Enabling designers to integrate the fundamentals of Life Cycle Assessment into design practices.

A case study at the Industrial Design Engineering faculty in Delft.

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Executive summary

Humans have a substantial impact on global weather and climate, which can affect human health, biodiversity of ecosystems, and natural resource availability. Designers have a large accountability in this regard, as they are responsible for the creating of products, services, systems or strategies. Life Cycle Assessment (LCA), a quantitative, holistic, and context-specific environmental assessment method, has the potential to aid designers in making environmentally sustainable design decisions. However, the effective implementation of LCA in a design context has been falling short. This study aims to answer the question: *What is needed to enable design students, particularly at the Industrial Design faculty in Delft, without prior experience in Life Cycle Assessment to effectively incorporate the fundamentals of the LCA method into their design practices?*

First addressed is the sub-question: *What are the problems that design students experience when performing LCA for the first time?* To answer this question, a case study is done at the Industrial Design Engineering (IDE) faculty in Delft. Here, students and teachers were interviewed and observed. Observed problems were bundled into problem clusters and abstracted into themes. The main reasons to limit the effectiveness of LCA for designers inexperienced with LCA, are a designers' mindset, motivation, comprehension, their capabilities, and time for LCA. Many small student problems are encompassed by these overarching themes.

The themes are depicted in a system causal loop diagram and relationships are identified. Herewith, the second research question is addressed: *What are the relations between the identified problems and what effect could possible interventions to the system have?* Within this system model, the time for LCA is the most central node. It influences a designer's motivation, capabilities and comprehension of LCA. Also, designers' comprehension and capabilities are interrelated themes. Besides themes in the power of the designer, there are external themes, namely social factors, regulations and company policies, data quality and quantity, LCA method and tools and LCA education. The external themes also influence the designer system. These influences are depicted as possible interventions to improve the designers' incorporation of LCA in design practices. The findings contribute to academic literature by developing a system model that outlines the issues and themes encountered by inexperienced designers when conducting an LCA for the first time.

The system model needs to be tested in real life practices and can be a good basis to explore interventions and improvements to the system. One intervention is explored in the last research phase. The final sub-question was: *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?* The intervention is chosen based on available time, pilot test location and researcher capabilities. To test this intervention and demonstrate theme influences, an improved LCA calculation tool is pilot tested at the IDE faculty. The tool was found to have a good fit to design practices and a complete overview of LCA fundamentals. It also offers early LCA implementation through an inventory phase that slowly increases complexity matching to the designers' capabilities. This is supported by easier and earlier implementation of robustness assessment (sensitivity analysis or scenario tests) to enable low threshold assumption making and testing to help nuanced result interpretation. From tool evaluation at the IDE faculty, it can be concluded that the design measures have been successfully implemented and the aims are met for this sample group. The research sample provided positive feedback to the tool and its improved characteristics.

There are some points of discussion. For instance, this study has been focused on designers inexperienced with LCA, but many findings can be relevant for the broader field of designers. Also, it can be a good steppingstone for inexperienced designers to gain skills and get into more advanced

LCA software tools. The case study was performed at the IDE faculty in Delft, with which research results are partly context specific, it is therefore important to be aware of the politically and financially stable, knowledgeable and economically developed context. Besides, there are cultural and social influences such as the way of communication by the research sample and researcher. As this has been qualitative social research, understanding of communication is important. In the deductive part of this study, there have been design choices such as the choice for an improved tool as manifestation of theoretic results. Also, prioritization of design requirements has been done by the researcher to scope the concept evaluation to three main improvements.

The tool has some application and functional limitations. The improved LCA tool is only an example implementation of the research findings, and more tools and methods can be developed to integrate LCA into the design process. For instance, in application of the tool a designer is taking a sidestep from the design process. This can be mentally challenging and requires a mindset change for the designer. The designer has to get into abstract thinking and quantification of design parameters. It may be more effective to have a design method or adapted LCA method that integrates LCA continuously over the design cycle so that designers naturally run into an LCA performance during their design process. Life Cycle Thinking, an approach considering products in a holistic manner, can be used as an awareness-enhancing technique to start off this mindset process designers have to go through. With Life Cycle Thinking, consciousness about the system of a product and abstract thinking is initiated. This subject should be further explored. Functional limits of the tool include Excel, database and aesthetic shortcomings which should be considered in future iterations as well as conversion to more a more suitable software program.

Regarding tool evaluation there are shortcomings as well, due to time limitations during the LCA course, the sample group was small, the assignment simple and evaluation short. Most importantly, there was no opportunity for a zero measurement. This has, as a result that the findings can generate no conclusions on the relative improvement. These matters should be addressed in future research.

This study has both scientific and societal relevance. It provides a theoretic system for demonstrating the dynamics of themes related to a designer's use of LCA. This framework can be utilized in literature to identify and gauge the effects of interventions to the system. Additionally, it can be used by designers to identify their own challenges concerning the use of LCA and develop strategies to address these. If designers can effectively identify and address their problems with LCA utilization, product (system) design can become more environmentally friendly, as environmental assessment is done more accurately.

Despite its limitations regarding the research sample and tool evaluation, this study shows a system model and one intervention example *to enable designers without prior experience in Life Cycle Assessment, particularly at the IDE faculty in Delft, to effectively incorporate the fundamentals of the LCA method into their design practices*. The IDE case study found that student problems can be clustered and abstracted into 10 themes that influence an inexperienced designer, namely a designers' motivation, mindset, time for LCA, capabilities and comprehension of LCA. The draft of possible interventions shows that a new LCA method or tool could influence a designers' comprehension of LCA, time for LCA and the capability/complexity coherence. This intervention is chosen based on research resources (time, location and researcher skills). To test this intervention, the main research results have been implemented into an improved LCA tool and tested at the IDE faculty. Students responded positively to the main tool improvements.

Preface

I am grateful for the opportunity to have followed the program of Industrial Ecology from both Leiden University and the Technical University of Delft. This thesis is the final work of the Master of Science degree. I can look back at a program with great enthusiastic peers and professors, who have inspired me both academically and personally. It was a program that has profoundly interested me and challenged my skills. With a background in Industrial Design Engineering, this thesis has given me the opportunity to combine interests.

I am grateful to Benjamin Sprecher for his day-to-day supervision and valuable advice throughout the thesis process. I am also thankful to Jeroen Guinée for sharing his LCA expertise and helping me elevate the quality of this thesis.

I would like to also thank my study friends, who have been a great source of motivation and inspiration. They have supported me with encouraging and valuable conversations throughout this period. Lastly, I would like to thank my friends and family for the continuous support and for the faith in me.

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List of Abbreviations

CAD – Computer Aided Design

CML – Centrum voor Milieu Wetenschappen (Institute of environmental sciences)

DfS - Design for Sustainability

ECAM – Environmental and Circularity Assessment Methods

ECTS – European Credit Transfer and Accumulation System

FU – Functional Unit

IDE – Industrial Design Engineering

IE – Industrial Ecology

IPCC – International Panel on Climate Change

ISO – International Organisation for Standardisation

LC - Life Cycle

LCA – Life cycle assessment

LCI – Life Cycle Inventory

LCT – Life Cycle Thinking

PSS – Product-Service Systems

QFD – Quality Function Deployment

QFDE – Quality Function Deployment for Environment

SDE – Sustainable Design Engineering

SDS – Sustainable Design Strategies

SI – Sustainable Impact

TU – Technical University

TRL – Technology Readiness Level

Glossary

Alternative: one of a set of product systems studied in a particular LCA, e.g. for comparison (note: some LCA steps are carried out for all alternatives together (e.g. selection of impact categories), while others are repeated for each alternative (e.g. characterization) (Guinée et al., 2002).

Completeness check: A step of the Interpretation phase to verify whether the information yielded by the preceding phases is adequate for drawing conclusions in accordance with the Goal and scope definition (Guinée et al., 2002).

Consistency check: A step of the Interpretation phase to verify whether assumptions, methods and data have been applied consistently throughout the study and in accordance with the Goal and scope definition (Guinée et al., 2002).

Contribution analysis: A step of the Interpretation phase to assess the contributions of individual life cycle stages, (groups of) processes, environmental interventions and indicator results to the overall LCA result (e.g. as a percentage) (Guinée et al., 2002).

Designers inexperienced with LCA: People that have the aspiration to make a design to fulfill a certain problem in society in a sustainable matter. They feel the urge to perform an LCA but have no or very little prior experience in modeling or reading an LCA. From here on 'designers inexperienced with LCA' is further referred to as 'inexperienced designer'

Function: A service provided by a product system or unit process (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, e.g. 1000 hours of light (adapted from ISO) (Guinée et al., 2002).

Goal and scope definition: The first phase of an LCA, establishing the aim of the intended study, the functional unit, the reference flow, the product system(s) under study and the breadth and depth of the study in relation to this aim (Guinée et al., 2002).

Impact assessment: The third phase of an LCA, concerned with understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study (Guinée et al., 2002).

Industrial design: A profession aiming to design a product, service, strategy or system to fulfill a need in society. Generally, the solution involves large scale production and implementation. In this thesis industrial designer is referred to as 'designer'.

Industrial Ecology: A systemic approach to achieving and maintaining a sustainable industrial ecosystem during continuous economic, cultural, and technological evolution. By assessing society as an ecosystem in symbiosis with its environment, resources (e.g. material, energy and capital) can be sustainably managed and measured (Kapur & Graedel, 2004).

Interpretation: the fourth phase of an LCA, in which the results of the Inventory analysis and/or Impact assessment are interpreted in the light of the Goal and scope definition (e.g. by means of contribution, perturbation and uncertainty analysis, comparison with other studies) in order to draw up conclusions and recommendations (Guinée et al., 2002).

Inventory analysis: The second phase of an LCA, in which the relevant inputs and outputs of the product system(s) under study throughout the life cycle are, as far as possible, compiled and quantified (Guinée et al., 2002).

LCA practitioner: An individual group or organization conducting an LCA (Guinée et al., 2002).

Life Cycle Assessment (LCA): Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle; the term may refer to either a procedural method or a specific study (Guinée et al., 2002).

Life Cycle Thinking (LCT): '… the way of thinking that includes the economic, environmental, and social consequences of a product or process throughout its life. More precisely, it consists of a theoretical approach that investigates improvements and reductions in the impacts of services and products at all stages of processing, including extraction, conversion, transformation, distribution, use, and final destination.' (Jacob-Lopes et al., 2021).

Method: A procedure, technique, or way of doing something, especially in accordance with a definite plan (*Method Definition - Dictionary.Com*, n.d.). This research uses research methods, such as defined in chapter 3 and studies the LCA method implementation through a designer's perspective.

Product: In this thesis a product is referred to as a physical product, service, strategy or system that provides a function in society.

Product design: The design process leading up to a 'product'. It general includes the following phases, criteria, provisional design, expected properties, value of the design and approved design (van Boeijen et al., 2020). The designer activities joining those phases are to synthesize, simulate, evaluate, decide and iterate.

Product system: A set of unit processes interlinked by material, energy, product, waste or service flows and performing one or more defined functions (Guinée et al., 2002).

Reference flow: Quantified flow generally connected to the use phase of a product system and representing one way (i.e. by a specific product alternative) of obtaining the functional unit (Guinée et al., 2002).

Sensitivity and uncertainty analysis: A step of the Interpretation phase to assess the robustness of the overall LCA results with respect to variations and uncertainties in the methods and data used (Guinée et al., 2002).

Simplified LCA: A simplified variety of detailed LCA conducted according to guidelines not in full compliance with the ISO 1404X standards and representative of studies typically requiring from 1 to 20 person-days of work (Guinée et al., 2002).

System: A system is a '...network of multiple variables that are connected to each other through causal relationships', based on which the network '.. expresses some sort of behaviour, which can only be characterized through observation as a whole' (Haraldsson, 2004). More simply stated a system is a '…collection of connected things … that influence one another' (Toole, 2005).

Theoretical model: 'Theories are plausible explanatory propositions devised to link possible causes to their effects. Generally, models are schematic representations of reality or of one's view of a possible world, constructed to improve one's understanding about the world and/or to make predictions' (Wunsch, 1994).

Tool: In this thesis, tool is referred to as a calculation software to support modeling and calculation steps of the LCA method. A tool, in this case, can provide more functionalities than just calculation for instance structure, guidance, data visualization and database accessibility.

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

1 Introduction

Humans have a profound impact on the Earth through disrupting natural patterns and phenomena. This interference of ecosystems and natural cycles can significantly influence global weather and climate, impacting human health, ecosystem biodiversity, and natural resource availability (IPCC, 2022). Moreover, the disturbance of local ecosystems can have immense consequences for the way we live and the world around us (Masson-Delmotte et al., 2021). These environmental impacts can affect political and cultural relations too, for instance through migration and agricultural land degradation. Resource extraction has tripled in the last 50 years while the global population doubled. This has had significant impacts and contributed to approximately 90% of biodiversity loss, water stress, and around 50% of climate change impacts (United Nations Environment Programme, 2020). To address this, it is essential to responsibly manage resources and reduce natural resource extraction, energy use and greenhouse gas emissions from economic activity.

Industrial designers (henceforth: Designers) have a great impact on economic activity. Almost all the human environment has been created or constructed through human effort, meaning designers have a huge responsibility to make wise decisions. The production of physical products requires materials to be collected, manufactured, and transported, all of which can cause negative externalities to the environment. Additionally, the use and disposal of physical products may also cause externalities that are often not considered, as well as services such as data storage and delivery of goods. All in all, the functions in society that are fulfilled by either physical products or services, designed and engineered, all have some environmental impact (Watkins et al., 2021). This impact can be positive and negative with global or local effects on any of the natural spheres (bio-, cryo-, hydro-, litho- or atmosphere). For many years, people have been trying to measure and illustrate the human influence on their environment. Until recent, the integration of sustainability in the Industrial Design field was still limited (Jiang et al., 2021).

Many concepts, principles, and tools have been developed and used by designers to aid the creation of sustainable design. Examples of design principles are Design for Attachment, Trust, Durability, Maintenance and Repair, Dis- and Reassembly, Standardization, Compatibility, Adaptability, and Upgradability (Bakker et al., 2019). In addition, there are strategic models/approaches such as the Butterfly Diagram (MacArthur, 2013), the Sustainable Business Model Archetypes (Bocken et al., 2014), the LiDS Wheel (Brezet et al., 1997), and the Triple-Layered Business Model Canvas (Joyce & Paquin, 2016). As many of these principles and methods work on a qualitative level, acting as 'rules of thumb', they lack the quantification of environmental impacts and thus evidence-based decision-making.

Life Cycle Assessment (LCA) is a method that is widely known and used in academic and business practices. It is a method to quantitatively assess the environmental impacts of a product system through their whole life cycle. The International Organization for Standardization (ISO) has developed a few standards for the method, namely ISO 14040 and 14044 (ISO, 2006a, 2006b). Many adaptations to LCA have been made for implementation on different research questions (Guinée et al., 2018) or other than academic practices for instance those of Industrial Design (Fleischer & Schmidt, 1997; Kjaer et al., 2018; Suppipat et al., 2023; Vinodh & Rathod, 2010). A quantitative, holistic method, such as LCA, is needed for effective environmental decision-making in the field of industrial design. First, because quantification is needed for reliable and more exact results that form the basis of environmental decision-making (Chatty et al., 2022). Second, it is important to make the assessment context-specific to fully understand the product systems impacts. For example, the impact of electrification of a certain process or product depends largely on the electricity mix of the country where the process takes place. Third, it is important for designers to use LCA themselves as opposed to outsourcing it to an expert team. Through self-performance more comprehension of the LCA process and its results is achieved leading to a sustainable thought process during design. More understanding of LCA's complexity will lead to more nuanced interpretation of results and creative integration to the design. Without quantitative environmental impact results, the chances of correct design-decisions are limited. These reasons make LCA useful during the design process and by designers themselves. Therefore, in this thesis LCA use by designers is addressed.

Besides being potentially very useful for designers, LCA also has its limitations regarding the practical use in Industrial Design practices. Some of those limitations have been addressed in literature. First, designers encounter a lack of resource availability (Beemsterboer et al., 2020; Jusselme et al., 2018; Lofthouse, 2006). Resources can include time, money and information (especially in the early design phases). Next, LCA is often not used early in the design process or as guidance to the designer for conscious environmental decision-making. LCA is rather used as an assessment method at the end (Millet et al., 2007). It then has limited influence on the design, because freedom in design-decisions reduces over time (Malmqvist et al., 2011; Villares et al., 2017). Chatty et al. (2022) also highlight the need of using LCA earlier and more iteratively during the design process.

1.1 Problem statement and research questions

Besides the general limitations for designers as discussed in the last paragraph, there is a lack of knowledge and understanding of the challenges for designers inexperienced with LCA (henceforth: inexperienced designers). It is expected that LCA problems are more evident and likely different for inexperienced designers. Inexperienced designers, as assessed in this study, exist in both the industry and university contexts. This research will focus on a case study in university context.

The goal of this study is to enhance the utility of LCA method for inexperienced designers, through the identification of problems, relations between problems and test of an intervention to the system. Eventually this is so that LCA can be used more effectively for support in environmentally responsible decision-making. The correct use of the LCA method by designers will likely improve the design on environmental performance. The fundamental elements of LCA, in this study, are based on the ISO standard 14040 (ISO, 2006a) and handbook on Life Cycle Assessment (Guinée et al., 2002). The fundamentals include the goal and scope, inventory analysis, impact assessment and interpretation phase. More elaboration is found in Table 11, Chapter 4.3.4.

