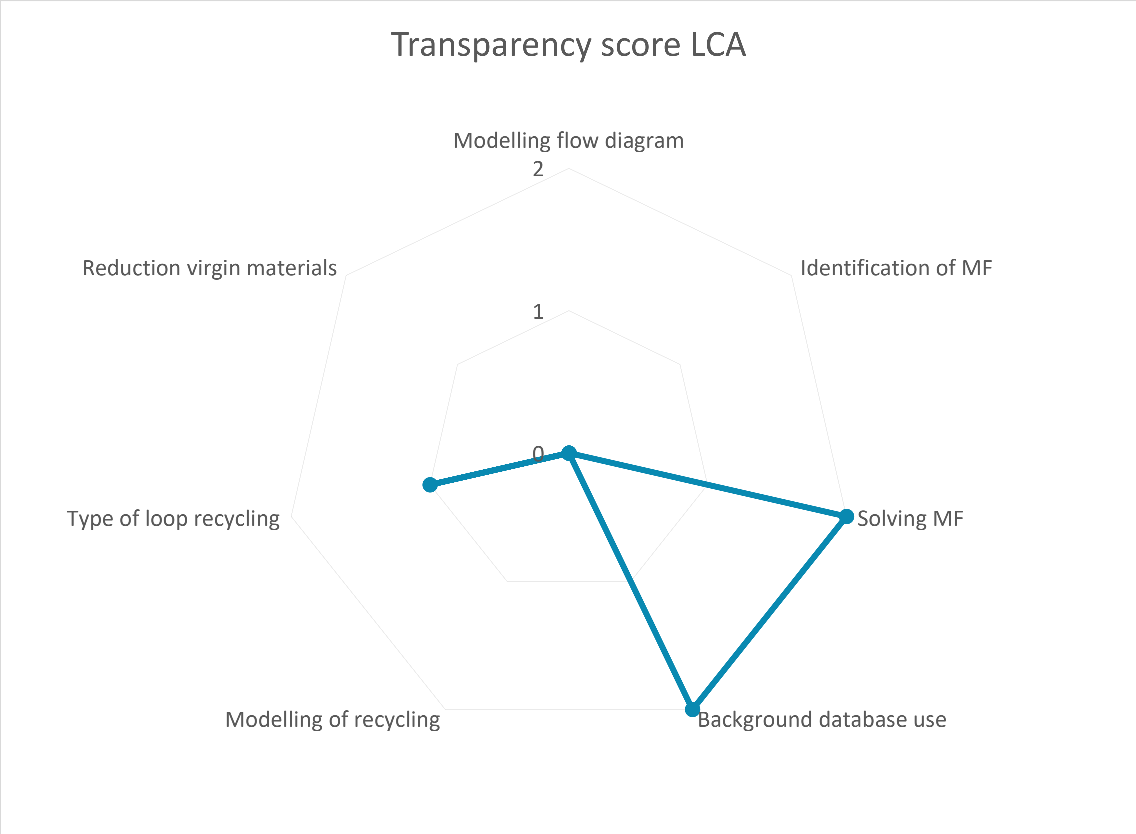


The report by Galve et al. (2022) is not very transparent. This once again makes it very difficult to compare the underlying assumption of the system model under study with the designed system model, the LCA practitioner can now see where room for improvement is.

In this study it is assumed that recycled materials are available for free. Where used materials go to is unclear due to missing flow diagram, so the perception on recyclable materials are unclear.

In this report is it also difficult to score solving MF: The use of recycled material is solved in a certain way, but the solving is different in terms of recyclable materials. The production of recycled material could be solved in a certain way. The method might lack here in capability to capture such discrepancies. It might be relevant to split this interpretation in the whole method: See what the perception is on allocation used materials and produced materials and how this is allocated.