This builds up to the following main research question:

What is needed to enable design students, particularly at the Industrial Design faculty in Delft, without prior experience in Life Cycle Assessment to effectively incorporate the fundamentals of the LCA method into their design practices?

To address this question a case study at the Industrial Design Engineering (IDE) faculty at the Technical University of Delft is performed. This leads to the following sub-questions:

1) *What are the problems that design students experience when performing LCA for the first time?*
2) *What are the relations between the identified problems and what effect could possible interventions to the system have?*
3) *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?*

1.2 Societal, scientific and IE related relevance of the research

This study contributes to the scientific knowledge on the problems between inexperienced designers and their LCA performance in educational context. The problems can be used to validate other literature. It can be the start to test designer problems also in different educational contexts an industry. Additionally, the relation between problems can be used to test interventions to the system and therewith improve the effectiveness of LCA implementation by inexperienced designers.

Inexperienced designers can use the identified problems to recognize their own bottlenecks and find solutions.

This study contributes to the field of Industrial Ecology, by assessing the practical implementation of one of its core methods, namely LCA. It addresses the limitations and potentials which arise when implemented by Industrial Design Engineering (IDE) students. Industrial Ecology offers a systemic approach to achieving and maintaining a sustainable industrial ecosystem during continuous economic, cultural, and technological evolution. By assessing society as an ecosystem in symbiosis with its environment, resources (e.g. material, energy and capital) can be sustainably managed and measured (Kapur & Graedel, 2004). This includes the notion that products and systems are assessed rather in a circular life cycle approach than a linear one, which is relevant for designers of products. It is evident that the field of Industrial Ecology has their view on responsible product design. The practical implementation of this view by means of LCA is assessed in this study.

This research has a societal relevance as it helps improve the effectiveness of LCA implementation by designers with an implemented intervention. Therewith, designers can potentially make more environmentally responsible choices during the design of product systems. This is relevant to society as for the environmental impact of product purchase, use and discarding, consumers depend on designers. Designers make choices over product design that effect civilization and their environment it is therefore vital, to make responsible choices.

1.3 Approach and thesis outline

For this study, an interpretive explanatory research approach is used (Bhattacherjee et al., 2019). The approach is suitable for identifying reasons behind complex, interrelated social phenomena. It is holistic and contextual and involves inductive research methods. First, case study research at the IDE faculty in Delft is applied to develop a theory. Second, the theoretic findings are implemented through a later defined medium and tested.

To begin, data collection is done through empirical research at the IDE faculty. Teachers are interviewed on their overall attitude towards LCA, and reoccurring problems students run into. Student problems are analyzed through participatory observations during lectures and assignments. The findings are then validated with existing literature. Following this, the data analysis is done through thematic analysis. A system model is formed showing relations in the identified problems. Also, possible interventions are drafted to hypothesize the effect of interventions to the system. Then, data implementation is done through the design of such an intervention, improving current LCA practices. In this last research, the problem is defined, academic and application context is described, design requirements are constructed and concepts are developed. A final concept is presented and tested at the IDE faculty. The research is primarily qualitative and literature insights add some quantitative data. Figure 6, shows the research flow as described above.

The report is structured as follows, chapter 2 describes the theoretical background such as basic LCA methodology, modes of LCA, the evolution of design for environment and current IDE education. Thereafter, chapter 3 presents the methods used for answering the research questions. Chapter 4.1

presents the results from thematic clustering with data from observations and interviews at the IDE faculty validated by literature. Chapter 4.2 presents the relationships between problem themes and proposes possible interventions. Chapter 4.3 elaborates on one of these interventions that can be applied in order to resolve the main student problems identified. Next, results are discussed (chapter 5), conclusions are drawn (chapter 6) and recommendations are made (chapter 7).

2 Theoretical background

In this chapter, key concepts from the study are described. This is used as background knowledge for the rest of this study. A short introduction of Life Cycle Assessment is given to understand what method is under investigation. A short description of LCA modes is given. Also, a rough evolution of design and environmental sustainability is given. Lastly, the context of case study, IDE faculty in Delft, is described.

2.1 Life Cycle Assessment

A short description of the Life Cycle Assessment method will be given based on the ISO1404X standards created by the International Organization for Standardization(ISO) and the elaboration and implementation of these standards in the 'Handbook on Life Cycle Assessment: Operational guide to the ISO standards' by Guinée et al. (2002).

Life Cycle Assessment is defined by the ISO as the 'compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle'(ISO, 2006a). The method is used for the analysis of all environmental burdens associated with the full product life cycle (LC). This roughly includes material extraction, manufacturing, use and disposal. The term 'product' is used in the broadest sense of the word, meaning all products, services and systems fulfilling a certain function in society (Guinée et al., 2002). The term 'product' will be used as such in the continuation of this study.

The main objectives of performing LCA are as identified by ISO 14040 (ISO, 2006a) are to:

1. Identifying opportunities to improve the environmental performance of products at various points in their life cycle,
2. Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),
3. The selection of relevant indicators of environmental performance, including measurement techniques, and
4. Marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

The one that applies mostly for designers is (1) Identifying opportunities to improve the environmental performance of products at various points in their life cycle and (2) Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign). The latter applies mostly to the comparison of design/concept alternatives.

ISO (2006b) identifies four phases of Life Cycle Assessment: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment and 4) Interpretation (Figure 1).

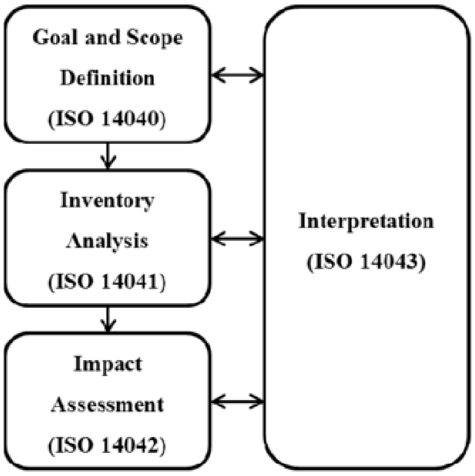

Figure 1: ISO framework for LCA (ISO, 2006b)

The goal and scope phase entails the research questions to be answered, the target audience, the intended application and scope in temporal, geographical and technological terms. At the goal and scope phase also function, functional unit, alternatives and reference flows are determined. The functional unit is the quantified function of the system indicating how much of a certain function is fulfilled with the system. The reference flow is closely related to the functional unit and represents one way of fulfilling the functional unit.

Take for example the product system of a walking shoe. The function could be: to protect human feet from cold, rain and sharp objects. The functional unit then could be: Protection of two human feet from cold, rain and sharp objects for 100 hours of walking in Norway. Two alternatives could be: a walking shoe from company X and a walking shoe from company Y. One reference flow is then the functional unit and one of the alternatives combined: Two human feet protected from cold, rain and sharp objects for 100 hours of walking in Norway by walking shoe from company X. This reference flow would be an outflow of the use process in your system flowchart.

Next, in the inventory phase, the inputs and outputs of the product system(s) involved in the life cycle are collected and quantified (Guinée et al., 2002). A flowchart describing the processes in the product system is created and the system boundaries are determined. This means the border between economy and environment, in relation to cut-offs and towards other product systems. Multifunctionality is the phenomenon that a certain process in the system contains a multitude of functions. Most often the way it expresses is that there are two valuable outflows from a process. This phenomenon needs solving, which is done in the inventory phase (e.g. through partitioning, system expansion or substitution). The Inventory phase also includes data collection for all the processes in the system, modelling in a software program if needed and calculation of all environmental inputs and outputs associated with the priorly determined functional unit. These environmental externalities following from calculations are called the inventory results.

In the impact assessment phase these inventory results are characterized through characterization factors into impact categories. This step is based on characterization models created by academia and (governmental) institutions such as Rijksinstituut voor Volksgezondheid en Milieu (RIVM) (Huijbregts et al., 2016) or Joint Research Centre (JRC), European commission (EC) (European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2010). After characterization the practitioner has the option to normalize results to a global or local average. Also, weighting of the impact categories can be done depending on the goal of the study and practitioners' preference. The results of this phase are environmental impact indicators either mid-point, end-point or single score.

Figure 2 shows, mid-point and end-point categories for the ReCiPe characterization model (Huijbregts et al., 2016) as an example. The benefit of midpoint orientation is that the category is close to the cause (or causing substances) and thus knowledge is detailed and more accurate. End-point categories state the impact closer to imaginable real-life practices which is beneficial, but uncertainty increases significantly as for end-point categories more (value-based) calculation steps must be done. Another benefit of mid-point categories is that trade-offs are transparent when modeling scenarios to the same alternative. With trade-offs, environmental impacts can be altered from one Life Cycle phase to the other (horizontally) or between impact categories (vertically). For end-point indicators there are only few indicators making trade-offs covered up, in some cases.

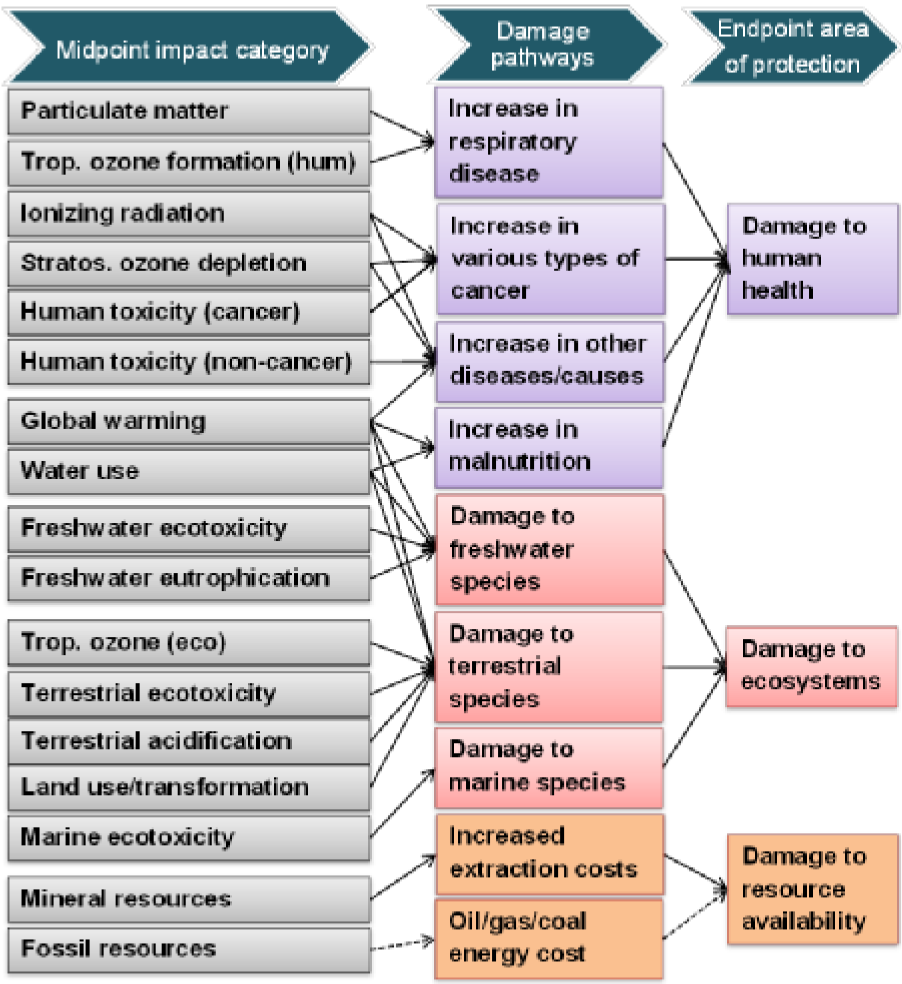

Figure 2: ReCiPe illustration of the characterization steps (Huijbregts et al., 2016)

The interpretation phase as described by ISO 14040 is something that is done continuously throughout the LCA study. It is important both for the practitioner to work iteratively and for verification and validation. The interpretation chapter in a report generally includes a consistency check, completeness check, contribution analysis, sensitivity and uncertainty analysis and result interpretation including discussion. If required, recommendations are provided here as well. For an LCA study to be properly scrutinized by external parties, these data analyses and evaluations are very useful and essential.

2.2 Modes of LCA

Since the origination of LCA, there has been many developments in the methodology and attempts to categorize adapted LCA modes for a clear and common language. Guinée et al. (2018) describe in their article titled 'Digesting the alphabet soup of LCA' the most distinctive modes to be consequential and attributional LCA. Consequential LCA assesses the changes in systems or scenarios and attributional LCA, models a situation as it is in current, past or future times. Seven out of eight modes focus on different ways of future modelling, so aim to estimate the effects of a scenario. Diverse goals and scopes ask for diversions of the methodology. Guinée et al. (2018) suggests using the term 'Explorative LCA' for all LCA modes that aim to model potential future scenarios.

For product design purposes explorative LCAs are most relevant especially during the design process. Explorative LCAs can be used to explore substance contributions, various scenarios, compare alternatives, test upscaling of unit processes and more. Results can be used for (design) decision purposes under many preconditions, as future data are very uncertain. A difference to design practices is that most often, explorative LCA's are used for long term projections aiming to model in the far future such as ten to hundreds of years. Whereas LCA's for product design purposes often develop in a faster paced setting for a closer future such as a few years, until market introduction.

Also, ex-ante LCA and ex-post LCA are distinguished (Guinée et al., 2018). Ex-ante LCA focusses on the assessment of emerging technologies. The challenges here are mainly to acquire projected data and define the system. This includes the future scope definition, unit process data (new production technologies, upscaling of processes), the absence of future background data, characterization factors and appearance of unknown unknowns (Cucurachi et al., 2018; van der Giesen et al., 2020). These challenges bring increased uncertainty in the Life Cycle Impact Assessment and has not been elaborately discussed in literature.

Besides different modes of LCA, there have been many simplifications of the method as described by Beemsterboer et al. (2020). Further elaboration on LCA simplifications and other adaptions suitable for designers can be found in chapter 4.3.2.

2.3 Design for environmental sustainability and LCA

In the field of Industrial Design, many methods to integrate environmental sustainability have been constructed and adapted from other fields. The field is generally known as Design for Sustainability (DfS) or Design for Environment (DfE) and has been around for decades.

Some history and evolution of DfS are addressed in the comprehensive overview paper of Ceschin & Gaziulusoy (2016). They distinguish four levels of sustainable design approaches developing from insular to systemic and from technology to people focused, see Figure 3. The product innovation level includes Green Design, Eco-design, Biomimicry, Emotionally durable design, and Design for sustainable behavior. Eco-design, around 1995 represents the first design approach where quantitative environmental assessment is done, namely through LCA. So LCA acts as an assessment part of the design approach. An early critique from Ceschin & Gaziulusoy (2016) is that with these LCAs no social and economic sustainability is considered. Additionally, the full life cycle approach has not been very effective but more of a formality, according to their study. The use phase is not genuinely considered and properly quantified leading to a lack of focus on consumer behavior. Therefore, it is claimed that additional design approaches, such as emotionally durable design and design for sustainable behavior, are needed in addition to LCA.

At the next level, Product-service system innovation, and design are shifting towards the inclusion of business models. In these cases, the function delivered is considered more important than ownership of the product delivering the function. This leads to innovation in service designs and system thinking with the ambition of decoupling economic value from material and energy consumption. As ownership, in these cases, is often shifted to the producer, quality, material, and energy optimization are stimulated intrinsically (Ceschin & Gaziulusoy, 2016).

Systemic design level is even more holistic than product-service system design. It integrates the perspective of Industrial Ecology and Cradle-to-cradle, to design approaches. Industrial Ecology focusses on achieving and maintaining sustainable industrial or urban ecosystems through economic, cultural and technological development (Kapur & Graedel, 2004). The basic principle of cradle-to-cradle is; 'Everything is a resource for something else' (McDonough & Braungart, 2002). In application this means designs should be created with the goal of being able to safely disassemble products and return biological nutrients to the soil or reuse them as high quality materials for new products without contamination (McDonough & Braungart, 2002).

In the systemic design level, even more socio-economic actors, assets and resources become evident and important in the ecosystem and design of a system/product/service (Ceschin & Gaziulusoy, 2016). A limitation addressed by Ceschin & Gaziulusoy (2016) is the lack of influence this design method has on individual consumer behavior. The individual consumption pattern (overconsumption or behavior during use) is not addressed, it should be used in combination with one of the levels addressed above to be more effective.

Lastly, the design of socio-technological system level evolved, the notion of designing for system innovation and transition through technological, social, organizational and institutional innovations. Theories such as Backcasting (Weaver et al., 2017), Strategic Niche Management (Kemp et al., 1998), and Transition Management (Rotmans et al., 2001) are the basis for this design approach. All these approaches are very high level an environmental assessment can be done on parts only. It needs to be combined with low level design approaches for practical implementation and assessment.

Within the last three levels, designers have to deal with, and possibly nudge, behavioral and cultural changes. These levels can be very influential and beneficial for the socio-environmental symbiosis, but it is often a slow-changing behavior that can influence these levels. Also here, environmental assessment methods are addressed in a different manner. Performing an LCA is perceived to be more complex in these systemic designs, especially regarding the socio-technological level. Kjaer et al. (2018) describe a set of additional guidelines for using LCA in a product-service system (PSS) evaluation. Largely it follows the conventional LCA framework but more attention by Kjaer et al. (2018) is given to avoiding rebound effects, the risk of biased results, and the cut-off errors. Rebound effects can be due to unknown or unpredictable behavior of the consumer in the use phase. For example, when car leasing would become financially interesting through a product-service system, consumers might decide to drive more kilometers, as they would pay less per km now, the rebound effect is more emissions during use (even though there might be less during production).

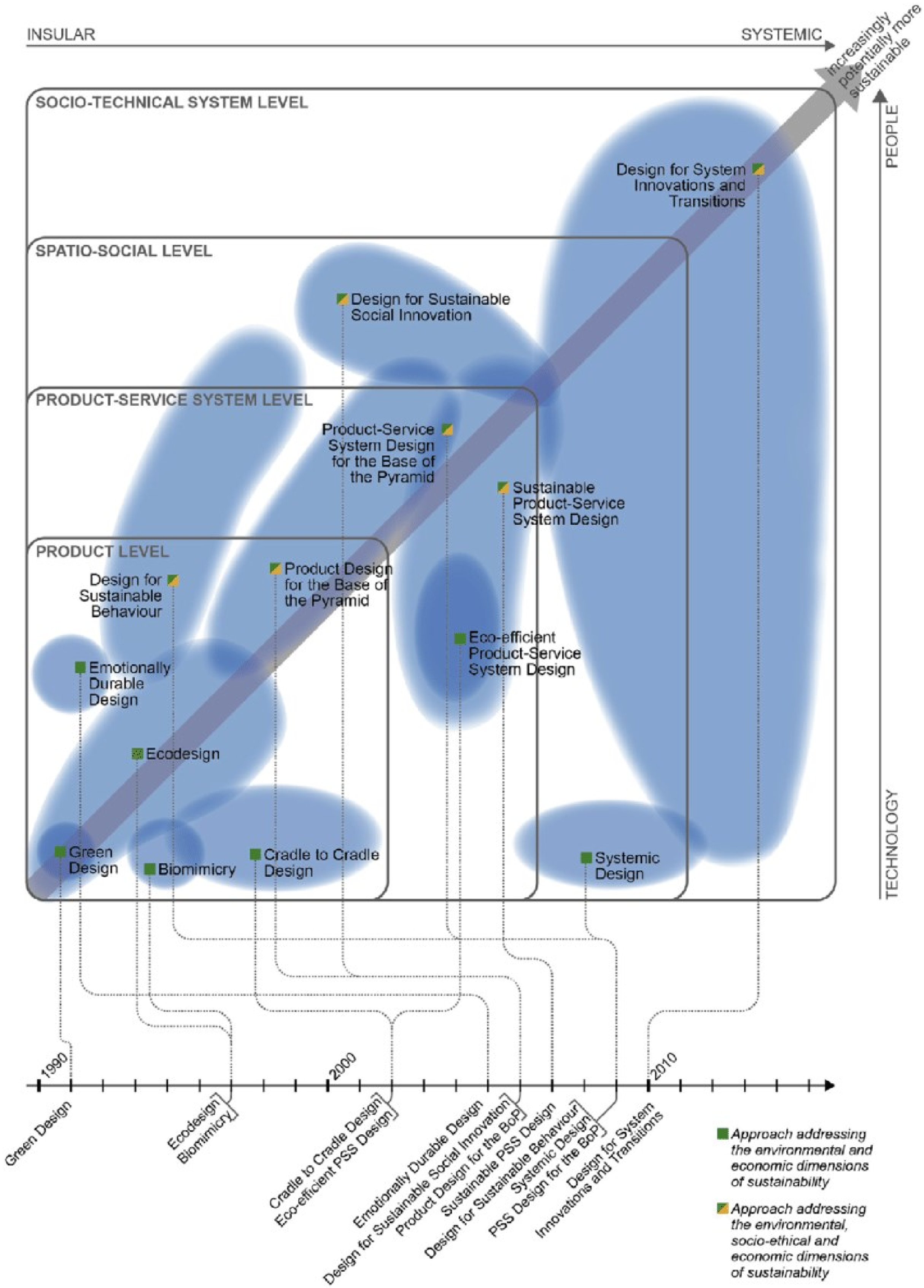

Figure 3: DfS evolution framework with DfS approaches mapped out (Ceschin & Gaziulusoy, 2016)

In conclusion, there are many DfE methods developed and implemented for different objectives. Many methods are qualitative and focus on economic or social sustainability. LCA has been used foremost at a product and product-service system level. What makes LCA unique is the fact that it is holistic, it assesses a full product life cycle, impact categories are broad and in-depth, well-argued measurable parameters (quantitative) and it is context specific. Guidelines and principles that are static will not overcome contextual changes or dynamic parameters and impact shifts. Designers do not have the tools to overhaul their perceptions regarding sustainability when using solely qualitative approaches. Assessing trade-offs becomes easier when a quantitative method is used. Nonetheless, there are limitations to LCA as well. LCA is not (yet) suitable nor broadly implemented in the 'spatio-social' and 'socio-technical system' level of design. The levels are too elevated for the quantitative and data-driven method of LCA and therefore not covered in this study either. Another, limitation of LCA is that it only covers one of three sustainability pillars namely environmental sustainability. Social-LCA (SLCA) and Life Cycle Costing (LCC) are methods that can cover the other sustainability pillars however, they are not addressed in the current study.

2.4 Case study context description

In this section the education module on DfS from the IDE faculty at the University of Technology Delft is described. There are several courses where sustainability is addressed in the IDE Bachelor (Figure 4). In the Masters, LCA is only taught in electives (e.g. Sustainable Design Strategies for Product Development) or individual projects. Focus of this study is the mandatory course 'Sustainable Impact' where LCA is first instructed to all bachelor students.

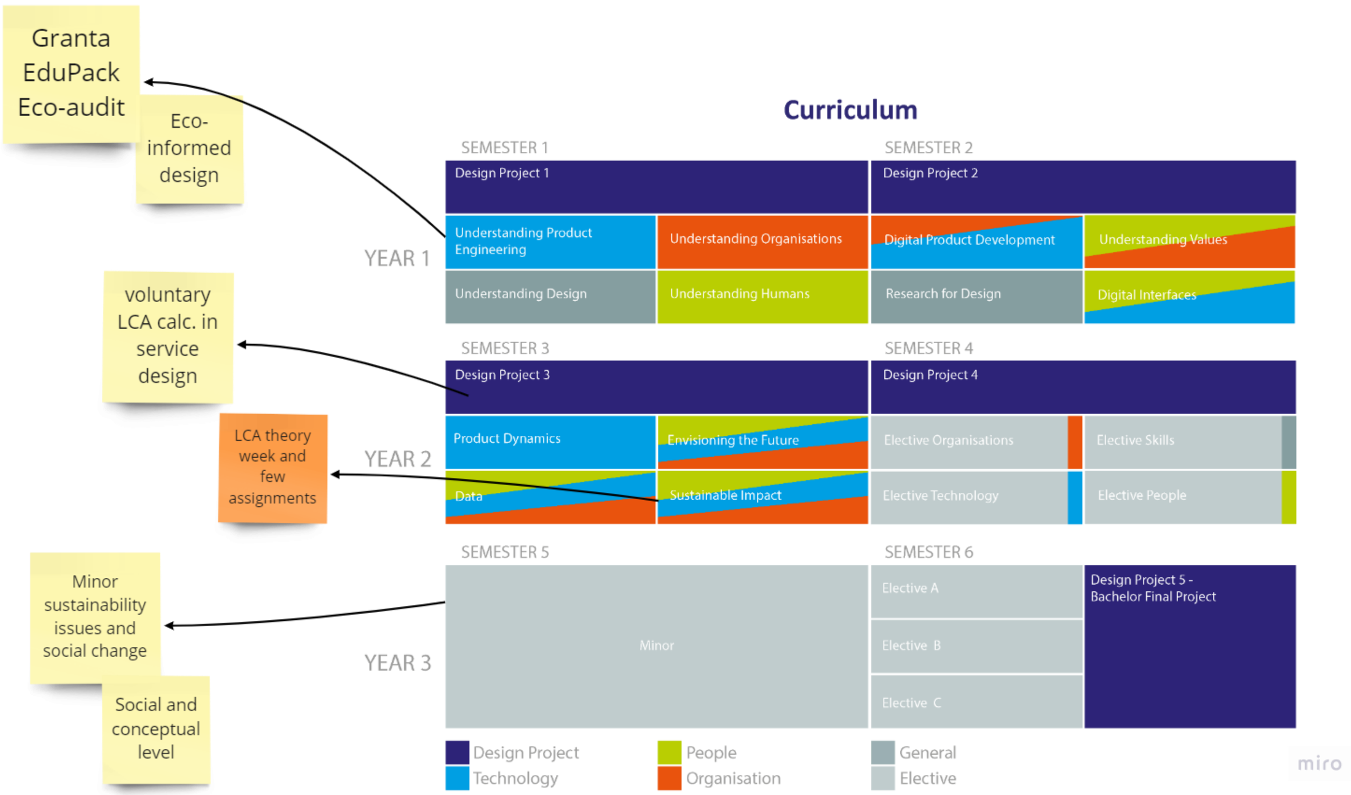

Figure 4: Appearance of design for environment in the bachelor of IDE

The Sustainable Impact course is taught in the second year of the bachelor program and is worth 7.5 ECTS (out of 120). One week (out of 8) is dedicated to LCA and the remaining weeks have the following subjects: people, planet, profit; Evolution, methods, systems; Energy effectiveness; Materials and sustainability; Design for recovery; Sustainable business models; Behavior change. In these other weeks, LCA is integrated during the material choices, and connected to Whole System Mapping exercise, The Eco-design Strategy Wheel and the Cradle-to-cradle perspective. These methods and perspectives are qualitative and touch upon Life Cycle Thinking (LCT) in product design. LCA is used in these cases as an example to verify qualitative theories.

Learning objectives regarding Life Cycle Assessment are stated as follows (*Week 3: Life Cycle Assessment - IOB3-5 Sustainable Impact (2022/23 Q2)*, n.d.):

- Read an LCA and use it to set sustainability priorities or compare design options.
- Explain what LCA measures and what it does not measure.
- Choose a fair and convenient functional unit.
- Calculate environmental impacts by performing a simplified LCA.

The course materials include paper readings, a course reader, video lectures, in-class lectures, three modelling assignments, practices exam questions and a Q and A platform. The classes (2 times 2 hours) consist of an interactive lecture combined with an in-class assignment and guidance.

In the course reader, LCA is a prominent topic. It covers topics such as reading an LCA, doing simplified LCA and scenarios, functional units and uncertainty, the latter are regarded as important topics or common pitfalls. Goals of making an LCA are discussed, such as setting priorities, choosing between options, making tradeoffs, benchmarking and setting goals, and avoiding greenwashing. The chapter explains various impact categories and how these relate to the planetary boundaries, as well as how impact categories are merged into single score categories. The reader recommends using existing LCAs from similar product systems and explains how to validate the quality. An assignment (2-10 hours) is included to design based on existing LCA(s), including finding relevant LCAs, identifying biggest impacts, prioritizing design strategies, brainstorming improvements, estimating improvements of the best idea and illustrating the best idea, as described in Appendix A.

In the chapter 'Doing Fast-Track LCA', practical instructions are provided on how to complete a simplified LCA using the ‘IDEMAT’ Excel tool (Joost Vogtlander, CC BY 4.0, “Tool in excel,” n.d.) or alternative tools. Guidance is also given on how to find direct substitutes or combine components to create proxies for data input. To put the instructions into practice, an exercise is included for a refrigerator and is completed in a 2-4 hour classroom class.

The last chapter of the course reader describes the most common flaws of an LCA (Faludi et al., 2022): scenarios, functional units and uncertainty. It is noted, for example, that no LCA data can have better than ±10% precision (Ashby, 2021). The chapter then explains how to handle uncertainty and interpret results, and provides tools to better estimate uncertainty, such as making sensitivity analyses. Lastly, the chapter gives examples and tips for constructing a functional unit. The chapter 'Design Strategies' explains design principles, tools, and best practices, which are all qualitative ideas that can be tested for effectiveness using LCA.

During the LCA week three types of modelling assignments are addressed. There is a refrigerator and C2C book assignment which are recurring during the course with different sustainability methods. The refrigerator assignment is done in-class and a Bill of Materials is given. In this assignment the only impact category selected is climate change as the carbon footprint (expressed in kg CO_2-eq). Additionally, a comparative LCA on two types of books is done. Here, no inventory is given, and the students are expected to express results in carbon footprint, eco-toxicity categories as well as eco-costs single-score category. This second assignment also addresses multifunctionality and end-of-life accounting as one of the books contains recycled paper.

Figure 5 shows the currently used Excel calculation tool that supports the assignments addressed priorly. The IDEMAT-database has been constructed and updated by Joost Vögtlander based on the Life Cycle Inventory (LCI) data from Sustainable Impact Metrics Foundation (SIMF) which is defined as a TU Delft ‘non-profit spin-off’. The IDEMAT database and tool is developed for designers, engineers, architects and manufacturing building industry. It is aimed to educate students and apply simplified LCA in the fuzzy front end of design. The database is built on peer-reviewed scientific papers an LCIs constructed by the following institutes: TU Delft, Plastics Europe, Probas, USLCI, ELCD, CES Edupack, Univ Chalmers and EI. IDEMAT claims to be in accordance with ISO 14040, 14044, EN15804, and the ILCD Handbook (Sustainability Impact Metrics, n.d.). In Appendix A, calculation rules regarding the IDEMAT-dataset are provided. As seen in Figure 5, a very narrow goal and scope description is asked for in the top left corner. The main focus of the tool is on input of the unit process table, the table where all value based in- and outflows are collected. Calculations towards impact assessment is done in a ‘blackbox’, whereafter impact contribution graphs are shown to the user. The LCA interpretation phase is not guided upon. More elaboration on the tool is given in chapter 4.3.3.

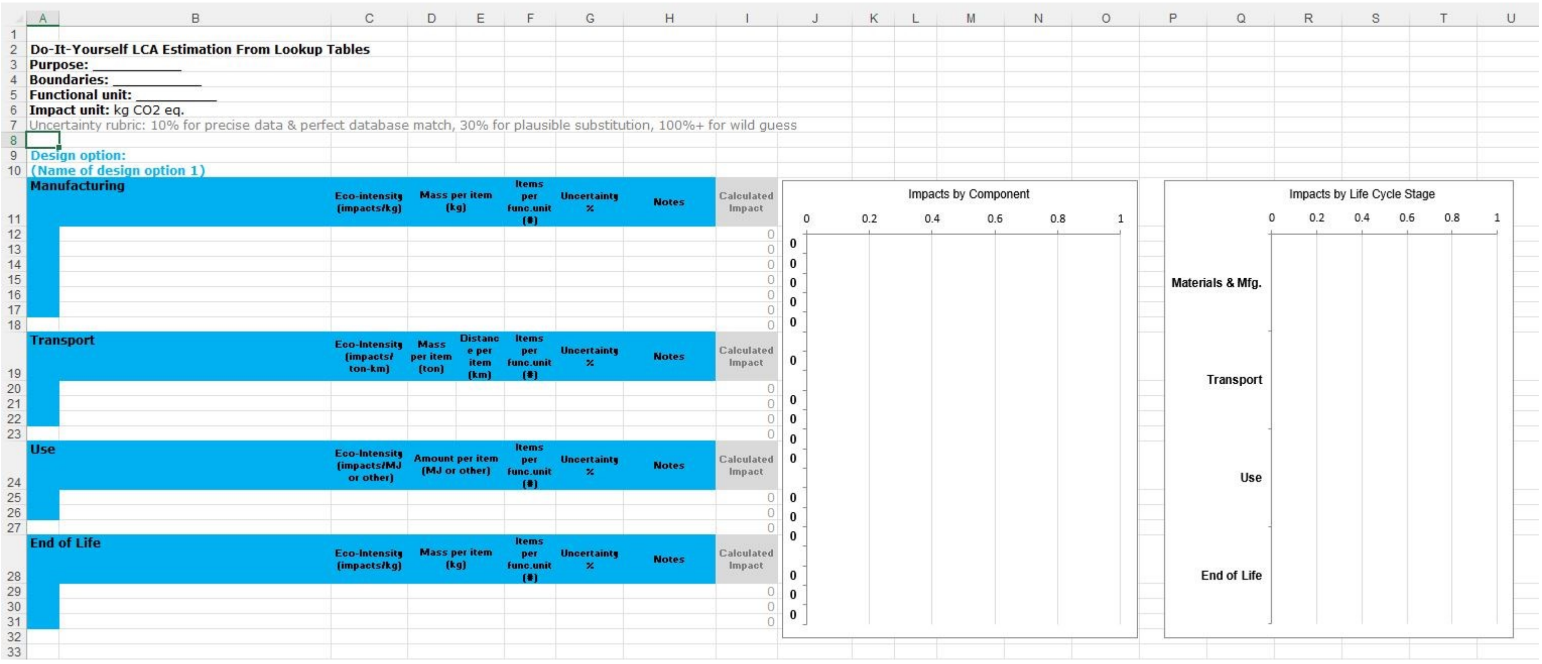

Figure 5: Screenshot of IDEMAT LCA calculation tool

3 Methods

This section describes the methods used to address the research question: *What is needed to enable design students, particularly at the Industrial Design faculty in Delft, without prior experience in Life Cycle Assessment to effectively incorporate the fundamentals of the LCA method into their design practices?*

The overall approach of this research is a case study research of qualitative nature (Bhattacherjee et al., 2019). The case study context is the Industrial Design Engineering faculty in Delft. The first part of the research is inductive, builds a theory (a system model) and the second part is deductive, implements and tests the theory, or particular one possible intervention.