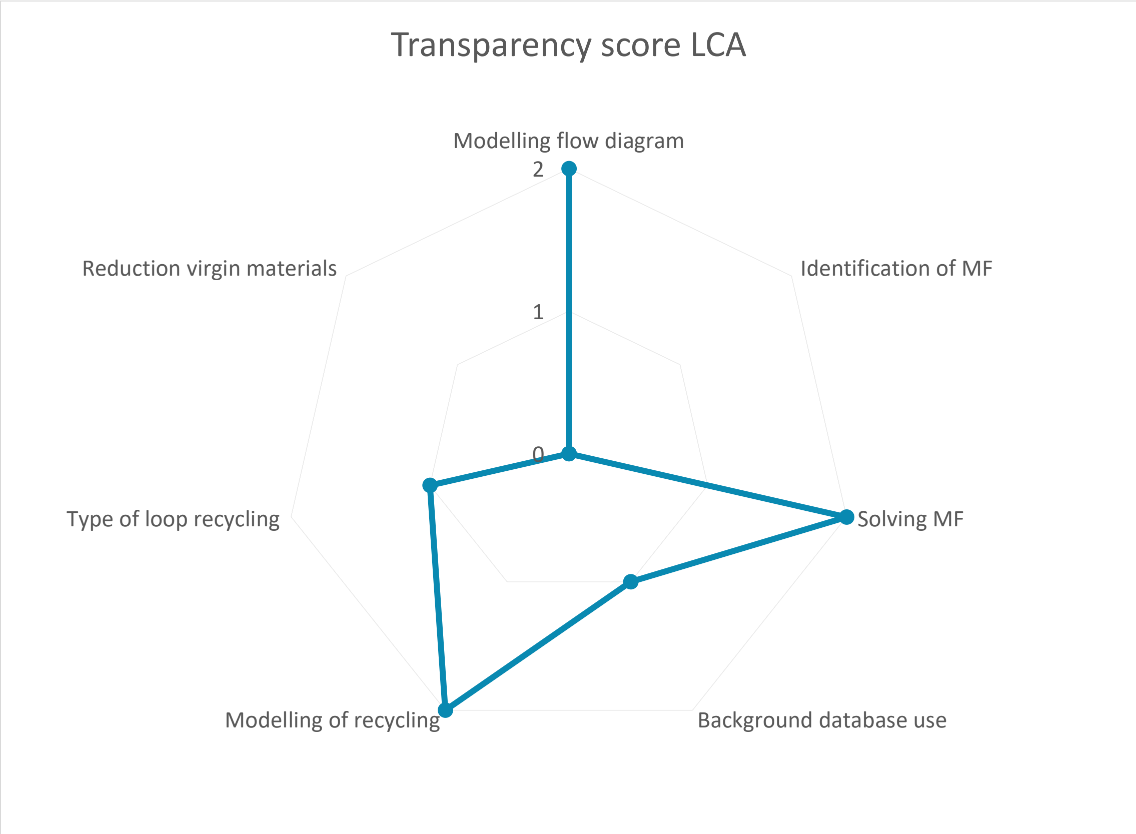
TEST: (KOODUVALLI ET AL., 2020)



The report by Kooduvalli (2020) is missing a lot of transparency. Especially relevant information considering the modelling of LCA. It is very hard to understand the assumptions done in this study and therefore it is difficult for a designer to take these underlying assumptions. Being aware of this is important, so the designer can decide whether the outcome of the LCA still serves the purpose the designer is referring to the LCA in the first place, but it is more important for the LCA practitioner to improve the quality of transparency of this LCA report.

Interesting it that the report does show insight in the possible influences the background data of ecoinvent has, but as the rest of the system model under study is unclear it is still hard to understand assumptions made in the rest of the study, this might imply a need of weighing the different key considerations within the LCA transparency wheel method. Or developing a step that creates awareness about the interdependencies of the different key considerations.

TEST: (STOTZ ET AL., 2017)



In the report by Stoltz (2017) there is quite clear communication about the solving of multifunctionality and the data insecurities, this results in a good take away for designers where the lack of knowledge is: the reasoning for type of loop recycling and what impact this has on reduction material use.

It is not specified what the effects the background database might have on the data, but as the database is specified, the one using the LCA can check the possible influences themselves to estimate if extra information is required or not.

In the report too, the lack of identification of multifunctionality makes it unclear which perception on material values are taken for materials and how they influence recycling: If this is clear for the user of the LCA , an estimation can be done if the same value of materials (waste/good) can be realised and if the processes evaluated occur in the designed product system as well. In this part the vision on the CE principles will also be clear: Does everything have value? The room for improvement of transparency for the different key considerations should be clearer when looking at the transparency scores for the different key considerations.

APPENDIX DIGITAL

APPENDIX A: LITERATURE REVIEW

This is the digital appendix that can be found in the file: AppendixA.xsls

Index appendix A:

A1 Literature selection CS-s1	The literature search according to the prisma method for literature review of circular economy case studies search 1.
A2 Literature selection CS-s2	The literature search according to the prisma method for literature review of circular economy case studies search 2
A3 Literature review CS-conc	Case studies literature review: the main information used for the conclusions in one overview
A4 Literature review CS-dtl	Case studies literature review: all information documented during the research, not all considered relevant
A5 Literature selection MFmet	The literature search according to the prisma method for literature review of methodological literature about multifunctionality in LCAs
A6 Lit review MFmet conclusion	Methodological literature about multifunctionality in LCA literature review: the main information used for the conclusions in one overview
A7 Lit review MFmet dtl	Methodological literature about multifunctionality in LCA literature review: all information documented during the research, not all considered relevant
A8 Table percentages reviewCS	The percentual conclusions of the case study review
Quick prisma scan	quick prisma scan used in order to get a feeling of which search terms to use in order to get relevant results in the literature search

APPENDIX B: LCA TRANSPARENCY WHEEL

This is the digital appendix that can be found in excel file: AppendixB: LCA transparency wheel.

Index appendix B:

B1 TransparencyWheel	The linear form accompanying the ' LCA transparency wheel' tool'
B2 Scoring	The scoring excel sheet to create a radar diagram for the 'LCA transparency wheel tool'
B3 -B7	The 5 different reports, individual score on the transparency score sheet
	Scoring (Kouloumpis et al., 2020)
	Scoring (Monteiro et al., 2022)
	Scoring (Galve et al., 2022)
	Scoring (Kooduvalli et al., 2020)
	Scoring (Stotz et al., 2017)
B8-9	Two drafts of the 'LCA transparency wheel' tool excel