Figure 6 shows the method flow diagram for this research. It consists of several phases, depicted in the first column and uses several methods, as depicted in the second column. The third column represents the type of results that are outcome of the methods. The last column shows the reasoning of the research phase, namely inductive at first and deductive later.

First, preparation of the research is done through literature research and documentation analysis. A theoretical background description based on documentation and literature. Second, the data collection is done through participant observations and interviews (Bhattacherjee et al., 2019), validated by literature research. Third, the data analysis is done through thematic analysis (Guest et al., 2011), system modeling and drafting of possible interventions. The choice of an intervention to test is based on research resources (time, location and researcher skills). A semi-structured literature review is done to gain a context description for the chosen intervention. Fourth, data implementation is done by various design methods (van Boeijen et al., 2020). Finally, the concept is presented and concept-evaluation is done through an online and in-class survey (Bhattacherjee et al., 2019). In this chapter the methods will be described per research sub-question.

The research preparation is found in the previous chapters.

Chapter 3.1 explains the data collection phase through the methods, empirical research at the IDE faculty with teacher interviews and participant observations with students.

Chapter 3.2 addresses the data analysis phase through the methods; thematic analysis and system modeling that are used to answer the first two sub-questions: *What are the problems that design students experience when performing LCA for the first time?* and *What are the relations between the identified problems and what effect could possible interventions to the system have?*

Chapter 3.3 goes into the data implementation and evaluation phase through design methods and a student survey. They are used for answering the sub-question: *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?*

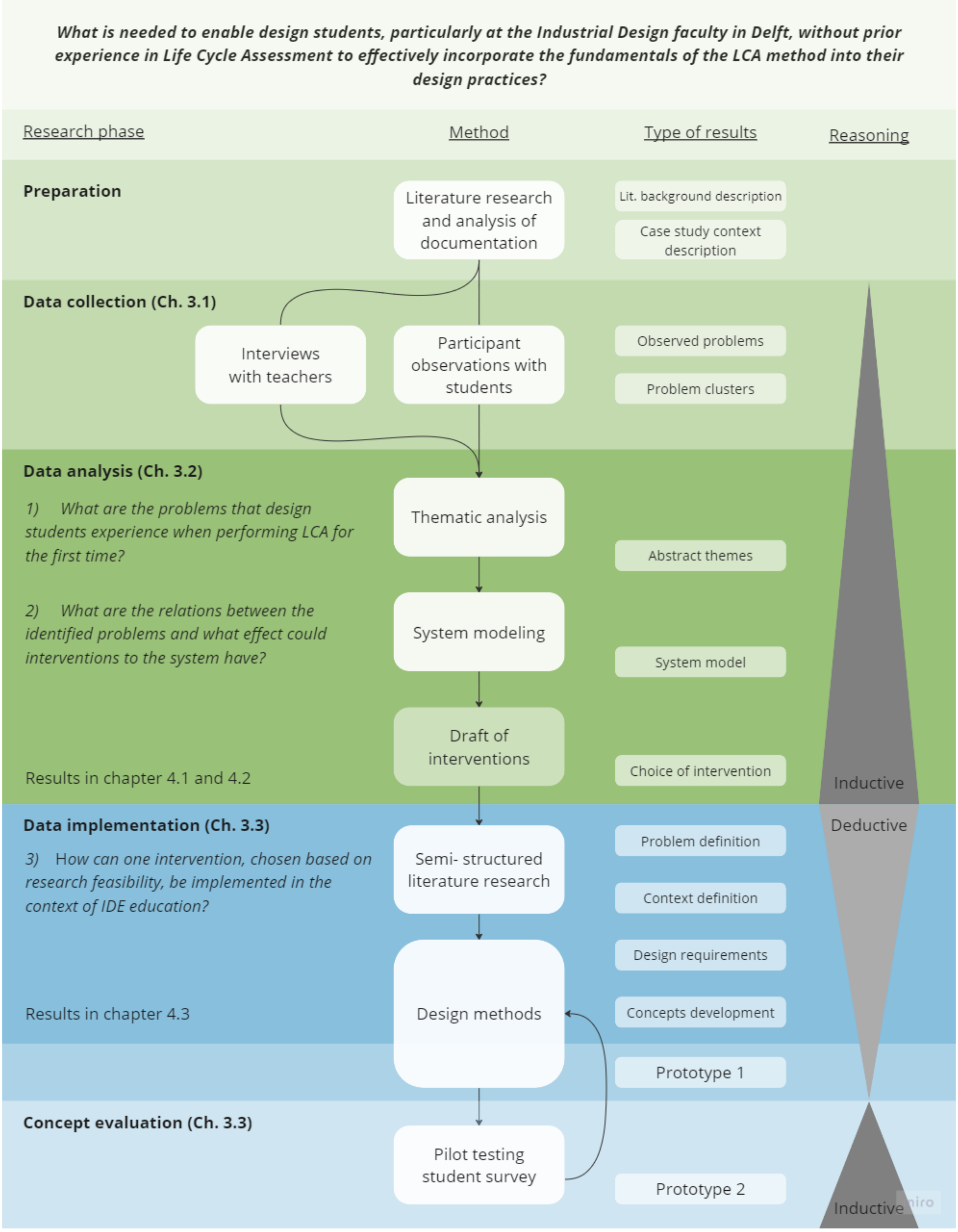

Figure 6: Method flow diagram describing the methods and their characteristics used to answer the main and sub-questions

3.1 Data collection

This chapter describes the methods used for data collection. These methods are empirical research consisting of interviews and observation with teachers and students at the faculty of Industrial Design Engineering (IDE) in Delft. Results are supported with literature findings.

Interviews with teachers

The goal of the teacher interviews is to gain primary qualitative data of unobservable facts, namely preferences, attitudes and behaviors from teachers towards LCA for inexperienced designers.

The data collection is done through semi-structured interviews with teachers. 7 teacher and assistants that educate LCA both conceptually and practically (modelling) are interviewed. The interviews have a length of 30-60 minutes. Sampling is done through e-mail to all LCA teachers and participation was voluntary. Interviews, performed at the IDE faculty, have been recorded.

The interviews are documented by notation and summarizing of answers to the interview questions. The interviews are also listened to again for confirmation and interpretation. A pattern is sought in the summarized results leading to problem clusters that overarch several student problems. The interviews were also useful to get insight into the context of student problems regarding LCA as teachers who teach LCA for several years can take some more distance and have an overview of the problems.

The data are validated by using existing literature on designer problems regarding the use of LCA and specific student problems regarding DfS and LCA. The literature foremost consists of case studies in different contexts.

Interview questions and results can be found in appendix B (Excel document).

Participant observations with students

The goal of the participant observations with students is to gain primary qualitative data describing the problems that students run into during LCA workshops and lectures.

Data are collected through participant observation (Kawulich, 2005). Participant observation is part of interpretative inductive research. Observation in general entails watching the research group in their natural activities without disturbance of their activities. In participant observation the researcher joins the research group and their activities and can observe closely. Overall, the goal is to gain familiarity with the research group and their issues by actively engaging with the research group and their context.

In this research, the researcher has been acting as a teaching assistant answering questions in the exact research context, namely the classroom where LCA is taught and practiced initially. The researcher not only observes students, but also engages them in conversation by responding to problems and questions about the task and posing additional questions to discover the source of confusion and problems.

The use of participant observation research in this research has many advantages. One major advantage is that the researcher, acting as a teaching assistant, can observe and interact with students without them feeling any pressure to give a socially desirable answer. Additionally, there is no risk of recall bias since the observations performed in the moment, meaning students don't need to remember the questions asked during class at a later time. Lastly, students are often unaware of the problems they encounter during assignments and lectures and may not remember them after they've been solved.

Documentation of the participant observations is done through notation of frequently asked questions of students and general student attitudes. It is documented by the researcher and by the 3 teachers. The questions are ordered according to the four LCA phases from ISO 14040. The participant observation is done during both the lecture hours and workshops.

The sampling of the participant observation is done on a random basis during the workshop hours (4x2 hour sessions) at the end of November 2022 from the course 'IOB3-5 Sustainable Impact'. In total around 150 students were present to listen to the lectures and make the assignment. During these sessions there were parallel classes. Also, a 4-hour session during the master course 'Sustainable design strategies for product development' has been attended. So, the sample includes design students with either +-2 or 4 years of design education. The age range of participants was either 18 to 21 years old in the bachelor or 21 to 25 years old in the master course.

The data is documented and ordered by ISO 14040 phase. The observed problems are interpreted on the reason why they would occur and labeled accordingly. Next, observed problems that are closely related, are clustered to together in so-called problem clusters. The step from observed problem to clustered problem is a qualitative and iterative process. Some observed problems contribute to two problem clusters, or some are not at all turned into a problem cluster.

Participant observation notes can be found in appendix C.

Possible biases of interviews and participant observations

The interviews and participant observations both have a moderate external validity (generalizability) as they are performed in the case study context and validated with academic literature in different contexts. However, there are limits to its generalizability, this will be discussed in chapter 5.

The internal validity, the extent to which cause and effect can be isolated, is more difficult. This is, because the research has been in university context with many potential causational factors that could have impacted the outcome (e.g. personal student problems, teaching skills or the time of the day).

The interviews and participant results may have possible biases. First, there could be a social desirability bias as sustainability is a topic gaining popularity (Flynn et al., 2021) and being negative about it can be violating your social image in certain environments. This might bias the results to a predominantly positive view towards LCA. Second, the interviews are sensitive to steering by interviewer as it is semi-structured and follow-up questions can be steering the subject. In participant observation the researcher is considered part of the social phenomenon. The teacher must therefore take a neutral and unbiased stance because a subjective stance can influence the results. Third, interviews and observations have been manually summarized by the researcher which can be prone to biases. Fourth, there might be a sampling bias. For teachers there was a voluntary application which might lead to a sample with teachers motivated towards improving education, LCA or sustainability. In the participant observations there might be a bias towards motivated students as those are the ones participating in class (around 50% of 300 students). Finally, for teachers a recall bias might be applicable, as for some teachers it has been max. 1 year ago that they have last taught LCA. In chapter 5.3, more details are provided on the limitations of the methods used.

Results from this research phase will include observed problems and problem clusters.

3.2 Data analysis

This section describes the methods, thematic analysis and system modeling, used to answer the following research sub-question: *What are the relations between the identified problems and what effect could possible interventions to the system have?*

In order to reach the ultimate goal to '*enable design students …. to effectively incorporate the fundamentals of the LCA method into their design practices'* it is essential to consider the effects of different manners to enable (or interventions). However, from a large collection of student problems, it is hard to determine what effect an intervention would have. Therefore, the identified problems are clustered and overarching themes are sought. This way, it is possible to overview the problems/themes and seek dynamics between them. Knowing the dynamics will let us predict the effect of interventions.

Thematic analysis

The goal of thematic analysis (Guest et al., 2011) is to develop a more general view from many scattered datapoints. In this research those datapoints are the student problems. Thematic analysis is an inductive method where qualitative data can be systematically and rigorously analyzed. First, one ought to become familiar with the data. Second, the data is coded with terms or statements, defined by the researcher, that cover overarching subjects. Third, themes are sought that overarch the data. Finally, the themes are reviewed and iterated upon (Maguire & Delahunt, 2017). The iteration and review, preferably also done by an external party, is important.

For this research, data input are the problem clusters from empirical research at the IDE faculty. As participant observation and interviews has been done by the researcher, familiarity is already well established. The data input from empirical research are the problem clusters. Coding the data with overarching terms or statements has been done by seeking patterns in the frequently asked questions, the interview results and observations. Criteria used for coding the problem clusters is the nature/origin of these student problems. So first, causes for the student problems are sought. For instance, what is the reason for students asking a certain question. But also, what is the underlying reason for certain student behaviors and experiences. After the cause of the problems have been defined, the student problems are clustered/categorized per cause. In this exercise, the causes might change slightly and get more nuanced. The eventual themes are thus overarching reasons behind the student problems.

This step is inductive and thus building up to a theory. It involves a significant amount of researcher bias, as clustering can be done in many ways. Therefore, some feedback has been consulted from peer Industrial Ecology students and external people not involved in design education.

System modeling

The themes identified in the thematic analysis do not stand alone. Rather they are connected in some way forming a so-called 'system'. A system is a set of parts that interact with one another and form a whole that is greater than the sum of its individual parts. Modeling the identified themes in a system is essential to understand the (systemic) effect of possible interventions or improvements to a certain theme. The interaction in a system can be modeled in a causal loop diagram. The goal of a causal loop diagram is to map out the system structure and understand (feedback) dynamics (Haraldsson, 2004). Creating a causal loop diagram is done through identification of cause-effect relationships between variables in a system, in this research; the themes. Thereafter, the 'polarity' of the relationship between themes is identified. This is either positive, increased variable A will increase B, or negative, increased A will decrease B. Lastly, possible loops are identified that describe the cascade that a certain increase or decrease of a theme can have. Loops can be reinforcing or balancing. Figure 7, shows an example of a causal loop diagram. In the current research, loops are not identified fully but rather possible interventions are drafted for the expected effect on the system. The next paragraph will elaborate on this intervention drafting.

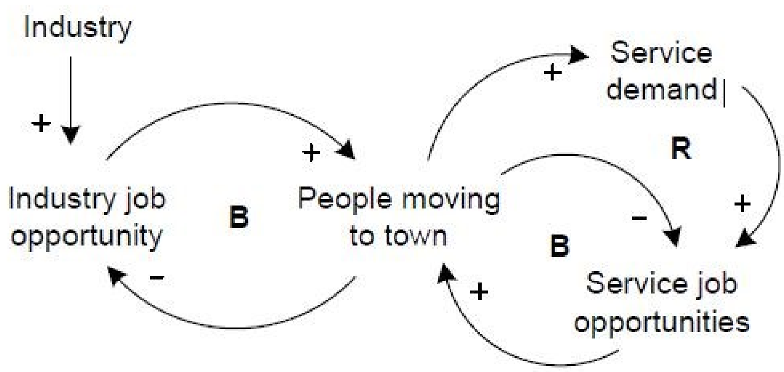

Figure 7: An example of a system model, causal loop diagram. The '+'-signs indicate positive polarity of the relation between variables, '-'-signs indicate negative polarity of the relation. B stands for balancing loop and R stands for reinforcing loop.

Draft of possible interventions

From the system model, dynamics between themes can be assessed. Especially dynamics following from external interventions are interesting for this research to know. This is because one of the goals is to develop an intervention to improve the incorporation of LCA by inexperienced designers. Before designing this intervention, several possibilities can be modeled.

In academics, this phase would generally include elaborate 'scenario development'. Scenarios are normally generated by insights from stakeholders in the system (e.g. surveys, workshops or the Delphi Method). The judgement of different stakeholders is combined, and a collective view can be gathered during workshops. Explorative scenarios generally answer the question: 'What can happen?' and are helpful for strategy development (Börjeson et al., 2006).

Due the temporal scope of this research and limited access to stakeholders, no elaborate scenarios are developed. Instead, possible interventions to the system are drafted. This is done by the researcher alone and the reason for these drafts is to communicate possible interventions and hypothesize the influence on the system. One of the possible interventions is chosen based on research resources namely time, pilot test location and capabilities of the researcher.

Results from this research phase will include themes describing student problems, a system model and a chosen intervention (Figure 6).

3.3 Data implementation/intervention testing

A semi-structured literature review and design methods are used to test the chosen intervention and answer the final research sub-question: *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?*

To answer this research question, a context description is achieved by a semi-structured literature review. The problem definition and context description are based on current developments of LCA for designers in literature and documentation. Results from the empirical research and semi-structured literature research are translated into a list of design requirements and implementation thereafter. The design is done by the researcher, with the design process based on the Delft Design Guide (van Boeijen et al., 2020). The next section will elaborate on these methods.

Problem definition
The goal of a problem definition is to provide a common language between the researcher and readers of the research (or other stakeholders). Problem definition is done by defining; why is this the problem, for whom, when and where, what are relevant context factors. Additionally, one may define what is the desired situation and what are the possible side effects to be avoided. Next, the scope is defined, appropriate for this research. Finally, a problem definition is written down, this is an iterative process (van Boeijen et al., 2020).

For this research, the data inputs for the problem definition are from the empirical research, the student problems and system model. Additionally, there is current method and tool developments from literature, documentation of the current practices LCA tool and LCA fundamental elements gained from (Guinée, 2002; ISO, 2006a).

Academic context: Semi-structured literature research
A semi-structured literature research is intended to overview a research topic and assess its progress over time (Snyder, 2019). Steps to follow for semi-structured literature research differ per user of the method. In general, a research question and goal are constructed, search queries are composed, and search engines are decided upon. Queries are applied to the search engines and paper results are documented. The papers are roughly read, and selection of papers is done based on selection criteria. The selected papers are more thoroughly read, and an analysis can be applied. Analyses in semi-structured literature review are commonly qualitative of nature and can include thematic analysis as discussed priorly (Guest et al., 2011). The main take-aways from the literature research are documented as preferred.

In this research, the goal is to find the current LCA method developments in academic literature regarding the use of LCA as a decision-making tool in early-stage design. The early-stage design phase is addressed in this goal, as this is the phase where there is still design freedom and room for environmentally positive decision-making. The objective is to get a context description for further intervention implementation. The question for this literature review is found in Table 1. The data needed are the current state practices, barriers and drivers.

The review is performed with search queries as described in Table 1 and snowballing method based on expert consultation. Case studies, review papers, method development papers are included. The selection is based on the following criteria: 1) In the papers LCA should be used as a design-decision tool, not only as final assessment, 2) papers focused on social or monetary LCA are excluded. Web-of-science and Scopus are used as search engines. They are validated search engines and the same papers appeared when including more search engines. Also, it is decided that all search queries need to appear in the abstract. This is to assure these terms are in the core focus of the paper.

Analysis of selected papers is done with a mild version of thematic analysis (Guest et al., 2011) and main take-aways are documented in chapter 4.3.2.

Table 1: Search query for semi-structured literature review.

What are the developments in academic literature regarding the use of LCA as a decision-making support in early-stage design?		
Search engine	**Search query**	**Results**
Web of science	ABS (LCA OR "Life Cycle Assessment" OR "Life Cycle Analysis" OR "life-cycle analysis" OR "life-cycle assessment" OR "life cycle impact assessment") AND ABS ("design tool" OR "product design" OR "Service design") AND ABS ("Early stage" OR early-stage OR "Early design stage" OR ex-ante OR "ex ante")	25
Scopus	ABS (LCA OR "Life Cycle Assessment" OR "Life Cycle Analysis" OR "life-cycle analysis" OR "life-cycle assessment" OR "life cycle impact assessment") AND ABS ("design tool" OR "product design" OR "Service design") AND ABS ("Early stage" OR early-stage OR "Early design stage" OR ex-ante OR "ex ante")	51
Snowballing	Through professor/interview recommendations and from the paper Beemsterboer et al. (2020).	5
Exclusion	- In the papers, LCA should be used as a design-decision tool not only as final assessment. - Papers focused on social or monetary LCA are excluded. - Non-unique papers are single counted.	-55
Final sample		26

Besides literature research on LCA as a method, grey literature and documentation is needed on LCA modeling software/tools to get a context description for LCA tools. This is done through a search for often used tools and assessment of the tools based on (fundamental) LCA steps. Some additional assessment criteria are included such as the usability, interface, accessibility and finally suitability for designers. Lastly, the tools are compared on those criteria and connections are sought to the needs of a designer.

Application context: 'contextmapping'

The other part of the context is the application context, namely the IDE faculty with its design students. The methods used for analyzing this context can be called 'contextmapping' in design practices.

In this research it includes more than one method, namely the previously used interviews, participant observations. The contextmapping has thus already been described in chapter 3.1. The insights are the basis for constructing the list of design requirements. (van Boeijen et al., 2020).

List of requirements

The goal of the list of requirements is to set boundaries to the ideation process. The first step is to create a structure for the requirements. Then, one collects as many requirements as possible and identifies gaps in their knowledge regarding the requirements. Lastly, overlapping or abundant requirements are eliminated and possibly a hierarchy is constructed. The list of requirements is constantly refined and updated. (van Boeijen et al., 2020).

In this research, design requirements are selected based on the chosen intervention from the previous research phase and corresponding problems. Figure 8 illustrates the construction of design requirements. The design requirements are structured by context requirements gained from literature, incumbent LCA tool and LCA fundamentals (Guinée, 2002; ISO, 2006a) and user group requirements (based on empirical IDE research), see Figure 8. Another structure is made based on the system themes that are affected. A hierarchy is constructed where the 3 most important and overarching requirements are extracted.

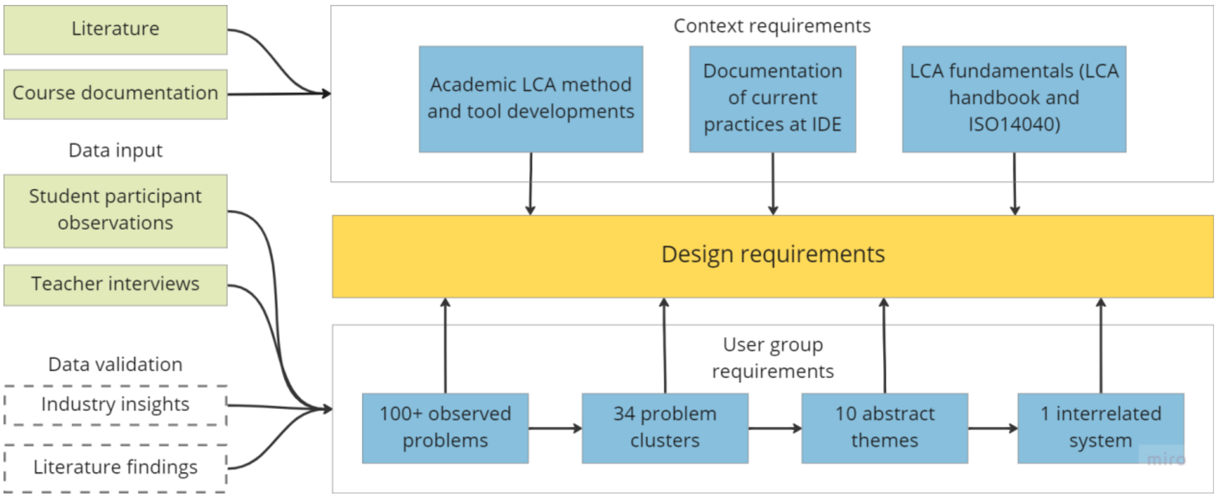

Figure 8: The composition of design requirements

Partial function fulfillment: How-Tos

After the list of design requirements is composed, brainstorming with partial function fulfillment is done. In design terms this can referred to as the method 'How-Tos'. This means design requirements are individually solved and eventually merged. Solving the individual design requirements is done by constructing a question such as 'How to explain a Functional Unit to design students?'. As many answers as possible to this question are generated. The answers or solutions are thereafter ordered, possibly eliminated or merged (van Boeijen et al., 2020).

In this research, this is where concept development is done. Several combinations of function fulfilment (or How-Tos) are combined to get several concepts. Finally, these concepts are combined again and prototype 1 is presented.

Tool evaluation: Student survey

A tool or questionnaire is a tool used in research which consists of a set of questions designed to collect standardized responses from participants. A survey can have open-ended questions in which participants can provide their own answer. It can also have closed questions where for example multiple choices are given. The latter is more suitable for statistical analysis, and the first may be more insightful as it is more nuanced (Bhattacherjee et al., 2019).

In this research, a student survey is used to test the effectiveness of intervention implementation, namely an improved LCA tool in the IDE context. Evaluation is done during the IDE master elective course Environmental and Circularity Assessment Methods (ECAM). The sample is a group of 20 IDE master students.

The effectiveness of the improved LCA tool and its design requirements is tested by providing an exercise (Appendix G). The exercise was simple: Construct an LCA of a children's kart based on three characteristics given and assess the environmental impact of alternatives. The three characteristics were the main material (wood, plastic or metal), the max child's weight and the total weight of the kart. Apart from those three data points, students had to design the kart and fill in estimations of materials, manufacturing, use, distribution and end-of-life. Further LCA instructions were given in a lecture by Benjamin Sprecher and guidance is given in the LCA tool. The time for making the exercise was one week.

After the exercise, the three main design requirements were evaluated to measure the effectiveness of the improved LCA tool.

The data collection was done with an online survey provided in class one week after the assignment was given. Before the survey, a call for general feedback was done by a plenary discussion. The analysis of the survey data is done qualitatively by analysis of reoccurring issues and interpretation of the results. Survey questions and results can be found in Appendix G.

The result of this last research phase is a problem definition, (academic and application) context description, a list of design requirements, concepts development, prototype 1 and prototype 2.

4 Results

The result section is split over three parts answering the research sub-questions successively.

Chapter 4.1 answers; *What are the problems that design students experience when performing LCA for the first time?*

Chapter 4.2 answers; *What are the relations between the identified problems and what effect could possible interventions to the system have?*

Chapter 4.3 answers*; How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?*

First, an overview of student problems regarding the use of LCA for the first time by designers inexperienced with LCA is given (chapter 4.1). The problems are categorized/clustered and abstracted into themes through thematic analysis. The results from thematic analysis, are split over internal (4.1.1) and external (4.1.2) themes. Theme relations are identified and depicted in a system model.

Second, from the system model, hypothetical interventions for more effective LCA implementation are drafted (chapter 4.2). The possible interventions are drafted to understand the effect of interventions to the themes and their interrelations. Understanding the dynamics, one intervention can be chosen to test at the IDE faculty. The interventions that is possible within the research scope (time, location and skills) is chosen.

Third, the chosen intervention, an improved LCA tool, is implemented at the IDE faculty and evaluated for its effectiveness. For an academic context description, current developments of LCA methods and tools for designers are researched in a semi-structured literature review (chapter 4.3.2). This includes literature insights regarding LCA method adaptation and evaluation of existing LCA software tools. Next, the problem definition (4.3.1) is given and a context description (4.3.3) is provided. Also, a list of design requirements (4.3.4) is constructed and prototype 1 of the improved LCA tool is presented (4.3.5). The tool is evaluation on its effectiveness for LCA incorporation by inexperienced designers at the IDE faculty and results are discussed (4.3.6). Finally, tool limitations are stated and discussed (4.3.7).

4.1 Overview of problems for inexperienced designers

This chapter is structured according to the thematic analysis method outlined in Chapter 3.2. Figure 9 illustrates that 100+ observed problems are clustered into 34 problem clusters, abstracted into 10 themes and 1 system model (the transformation is listed in the Excel sheet from Appendix C).

The clusters are created based on problems that are closely related to each other or show a pattern. For instance, the questions: 'Why is transport within the boundaries? What phase does energy use belong to? and How do I handle not knowing the life-time?' all contribute to the problem cluster: 'Students have trouble understanding a functional unit and system boundaries'.

From these problem clusters, 10 themes are derived (Table 2). This is done by defining the reason behind student problems, the theme that is overarching to the problem clusters. For example, what is the reason for students to rush through data collection while making mistakes and neglecting steps? The reason is expected to be limited Time for LCA and Motivation. These are two of the overarching themes. More elaboration on the contribution of problem clusters to the themes is found in this chapter. The themes are divided into internal themes, which are in the power of the designer with no experience in life-cycle assessment, and external themes, which are beyond the designer's power. All themes influence the effectiveness of LCA for designers inexperienced with LCA. In this study they are considered a homogenous group that all have limited LCA expertise. All themes depicted are a current state representation (2022 at the IDE faculty Delft) and are evidently subject to changes in time.

Through system modelling (explained in chapter 3.2) the relations between themes are determined and a causal loop diagram is created (Figure 10).

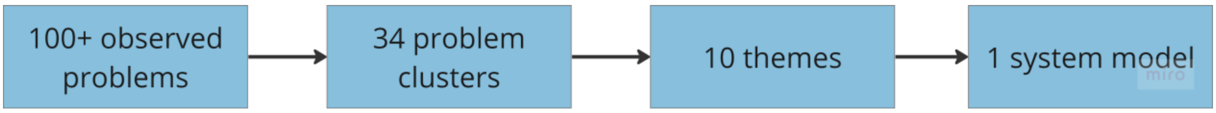

Figure 9: The process of concentrating observed problems, to problem clusters, to themes and eventually one system model.

The 10 themes that are identified from the thematic analysis are as depicted in Table 2.

Table 2: The 10 overarching themes generated based on problem clusters

Internal themes	**External themes**
1. Mindset	6. Social factors
2. Motivation	7. Regulations and internal policies
3. Complexity/capability consistency	8. Data quality and quantity
4. Time for LCA	9. LCA methods and tools
5. Comprehension of LCA method	10. LCA education

Within the themes there is an intrarelationship as well as an interrelation. These relationships are described per theme in the coming chapter. To illustrate the relations, a simple system model, namely a causal loop diagram is created showing the interrelations that the abovementioned themes have (Figure 10). All orange nodes are in the power of the designer inexperienced with LCA, whereas the blue nodes are external themes. The plus signs in Figure 10 represent positive feedback. This means for example, if there is a lack of regulations and company policies there will be less motivation and time for designers, leading to a bad coherence between capabilities and complexity, less comprehension and less effectiveness of LCA for inexperienced designers eventually. The theme of social factors causes delayed feedback and is therefore depicted by a '=' sign (Figure 10).

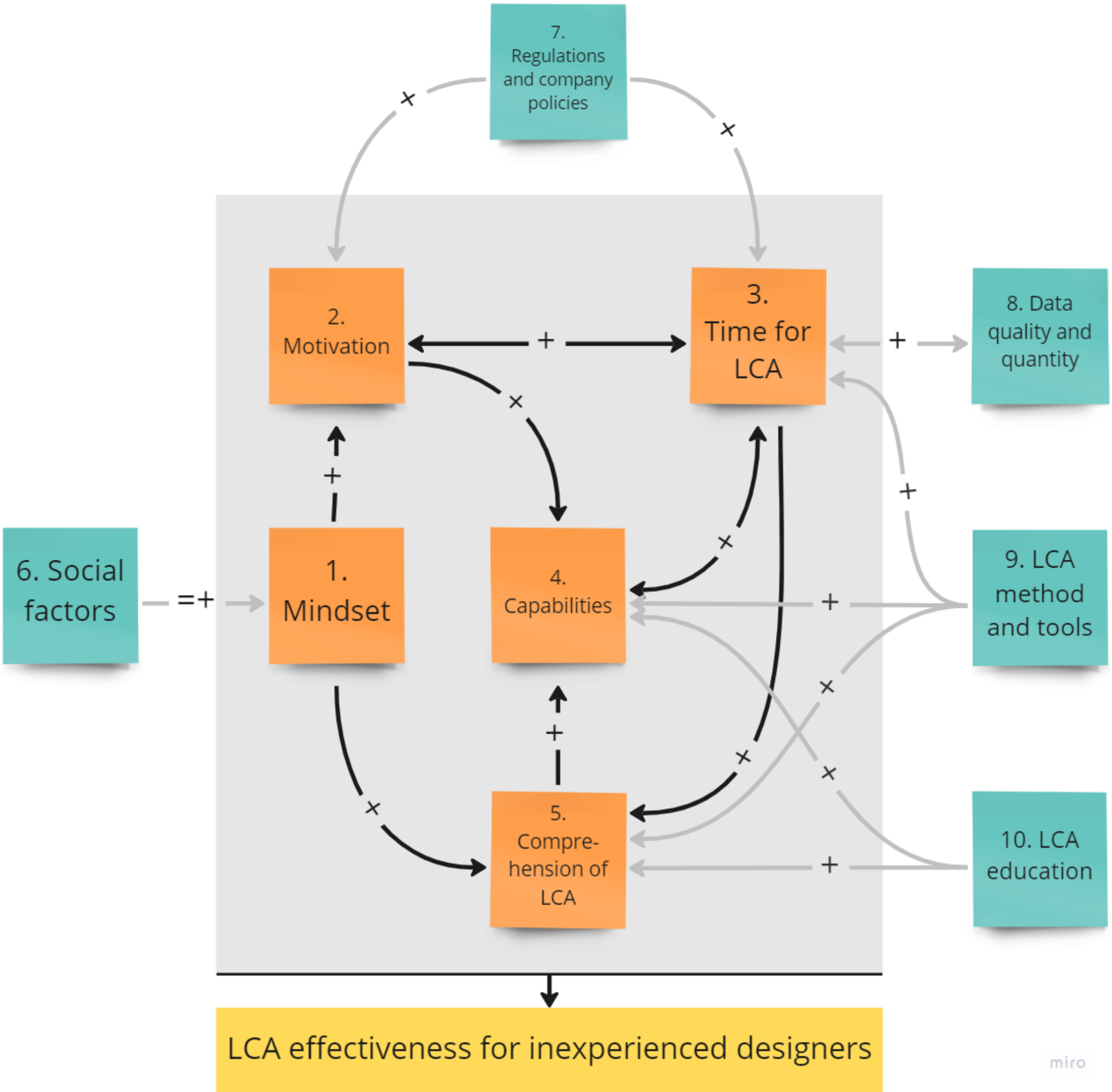

Figure 10: The system of themes influencing the effectiveness of LCA implementation for designers.

4.1.1 Internal themes influencing inexperienced designers.

As defined earlier, there are 5 themes identified that influence the effectiveness of LCA for designers inexperienced with LCA and lay within the power of an inexperienced designer. Table 3 gives an overview and summary of the themes. All themes consist of several problem clusters from student observations, teacher interviews supported by industry insights and literature findings. The problem clusters supporting the theme are described in the paragraphs below.

Table 3: Overview of internal themes influencing effectiveness of LCA for designers.

Internal theme	Summary	Direct influences
1. Mindset	Due to quantitative numbers and fixation, creativity is sometimes lost. A holistic vision is limiting designers. Interest, curiosity, trust could benefit an inexperienced designer in this situation.	Motivation Comprehension of LCA
2. Motivation	Only the essential elements of LCA are performed, results are taken for granted and they are willing to spend only limited time (3 hours - half a day) on LCA.	Capabilities
3. Time for LCA	Time restrictions, either internal or external lead to neglection of LCA elements such as goal and scope definition, sensitivity analysis and rushed interpretation.	Capabilities Information quality and quantity Comprehension of LCA
4. Capabilities	Designers inexperienced with LCA get overwhelmed by the data and skills that they must provide.	Comprehension of LCA Time for LCA
5. Comprehension of LCA method	Understanding of LCA fundamentals is lacking. The main obstacles are at functional unit, data collection (e.g. proxies, locations, searches), uncertainties, multifunctionality, system boundaries (e.g. for recycling) and impact categories.	Effectiveness of LCA

In the following sections, all themes are described as follows:

a) Short introduction/meaning
b) Their interrelations in the system
c) The internal arguments building up to the theme
d) The consequence on effectiveness of LCA by inexperienced designers

1) Mindset

The first internal theme identified is a designer's mindset. Table 4, shows problem clusters leading to the identification of 'mindset' as an influential theme for effectiveness of LCA for designers. In short, a (student) designers' mindset is lacking curiosity and trust to make LCA work effectively. For example, many (student) designers doubt the effectiveness of LCA with the number of uncertainties and assumptions. Also, the holistic mindset of designers can be a pitfall, as designers need to include many design parameters of which environmental sustainability is only one of them. Furthermore, a quantitative process and results can limit creativity, overwhelm or fixate inexperienced designers.

A beneficial mindset for LCA use by an inexperienced designer would be to consider sustainability as important, embrace the complexity, utilizing the holistic capability for the better, trusting in the power of LCA, being curious, and maintaining a critical perspective. This is a result from student participant observations as the opposites of those characteristics prove to be counterproductive. One's mindset can shift quickly or slowly over time. Education, upbringing, family, friends, news, politics, and other factors can all contribute to changes in mindset.

Table 4: Problem clusters and sources leading the theme: 'Mindset'

Problem clusters	Source
1. The designers' holistic mindset can be a benefit for systemic thinking or a pitfall when attention is split over many design parameters.	Teacher interviews
2. Designers' creativity is limited by quantitative process and results	Teacher interviews
3. Students don't want to see or engage in the complexity of LCA	Teacher interviews
4. Students' interest towards sustainability is growing	Teacher interviews
5. Designers often feel overwhelmed by the amount of data needed	(Lofthouse, 2006)
6. Quantitative results can cause fixation to one result for the interpreter (limitation of creativity)	(Liikkanen & Perttula, 2010; Millet et al., 2007; Purcell & Gero, 1996; Sousa & Wallace, 2006)
7. (student) designers sometimes don't see the relevance to their work, they lack curiosity and a critical mindset	Student participant observations
8. The usefulness of LCA results with so many assumptions and uncertainties is questioned	Student participant observations
9. Some LCA terms are too abstract for designers	Student participant observations

A designer's mindset is influenced primarily by external processes from social factors. In turn, a beneficial mindset influences the motivation (2) available for LCA, the comprehension of LCA (5) and in turn the effectiveness of the LCA method and tool (figure 6).

The first finding was that both teachers and students have a critical attitude towards LCA. There is doubt over the accuracy of the data input and output. Some argue that the high uncertainty of the data renders the method invalid, while others point out the need to interpret the results with caution and under many preconditions. It is important to maintain a critical outlook, but it should be paired with curiosity or trust.

Next, there are two problems related to the use of quantitative results. First, students may struggle to interpret quantitative data due to a lack of familiarity with quantitative methods in comparison to qualitative methods which are more commonly used in design courses. Secondly, teachers as well as literature state that quantitative results will limit designers' creativity. This is because designers generally regard quantitative results as being the ultimate truth and only one solution is considered. While commonly, a combination of options is possible and effective for impact improvement as well. In literature this phenomenon is described as fixation (Liikkanen & Perttula, 2010; Millet et al., 2007; Purcell & Gero, 1996; Sousa & Wallace, 2006).

Additionally, designers are hesitant diving into the complexity of LCA. The paradoxicality, trade-offs and nuances are neglected because having only one solution is easier and faster. It is expected that this has to do with a lack of time, skills and being overwhelmed by the number of parameters that they must deal with in design.

Teacher interviews show that students typically prefer clear results and distinctions, yet incorporating sustainability into the design process brings a great deal of complexity. In-class observations indicate that some students may ignore uncertainty bars/fades in the result graphs to achieve a single, clear solution.

Another finding from teachers’ interviews, that at first seems to contradict the priorly described avoidance of complexity, is that students’ interest towards sustainability is growing. In general design projects, more curiosity is expressed by students. An important distinction should be made that growing interest does not necessarily mean growing motivation as seen in the resistance to engage in complexity. Even though the course is under continuous improvement, the presence for LCA lectures is still +-50%.

Additionally, teachers argue that designers' holistic mindset and approach can be beneficial as well as problematic when utilizing LCA. A result that teachers notice, is that students in project courses have to split their attention and time over many design parameters (e.g. customer, technical, function, costs, cultural, company, health, safety and legal). This results in little time going into sustainability assessment and thus time-consuming (often quantitative) methods are not the first option. In contrary, the benefit of having a holistic mindset is that systems thinking is more familiar or easy to adopt. This can increase students’ understanding and performance of LCA.

Besides the number of parameters needed, literature claim designers are also overwhelmed by the depth of data that is needed (Beemsterboer et al., 2020; Lofthouse, 2006; Villares et al., 2017). This holds true especially in the early phase of design. For example, the number and detail of processes that they must collect information about and the product detail that they seem to need for being accurate. As addressed in the complexity/capability discrepancy theme (3), available information and complexity does not match designers’ capabilities and influences the mindset.

A finding, closely related to the comprehension of LCA, is the fact that some LCA terms and steps (such as functional unit) are on a too abstract level than designers are acquainted with. Thinking on a more abstract level seems to be an obstacle for some designers.

In conclusion, a positive designer's mindset is essential for LCA to be successful as a tool for inexperienced designers. A designer's mindset can improve a designers’ capabilities (4) trough motivation (2) and can directly influence the comprehension of LCA (5). Curiosity and trust are particularly beneficial for the mindset. When confronted with uncertainties around data and modeling, a curious mindset can increase the motivation to search for data, but even more importantly, it can increase robustness assessment. A curious attitude can also help to conquer the feeling of being overwhelmed by quantitative numbers, data requirements, and other complexity discrepancies. However, it can take time to change a designers’ mindset through upbringing, culture, politics, society and education.

2) Motivation

Next, some problem clusters can be grouped under a designers’ motivation. The difference between motivation and mindset can be described as follows. Motivation is the driving force behind reaching a goal, while mindset relates to the individual's attitude or perspective on how they approach the goal.

In short, the IDE faculty interviews have indicated that a lack of motivation is a recurring problem. This is argued by lecture attendance, student conversation and in-class participant observation. The empirical research is further supported by industry insights and literature, which both suggest that motivation, time and money are closely linked. High levels of motivation can lead to more time and money being available for LCA, and more money can make designers more motivated or obligated to consider LCA.

Table 5: Problem clusters and sources leading to the theme: 'Motivation'

Problem clusters	**Source**
1. Show up for class limited (50%)	Teacher interviews
2. Students would only do LCA if they are obliged to, or they consider it strictly necessary.	Student participant observations
3. Students want to spend between 3 hours and half a day on LCA	Student participant observations
4. Sensitivity analysis or scenario testing is often not considered	Student participant observations
5. If several numbers are given in assignment, the urge is to use all numbers in the calculation. Individually thinking about what to do is difficult.	Student participant observations
6. Students tend to go for the easiest options (e.g. single-score for impact categories)	Student participant observations

In the system described priorly (Figure 10), motivation (2) is influenced by the mindset (1) and externally by regulations and company policies (7). External regulations include governmental interventions and market forces. Company policies could be influenced by those, or vision/policy change can come from within the company. In turn, motivation influences the capabilities (4) and time for LCA (3), which influence more themes thereafter (Figure 10).

The participant observations with students and interviews with teachers indicated that students would only do an LCA in the future if they were required to or felt it was necessary, and that they would invest at most 3 hours to a half day on it. Although teacher interviews noted a growing interest in sustainability among students, it is unknown if this has increased their motivation for LCA.

Participant observations during class have revealed that many students only do the minimum required for the assignment. In some cases, they do not even do the assignment at all. Attendance is estimated to be at 50%. In this trend, it is seen that students sometimes skip or avoid certain LCA steps. Moreover, a robustness assessment, such as sensitivity analysis, is rarely done, and many students rush through the goal and scope phase in order to begin data collection.

Results from the industry indicate that Life Cycle Assessment (LCA) is not a common practice used by designers in their regular work but is instead outsourced to a separate team only when necessary. At the company interviewed, sustainability targets were established, which require designers to consider environmental impacts and meet the target. This is needed to encourage and guide designers. The sustainability team also provides guidelines and quick qualitative scoring tools. Designers often reach out to the sustainability team with questions or requests for tools. This demonstrates some level of motivation from the design team.

In summary, motivation is essential for designers to incorporate LCA into the design process. Motivation influences the capabilities, and the time designers are willing to invest in it. As a result from the system modeling, the mindset of designers (1), external regulations and company policies

(7) can shape the level of motivation and time invested. Therefore, it is important for both companies and governments to provide the necessary funds and regulations. This could be done by providing better software, increasing education and creating interdisciplinary teams. Creating a beneficial mindset is moving more slowly but could also encourage designers to implement LCA in their work.

3) Time for LCA

Many problem clusters found can be allocated to the lack of time for LCA (Table 6). In short, time limits cause neglection of LCA elements (e.g. goal and scope definition, sensitivity analyses etc) and rushing though LCA steps. As in many sectors in (capitalist) society, time for a task is highly connected to the amount of money that is available. They are therefore entangled. Evidently in educational practices, money is less clearly present (especially for students). Still time is limited and needs to be split over many subjects. The shortage of time leads to many implications in the system. More time could increase the consistency between capabilities and complexity by for example better software, better education and set up interdisciplinary teams.

Table 6: Problem clusters and sources leading to the theme: 'Time for LCA'

Problem clusters	Source
1. Designers encounter lack of time (due to motivation and money)	(Beemsterboer et al., 2020) (Jusselme et al., 2018)
2. Data preparation and input are the most time-consuming	Suppipat et al. (2021)
3. Time stress leads to ignoring LCA structure (e.g. skipping G&S)	Student participant observations
4. Time stress leads to rushing in data collection and making unnecessary mistakes on the way (rash decisions or neglection)	Student participant observations
5. Robustness assessment is not often considered due to motivation and time limits	Student participant observations
6. Spending only one week (4 lecture hours) on teaching LCA is too short for students to fully understand	Teacher interviews

Time is closely related to motivation (2) and is an ever-present problem for designers. In the world of business, time is money. It can decrease consistency between the capabilities of designers and the complexity of the LCA method (4), as well as negatively affecting comprehension (5) and the data quality and quantity (8). Conversely, having more time for LCA also increases comprehension (5), capabilities (4) and data quality and quantity (8) (Figure 6). A lack of time is demonstrated in student participant observations, industry insights and literature.

In the student participant observations, it became evident that students experience time stress. As a result, some LCA phases are skipped or rushed through, such as the goal and scope phase. Students rather start modelling one of their products in the inventory to start with but run into problems on their way. They, as a result, don't know what to base their assumptions on and what to measure after modelling. Also, default options (e.g. impact categories) are gladly used. This is linked to complexity/capability coherence (3) as well. Potentially most crucial is students skipping robustness assessment. This, while sensitivity analysis or scenario testing (robustness assessment) can help very effectively in making design-choices at the early design phases. With scenario tests, a designer can try different design options for the same concept very easily and with sensitivity analysis it could be easier to make assumptions as you can test them more easily.

In literature the lack of time is often highlighted and attempted to solve. Many papers have proposed strategies to address this problem, such as simplifying the LCA process. Beemsterboer et al. (2020) reviews and categorize these simplification strategies into five terms: exclusion, inventory data substitution, qualitative expert judgement, standardization, and automation. These terms are discussed in detail in chapter 4.2. Suppipat et al. (2021) claim that data preparation and input are the most time-consuming aspects of LCA.

Additionally, students indicate that preferably they would spend only 3 hours to half a day on modelling an LCA. This should be taken with a grain of salt, as students generally want to spend as little time as possible on courses and could have to do with the education module as well. Still, they experience a limited time for making LCA. This could be born by the fact that only one week (4 lecture hours) are spend on teaching and practicing LCA. As results from the teacher interviews this is also too little time for students to comprehend.

From industry interviews it became clear that design teams outsource their environmental assessment work to an expert team. This has to do with a lack of time but also expertise a design team has. They are provided with expert consultation, a qualitative scoring tool and sustainability guidelines for the early phases of design. In later stages they are provided with LCA results generated by an expert team. This has to do with the limited time designers get for LCA.

In conclusion, the effectiveness of LCA for inexperienced designers is heavily influenced by the lack of time that designers have. This is demonstrated in student participant observations, industry insights and literature. A lack of time can be influenced by money, motivation (2), capabilities (3), regulations and company policies (7), data quality and quantity (8) and LCA methods and tools (9). The importance that is given to LCA and sustainability by all stakeholders (e.g. student, university, governmental institutes, commercial institutes) largely determine the time spent on it. A lack of time leads, in literature findings, to many different structured simplifications (Beemsterboer et al., 2020). But in practice, it might lead to many unstructured simplifications as well, such as the exclusion of goal and scope steps, the blind use of default options for impact categories and the hasty use of inventory datapoints as proven by student observations. This eventually leads to inaccurate results or incorrect method implementation. In the tool development, these consequences should be avoided to improve the effectiveness of LCA for inexperienced designers. To generalize 'time for LCA' to a broader industrial context it is expected that money will be included in the theme as an entangled factor.

4) Capabilities

Another theme identified is the incoherence between complexity of the LCA tool and method and capabilities of designers. The incoherence is an interaction between capabilities (internal), education and LCA method and tool (external) (see Figure 10). In student observations this is demonstrated in the number of questions that are asked, the Excel or calculation skills that are missing and the feeling of unsettlement. Students likely lose themselves in the quantification in the inventory phase. Students are generally happy and surprised by the results but not super curious to dive into the reason behind the outcomes. When graphs are made, the duty is done. This is acknowledged by teachers. They also see stagnation or refusion by students when there is a bad balance of capability/complexity. Student designers might just stop their work or get distracted.

Table 7, provides an overview of the problem clusters and sources leading to the identification of capabilities and complexity incoherence as an influential theme.

Table 7: Problem clusters and sources leading to the factor: 'capabilities'

Problem clusters	Source
1. Students in the 2nd year of IDE are not accustomed to using Excel or look up tables for making calculations. This results in conflicts while making LCA calculations.	Teacher interviews
2. Students are hesitant in making assumptions (which increases time spent and frustration)	Teacher interviews
3. LCA is not capable of supporting early-stage sustainability design choices due excessive, complicated, quantitative input and output data.	(Telenko et al., 2016)
4. Students likely lose themselves in the data collection and quantitative numbers	Student participant observations
5. Students are generally happy and surprised by the results but not super curios to dive into the reason behind the outcomes. When graphs are made, the duty is done.	Student participant observations
6. Students tend to get a little helpless and panicked when they cannot find certain data (e.g. life-time or manufacturing processes)	Student participant observations
7. Many questions regard Excel and calculation practicalities	Student participant observations
8. Abstraction of product system and function	Student participant observations

The capabilities are closely related to motivation (2) and time for LCA (3). Externally, capabilities are largely influenced by LCA methods and tools (9) and LCA education (10). It influences comprehension of LCA (5) and time for LCA (3). So, the capability and complexity relation are very central in the system as seen in Figure 10.

Students and teachers in the IDE faculty recognize the disparity between the complexity of LCA and capabilities of designers in all LCA phases. As a result of complexity and partly motivation (2) and time (4) as well, skipping LCA steps is not uncommon. This happens in all LCA phases.

For example, in the goal and scope phase the functional unit is described very poorly (e.g. as 'one year'), the scope is not defined, and references flows are skipped. In the inventory phase it is seen that they have rather one datapoint available than many distinct datapoints (with location, technology details, time factor etc.). The choice between options is complex for designers partly as there is too little detail on their concept yet, or production locations are unknown. With an abundance of datapoints, student designers freeze and might even give up or get distracted. When there is no datapoint, for the process that they are looking for, they tend to get a little helpless and panicked. This might have to do with the fact that they are scared to make assumptions and take proxies.

For the impact assessment phase, students often avoid mid-point and end-point categories in favor of a single-score category they can easily interpret. In the interviews it is noted that the weighing of categories is too complex. Questions were asked such as: 'But now what concept is best? Because on this category it says 1 and on the other it says 3'. So, student designers seem to want to avoid complex mid-point categories, designers look for the simpler, quicker options in LCA and would rather have one outcome than many nuanced. During industry interviews, it was clear that only one end-point category, namely carbon footprint (kg CO_2 eq), was used. This was a result from company policies, namely the design targets for the designers.

When results are shown in graphs, students are generally happy and sometimes surprised but are hesitant to look for the reasons behind surprising results. The have a feeling when graphs are made, their duty is done, and decisions can be made. There is no curiosity to perform scenarios, robustness assessment or alike.

Regarding capabilities, for the second-year students, converting units, making small calculations and general Excel skills were difficult. They, for example did not understand what was tkm (unit for transportation of goods) and how to handle it in the transportation section of the Excel sheet. Also, there were questions why their calculation didn't work while they were using commas instead of dots (related to the language settings). Also, it was difficult to add rows in order to expand their system. In general, it can be concluded that students are not accustomed to using Excel for calculations or look up tables.

The incoherence between complexity and capabilities is confirmed in many papers and effects are reported upon (Beemsterboer et al., 2020; Lofthouse, 2006; Villares et al., 2017). Especially in early-stages of design, little detail of the product is available, leading to a misfit of data and overwhelmed designers. Eventually this can cause fixation on one concept or one material option because of the desire to have a singular outcome and need to define the concept detailed enough (Liikkanen & Perttula, 2010; Millet et al., 2007; Purcell & Gero, 1996; Sousa & Wallace, 2006). At the interpretation phase this means there is only one option best. During the design process, following a restricted method and the need to define many parameters of the design already can lead to loss of creativity (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2013; Lofthouse, 2006).

To conclude, available information about the product, complexity of the system and method do not match a designer's capabilities. Capabilities are lacking in the software or calculation skills, collecting quality data and understanding of the method. The incoherence between capabilities and complexity leads both to fixation on one concept or one process, and the loss of creativity.

5) Comprehension of LCA

The comprehension of LCA will have the most crucial influence on the effectiveness of LCA for inexperienced designers. When LCA is not properly understood, the process and results will be very ineffective and even faulty for environmental decision-making. Miscomprehension was uncovered in student and teacher interviews and student observations. In most ISO LCA phases, there are questions from students, but some phases more than others. The questions and unclarity will be discussed below. The exam pass rate for students in the second-year course 'Sustainable Impacts', is around 50%. This exemplifies the lack of understanding. However, it is also partly due to the external theme LCA education (10) and time for LCA (3) (4 hours lecture plus homework), consequentially lack of repetition, passive assignments and capabilities (4). It is therefore important to keep in mind the interconnectedness of comprehension with other themes such as education. Opinions on the course differ largely among teachers. Problem clusters that are solely due to educational practices are filtered out and can be found in chapter 4.1.2.

Table 8: Problem clusters and sources leading to the theme: 'Comprehension of LCA method'

Problem clusters	Source
1. Students are not used to quantitative methods in other courses	Teacher interviews
2. Many questions regard the functional unit	Teacher interviews
3. The lack of experience and repetition is a large cause of the miscomprehension	Teacher interviews
4. Input of data from a transparent database helps with fast understanding of process impact by designers	Teacher interviews
5. Accurate interpretation of quantitative results is a big challenge	Industry insight
6. Self-determination of uncertainty of data is a conscious step but could be inaccurate.	Education module
7. Some LCA steps and terms are on an abstraction level too high for designers.	Student participant observations
8. The uncertainty visualized as fading generally works well for interpretation by students.	Student participant observations
9. Students have trouble understanding a functional unit and system boundaries	Student participant observations
10. Many questions concern data collection (steps, proxies, location etc)	Student participant observations
11. Multifunctionality is a difficult concept, modelling choices often not connected to multifunctionality and IDEMAT is not transparent about multifunctionality	Student participant observations
12. Interpretation of results and their relevance is difficult for students	Student participant observations
13. Students do not know when to use LCA in the design process	Student participant observations
14. Students do not recognize LCA elements, even though they are very similar to design elements.	Student participant observations
15. The meaning of impact categories is not understood	Student participant observations

The comprehension of the LCA method is influenced by motivation (2), time for LCA (3) and capability/complexity consistency (4). Externally it is influenced by data quality and quantity (8). Comprehension of LCA method is an element with great direct influence on the effectiveness of LCA method and tool (Figure 6).

During the goal and scope phase there are many questions regarding the functional unit (FU). In class the focus was on determination of the number of items needed for the FU. This resulted in very narrow FUs, sometimes as little as ’15 years’ and confusion regarding the number of ‘items’/products needed. The elements a FU consists of are not clearly explained and thus students forget that for example the use scenario is important. Even the education module answer sheet claims ‘impacts per reader (assuming 1 reader per book lifetime)’ to be a good functional unit for a book comparison.

Abstraction of the function of products and services is hard for some designers. LCA is a method that both has very abstract elements as it has numeric, quantitative elements. To make the product into a function or a service that it provides, clearly was a challenge for student designers. Also, the determination of system boundaries is difficult. This might have to do with the feeling for impacts that students might not yet have, to determine an appropriate and fair system boundary.

Additionally, the consistency between alternatives is sometimes incorrect. This became evident for example with the comparative LCA of two books whereby it was proposed, by students, to include transportation from extraction only for the paper book.

The inventory phase has already been partly addressed in the time for LCA (3) and data quality and quantity (8). Besides the lack of information, there is also difficulties understanding the information. For example, there were a lot of questions regarding proxies for processes. Students did not know how to decide between similar processes or locations. Determination of some processes such as manufacturing and end-of-life processes is a struggle for many students as well. One of the reasons given, is the hesitance that students feel to make assumptions, even though estimating and educated guesses is something designers learn to get comfortable with in their standard education. Especially, making assumptions on the use-phase has been difficult, for example determining the lifetime. LCA is a method that clearly demonstrates the influence of assumptions through sensitivity analyses. It is essential to conduct robustness assessment in order to gain a better understanding of the methodology, as well as the impact of the assumptions made by the designers.

Defining the uncertainty of datapoints was therefore also difficult. In IDEMAT, students are asked to estimate the uncertainty of their datapoint based on the source, location etc. Very limited guidance is given regarding this choice.

Also, there were many questions on what is included in certain processes. This is a shortcoming of the depth of the IDEMAT database: there is no real unit process description. Also, IDEMAT is not transparent enough to find multifunctionality choices in background processes. In this line, multifunctionality is a difficult concept, modelling choices are often not connected to multifunctionality. This, while the economy is slowly changing towards circularity, multifunctionality will become more important for designers to acknowledge.

The confusion and difficulties in data collection also demands a lot of time.

In the impact assessment phase, there were questions regarding the content of impact categories. To students it is unclear what they mean, which to use or what is most important. It is observed, that partly due to time lack and avoiding complexity, many students choose to use only 1 end-point category or a single score category or the category that they assume is most understandable by a broad public. In the education module a robustness analysis is not required and therefore, not performed by many. Contribution analysis is preset and therefore passively done. What is beneficial for students is that the impact of all processes is separately shown in the calculation sheet.

In IDEMAT, the impact data is directly visible, making a faster interpretation possible. However, there are still many questions surrounding the meaning of impact categories and judging their importance. For example, regarding the units of (intermediate) results. Also, impact category results are automatically generated and may for that reason not be properly understood as it is not a conscious step. Also, it is seen that uncertainty is difficult to understand. Even though error bars/ fade outs are implemented, the relative difference between alternatives is hard to grasp for students. In IDEMAT they are asked to determine the uncertainty themselves, which adds to consciousness certainly, but may add incorrectness as well. Also, there were many questions on the usefulness of results with such high uncertainty.

More generally, there were many questions on how to actually implement LCA during a regular design process. In the class, LCA is used in a stand-alone tool, being a sidestep from the design process itself. There is no integration into the design process. The assessment is only done on provided examples (refrigerator, books and bottles) and both defaults as well as readily available data is provided. All exercises regard physical products and there are therefore many questions on how to integrate LCA for service systems. In industry, as described above, LCA is not at all implemented in the design process but only the results (gained from an expert team) are used for decision-making. With a lack of integration by the inexperienced designers, there is less comprehension by them, and possibly less effective sustainable design-choices.

To conclude this section, there are many problems in the comprehension of LCA by designers. In all phases there are steps unclear. Obviously, this is part of the learning process as well. Many comprehension problems may be attributed to the proper education, or the amount of time spend on LCA. Inexperienced designers obviously need time also to get accustomed to the terms and the way of quantification and abstraction. The biggest problems to understand LCA were regarding, the abstraction of a product system to a functional unit, system boundaries and what to exclude, working with assumptions and proxies, the definition of uncertainty, judging importance of impact categories and what impact categories to use.

More generally, it is seen that students do not always understand the value of following the full LCA structure and therefore some steps are mixed up. For example, goal and scope is not always finished before data collection starts.

Finally, when to do an LCA is not elaborately integrated in the course lectures and consequentially unclear for students. Objectives for doing an LCA is integrated in the course and two reasons are pointed out, namely the comparison of two alternatives and hotspots or priority setting of your concept improvements. What is not mentioned is using LCA as a design tool, and hence the need to continuously integrate it. This would bring another advantage besides LCA results, namely the consciousness of impacts through the design process by having the LCA method in parallel. Having LCA integrated as a continuous design method, the comprehension of designers improves with which the effectiveness of LCA in design improves as well.

4.1.2. External themes influencing the system.

There are 5 external themes identified who influence the system (Figure 10), they will all be shortly addressed in Table 9 and in paragraphs below. Social factors (6) and regulations and company policies (7) are speculative themes and not resulting from the empirical research. Also, it is very well possible that with further research, more external themes are identified.

Table 9: Summary of external themes

External theme	Summary	Direct influences
6. Social factors	Social and cultural stance towards sustainability is affecting a designers' interest and mindset towards sustainability in general and LCA consequently. *Note, this theme is not a result from empirical research but created by logic reasoning by researcher.*	Mindset
7. LCA regulation and company policies	European regulations such as on single-use plastics influence the motivation and time/money of (inexperienced) designers. *Note, this theme is not a result from empirical research but created by logic reasoning by researcher.*	Motivation and Time for LCA
8. Data quality and quantity	Databases, developed by external institutions have a very significant effect on the effectiveness of LCA for (inexperienced) designers. Also, the accessibility of databases thereby is important.	Time for LCA
9. LCA methods and tools	The development of LCA methods and tool in academia as well as businesses is of large importance to the inexperienced designer.	Time for LCA Capabilities Comprehension of LCA
10. LCA education	The form and conveyance of information is of large importance to the effectiveness of LCA for (inexperienced) designers.	Capabilities Comprehension of LCA

6. **Social factors**

Social factors are added to the system to make a more comprehensive overview, they do not fully result from empirical research at the IDE faculty. However, in teacher interviews it was suggested that student interest towards sustainability is rising due to social pressure. Potential social factors of this system include cultural, political and societal considerations. Social factors usually change very slowly over time and are geographically determined. For example, what is also seen from the empirical research, interest towards sustainability by student designers is growing because of societal pressure. Globally, around 64% of the people believe climate change is an emergency and action should be taken (Flynn et al., 2021). Apart from societal pressure the awareness and urgency can also arise from political attention. A more deep-rooted social factor is culture. For example, it can be culturally defined that affection towards nature is important and most often interest in environmental sustainability is high as a result.

7. **LCA regulation and company policies**

LCA regulation and company policies are added to make the system more representable for real-life practices (broadening the scope beyond university practices). *The theme is not a result from* *empirical research, but instead based on logical reasoning and researcher experience.* This theme includes environmental impact regulations on global, EU, national and local level as well as internal company policies. The latter can result from (inter)national regulations or are created from within a company. With regulation one can think of financial stimuli (e.g. subsidies, tax benefits, fines etc.) or a ban. An example of recent environmental impact regulation is the ban of certain single-use plastics (Directorate-General for Environment (European Commission), 2021), the development of a label for ultra-low emission vehicles (European Commission, 2023) or the guidelines on eco-design requirements for instance for electric motors and variable speed drivers (Union, 2021). Regulations in educational practices can be that the Technical University of Delft expands the rules for education on sustainability. This has effect on students in that matter.

8. **Data quality and quantity**

Data for LCA can be primary or secondary, in many studies the majority of data is secondary data and gained from databases. Databases are developed by external institutions. As an LCA practitioner using secondary unit process data, designers are very dependent on available, convenient and affordable databases. As LCA is a very data intensive method, the quality, quantity and accessibility of it has a big influence on the effectiveness of LCA for inexperienced designers. The data required are unit process data of all LC stages, use stage data such as product lifetime and maintenance data. Besides that, educational and guiding data are important as well. Especially because many designers are inexperienced with LCA or have much to learn.

Inventory data quality and quantity is influenced by entities making background databases, industry providing data and transparency/accessibility in these cases. Government regulation, market forces and consumer pressure can accelerate this process. Within the power of inexperienced designers, it is influenced by the amount of time (3) available. Consequentially, it influences the time needed for LCA (3) and the effectiveness of LCA method and tool (Figure 10).

In literature it is established that designers encounter a lack of information that fits their exact needs (Beemsterboer et al., 2020 and Jusselme et al., 2018). It is indicated by designers that they need more specific information that covers not only environmental impacts and fits the scope of product design (Lofthouse, 2006). A solution, as proposed by Karana et al. (2008), is the introduction of databases combining design parameters such as material stiffness, density, conduction etc., with environmental parameters. This could aid the comprehension of dynamics between design parameters and integrate LCA better in the design process. Also, databases that fit product design needs better, would benefit the accurate data input and therefore effectiveness of LCA. The databases could for example be improved on electronic components, chemicals (for maintenance) and age of technologies used.

Additionally, the accessibility of databases is not ideal for inexperienced designers right now, especially not in small companies. Often databases have a high price and calculation software too. Then, some databases only fit certain calculation software, making choices very limited and expensive.

Furthermore, designers need a structured conveyance of information for them to successfully adopt the complex dynamics of all possible (among which environmental) design parameters (Mathias, 1993). Only then will it create a fruitful environment for innovation. Thus, multi-criteria assessment might be effective. Three main characteristics of successful eco-design identified by Bovea & Pérez-Belis (2012) are: early implementation in the design process, life cycle approach and multi-criteria approach.

Besides databases, LCA software and learning platforms for designers are scarce. Lofthouse (2006) dedicated a paper to the opportunities and barriers of eco-design tools. Lofthouse (2006) concluded that designers need eco-design tools that incorporate the following eight elements: guidance, information, inspiration, education, visual elements, non-scientific language, dynamic access and coherence between elements. Highlighted is, that coherence and interaction between the elements is needed for successful implementation. Evident is that many of these elements from Lofthouse (2006) include data quality and quantity (5 out of 8 elements). Therefore, data quality and quantity (8) is an important theme resulting from literature.

Also, the information access is often widely dispersed (Lofthouse, 2006) and databases are paid platforms mostly. Industry confirms the primary data to be hard to access. The communication, transparency and infrastructure at suppliers are often not in place, leading to a great time delay and lower quality of data if suppliers don't know how to measure it.

Student in-class questions can validate these data concerns. The questions were concerning the steps to go through for data collection, including proxies, what locations to use, how to validate the quality and description of processes (e.g. multifunctionality choices and other assumptions). Also, literature validates the difficulties of future scope definition including contextual factors, background systems develop by the time of implementation, possible unknown unknowns regarding impact categories etc. (van der Giesen et al., 2020).

Finally, a branch of literature claims, LCA is not at all capable of supporting early-stage sustainability design choices due to lack of data (Telenko et al., 2016). This is because for quantifying environmental impacts of a product system, more detailed data are needed. Telenko et al. (2016) therefore suggests using DfE guidelines that are based on best-practice LCAs instead. Also the LCA simplifications addressed by Beemsterboer et al. (2020) in section 4 (time for LCA) give solutions to the limited data availability, for example, exclusion (process or detail) and qualitative expert judgement.

A counterargument to guidelines or other qualitative methods is that they cannot adapt to one's product system and its context factors. Not one design is the same and impacts can be very diverse and unexpected. For example, using a more durable material has a very different effect on product systems depending on their lifetimes and use scenarios. A durable material for a product with short lifetime (due to other reasons), causes high environmental impacts.

To conclude, both literature and empirical research at the IDE faculty, demonstrate that data quality and quantity is of high importance during LCA performance. The quality and quantity have direct influence on effectiveness of LCA in product design. It is therefore a very important theme and is inconveniently an external theme. Designers need more specific information that fits their scope of design, better databases and a structured conveyance of information. To improve the quality and quantity of data needed for doing an LCA, government regulation, market forces and consumer pressure can accelerate the process. Chapter 4.3.2 addresses data conveyance more elaborately.

9. **LCA methods and tools**

Methods and tools are usually developed externally as well. In some cases, it is within the company. Their role is to guide and (mathematically) support designers to perform LCA. As seen in Figure 10, methods and tools have a big influence on the system, three out of five themes are affected by it. In chapter 4.3, current developments in methods and tools are provided.

Recent studies in the field of Life Cycle Assessment (LCA) have explored ways to make it more accessible for inexperienced designers. The use of ex-ante LCA within the design process could provide more useful results as there is more design freedom in early-stage assessment, while also considering future contexts. However, the complexity of projected scope and inventory data can make the effort of early-stage design disproportionate. Qualitative (scoring) methods (e.g. ECQFD or function impact matrix) are on the other end of the spectrum, as they can reduce time and complexity while still allowing for some level of contextual consideration. However, these methods are also subject to bias and uncertainty due to the lack of quantitative measurements. Additionally, to further facilitate a design business match, the use of Technology Readiness Levels (TRLs) could be beneficial. This could increase recognition by inexperienced designers. Additionally, the integration of TRLs into unit process descriptions (databases) could improve the accuracy of the LCA, as practitioners can be more consistent in the use of processes with similar technological readiness. For instance, being transparent in the technology readiness of their own foreground processes and comparing them to the technology readiness of background processes. Finally, simplifications can reduce the time and complexity of LCA, but the uncertainty of the process and results may be increased (Beemsterboer et al., 2020). Chapter 4.3.2 will describe methodological developments from academia more elaborately.

Furthermore, current tools display a large variety in functionalities, interfaces, interactions, and accessibility. Appendix E shows a comparison between some of the often-used software tools. CMLCA and Simapro offer technically the most comprehensive software. They offer most elaborate number of functionalities and gradations in complexity. Whereas for example, Activity Browser, Granta Edupack and Ecochain provide a simpler interaction, they also offer less functionalities and flexibility. Databases are most often imported except for IDEMAT and EcoChain. All software programs have a different importing format which makes data conversion difficult. OpenLCA is one of the biggest free software programs, for many others you have to pay once or subscribe. Software tools will be further discussed in chapter 4.3.2.

10. **LCA education**

LCA education includes for example academic education, online education or internal company workshops. In the academic education at the IDE faculty in Delft there have been some education specific findings.

First of all, there has been many defaults used in the assignment and a lot of information is given. Also, there are no assignments where LCA should be made of their own product. These preparations for students could limit learning purposes. On the other hand, there are students complaining about having too much to think about. So, having defaults would not be a bad idea as long as the assignments' purpose clear is. This is something IDE education could improve in as well.

Secondly, there are unclarities for students on where to find information on LCA method, examples and the assignment. Many questions are regarding what data to use, how to decide on impact categories etc. Answers to these questions are available, but they are scattered over pdf documents, lectures, videos and the reader.

Third, from literature it is found that in design education, examples and visual aid are very effective for learning, while scientific language should be limited. Also, designers are looking for guidance, information and education in their tools (Lofthouse, 2006).

Fourth, the time used to teach LCA will affect the comprehension and effectiveness of LCA implementation largely. At the IDE faculty the current practices show that in the bachelor program only 1 week (with 4 lecture hours) is dedicated to LCA. From empirical research, resulted that this time is not sufficient.

Lastly, it is important what impact categories are suggested and used during the education. As addressed earlier, the single-score category eco-costs as used in IDEMAT, may have a bad influence on designers' mindset and therefore LCA effectiveness. This is because, expressing environmental impacts in monetary values, besides having moral conflict, it reinforces the societal tendency around monetary value. This might retain us from the long-term development towards a society in symbiosis with nature instead of opposed to. As long as monetary value is used to measure development, financial profit is the main yardstick.

In conclusion, in education it is important to be sensitive about what default options to use and what information to prepare for students. More generally, information and examples should be provided and not scattered over many platforms. Also, visual aid and limited scientific language have been proven to be effective for designers.

At this point the first sub-question can be addressed; *What are the problems that design students experience when performing LCA for the first time?*

As found in empirical research and validated by literature there are many problems that design students encounter. Largely, they can be divided over 5 internally influenceable themes namely, mindset, motivation, time for LCA, capabilities and comprehension, and 5 externally, social factors, regulations and company policies, data quality and quantity, LCA method and tools and education. On all themes, there are shortcomings currently observed in the case study. The mindset of students is proven to be far from ready to address quantitative numbers, start abstract thinking and deal will a large amount of data and uncertainty. The result is overwhelmed students, sometimes disinterested or unengaged and occasionally slightly upset. These effects can largely influence the quality and effectiveness of LCA method implementation. Then, a lack of motivation is seen in the limited class attendance (50%), the short time students are willing to spent on LCA (3 hours to half a day) and tendency to use the provided data or easiest options. Assignments are not done if they are not obligated. All these findings can be partly due to educational practices as well and distinction should be further assessed. Additionally, many problem clusters are due to the lack of time for LCA. For example, the neglection or rush through LCA elements such as goal and scope, data collection and robustness check (e.g. sensitivity, scenario tests). Next, there are capability shortcomings for student designers. For example, there are many Excel skills lacking, interpretation capabilities are lacking and one could say that abstraction of systems and functions is a lacking capability as well. Also, the capability of making assumptions is lacking. Finally, the understanding of LCA fundamentals is lacking. The main obstacles are at functional unit, data collection (e.g. proxies, locations, searches), uncertainties, multifunctionality, system boundaries (e.g. for recycling) and impact categories.

External influences on students, direct and indirect, are; social factors, regulation and company policies, data quality and quantity, LCA method and tools, and education of LCA. From the case study at IDE, foremost a limit in education and LCA tools is found. Educational practices are lacking in the amount of time provided. The tool and database made available to students is very limited as it does not cover all LCA phases and data collection is time intensive and difficult. No proper guidance is given to collect data, also regarding Goal and Scope no guidance is given. Also, social factors influence designers effective use of LCA quite significantly in their mindset and motivation. Social factors include often slow-moving, political, cultural, nurture and economic factors. Finally, data quality and quantity influence the LCA output quality and the use of LCA by inexperienced designers as it influences time on LCA extensively.

4.2 Possible interventions for more effective LCA implementation

The aforementioned themes form a system with interdependent components, as outlined in chapter 4.1 and illustrated in Figure 10. To gain a better understanding of the system's behavior, we can analyze the impacts of external stimuli (interventions) on system dynamics. Four possible interventions are drafted: 1) Regulations and internal policy improvement, 2) Data quality and quantity improvement and 3) LCA method and tools improvement 4) LCA education improvement. The intervention of social factors is not addressed due to its slow-moving nature, making it difficult to predict how interventions will affect the outcome. Below in Figure 11, all four possible interventions are shown with their imagined influence on the system. All possible interventions are hypothetical and need to be tested in practice for validation. In this thesis one intervention, that fits within the research scope, will be tested.

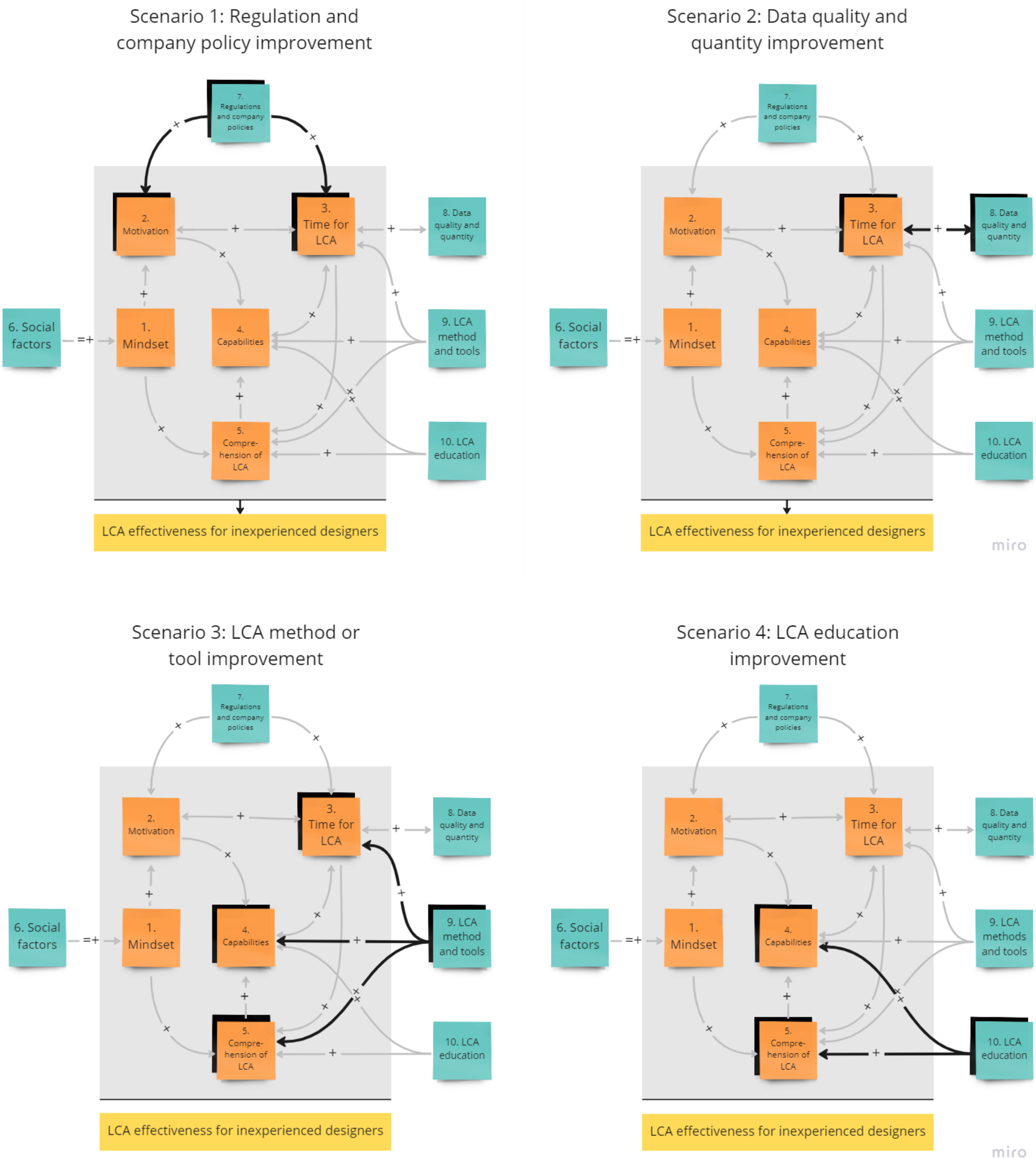

Figure 11: Possible interventions on the system model.

The change in regulations and company policies (intervention 1) is expected to influence motivation (2) and time for LCA (3), and three nodes thereafter namely data quality and quantity, capabilities and comprehension of LCA. The intervention can have a large effect on the system, but implementation could be a slow process and depends on (many) stakeholders.

In intervention 2, where data quality and quantity improve, there is an effect on time for LCA (3) and a direct improvement of effectiveness of LCA for designers. As time for LCA is such an interconnected theme, the rest of the system will also benefit, namely motivation, capabilities and comprehension of LCA. Just like regulations and company policies, the improvement of data quality and quantity is dependent on many stakeholders as well.

Intervention 3, the improvement of LCA method and tools, is expected to have a broad influence on the themes in the system and on the effectiveness of LCA for designers consequentially. A more fitting LCA tool or method can improve the coherence between capabilities and complexity (4), comprehension (5) and the time for LCA (3) is less of a problem. This, in turn, leads to more effective use of LCA for designers inexperienced with LCA.

Intervention 4, LCA education improvement, can affect the comprehension of LCA (5) and the capabilities of designers (4). The actual effects can well be tested at the IDE faculty but does not fit within the capabilities of the researcher.

Contemplating the current challenges, after considering external possible interventions, it is expected most feasible for this research to explore the improvement of LCA methods and tools (intervention 3) for inexperienced designers. It is most feasible for the temporal and geographical scope of this research, namely 6 months research at the IDE faculty in Delft. Besides being feasible, it is also expected to have a large effect, namely it may influence the designers time for LCA, the comprehension and capability/complexity coherence.

At this point, the second sub-questions can be answered*; What are the relations between the identified problems and what effect could possible interventions to the system have?*

To answer this sub-question and conclude this chapter, the relations between external and internal themes to the system are described. As concluded before, the effectiveness of LCA for inexperienced designers is influenced by several themes, namely a designer's mindset, motivation, time for LCA, coherence in capability and complexity and the comprehension of the LCA. External themes influence the internal themes of a designer and can also play an essential role for LCA to be effective in design practices. External themes include social factors, regulations and company policy, data quality and quantity, LCA methods and tools and LCA education. The most central theme in the system is time for LCA (3), it is related to most other internal themes. Thereafter, designers' capabilities (4) and comprehension (5) are very interrelated themes, influencing and being influenced by external themes such as LCA education and LCA method and tool. From the external themes, LCA method and tools (9) has the broadest influence on the internal system. It influences time for LCA, designer capabilities and comprehension.

Improvements of external themes can be described as interventions to the system. The improvement of regulations or company policy (7) and data quality and quantity (8) can both have large influence but depend on many stakeholders and can therefore take more time for implementation. The improvement or adaptation of LCA method and tools (9) and LCA education (10) are generally a more small-scale or local improvement and therefore faster implementation is possible.

After considering the possible interventions, it is expected most feasible within the research scope to improve the theme; LCA method and tools (intervention 3) for inexperienced designers to address the student problems.

4.3 Intervention implementation and test

As introduced earlier, the previous chapters have been theoretically based and hence outcomes need to be tested in practice. This chapter will report on the development and pilot tests done regarding intervention 3, namely the improvement of LCA method or tools.

Considering the temporal and geographical scope of this research, since research has been centered around the IDE faculty in Delft, findings will be operationalized in the IDEMAT LCA calculation tool as introduced in chapter 2.4. This is done to be consistent with research findings and the opportunity for evaluation testing.

The chapter consists of the following elements, in chapter 4.3.2 the academic context of an improved LCA tool is described with a short literature review on the use of LCA method in early-stage design processes. Also, LCA software tools are shown and compared on functional properties, interface and interaction and accessibility. Thereafter, the problem is defined (4.3.1), a context description given (4.3.3), design requirements (4.3.4), a concept presentation (4.3.5) and concept evaluation (4.3.6) is described.

Therewith, this chapter aims to answer the following research question:

3) How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?

4.3.1 Problem definition

The problem, as identified in the introduction, has at its core the ineffective use of LCA by designers inexperienced with LCA. The ineffective use, as found in empirical research at the IDE faculty is due to a designer's mindset, motivation, time for LCA, a capability/complexity incoherence and lack of comprehension. All themes identified, consist of a range of problem clusters as described in chapter 4.1. With the improvement of an LCA calculation tool it is expected to improve the comprehension of LCA, time for LCA and the capability/complexity coherence. Before designing an improved tool to test intervention 3, the academic and application context are described. The developments in LCA method for early-stage design is included to gain insights on how LCA can be adapted and simplified to fit early-stage design. The tool developments are included to see what functional, interaction and accessibility characteristics work well in other tools.

4.3.2 Academic context

Developments in the LCA method

To describe the context of LCA method and tools for designers (inexperienced with LCA), a semi-structured literature review was done. The literature review, as introduced in chapter 3.3 answers the following question: *What are the developments in academic literature regarding the use of LCA as a decision-making support in early-stage design?* The search queries are found in Table 1.

The results show a large difference in the number generated by Scopus (51) opposed to Web-of-Science (25). Also, there are 23 overlapping papers, Scopus mainly adds more papers. In Figure 12, statistics from Scopus on the literature is depicted. It is seen how there is a slight increase in the number of papers written in this subject from the year 2009 onwards, but there is not a consistent increase, it still fluctuates per year. 2009 was the year when 'Recent developments in Life Cycle

Assessment' (Finnveden et al., 2009), a highly cited review paper, is published. This mostly indicates a higher popularity towards LCA in general but not particularly towards LCA as a decision-making tool for designers in early-stage design. The paper was not particularly focused on LCA for early-stage design decision-making. Additionally, more than 50% of the papers from Scopus are conference papers, and 17 (out of 51) papers is from the United States. After selection on the criteria described in Table 1, it is seen that the majority of papers regard method or tool development (9 out of 26) and/or case studies (10 out of 26) (Appendix D), 2 review papers are also included.

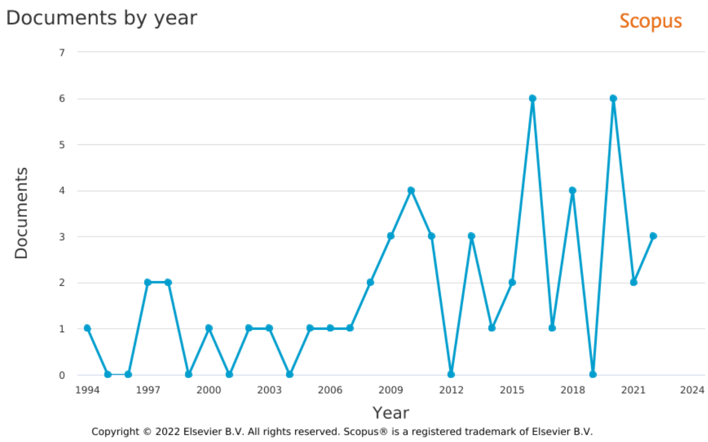

Figure 12: The publication year of articles from the literature review.

Relevant LCA method developments

As described in chapter 2.2, LCA knows many adaptions in literature as well as in the private sector. Below, adaptions to LCA that are especially relevant for early implementation and integration by the inexperienced designers are described.

Ex-ante LCA one of the more sophisticated, further developed modes of LCA tackling the shortcomings of LCA for designers. The focus of ex-ante LCA is to model for upscaling and future projections of processes. The paper by Villares et al. (2017) highlights the potential benefits and drawbacks of using ex-ante LCA in the design phase of a product or service. The authors conclude that LCA is a valuable tool for product and strategic development, as it can provide a quantitative assessment of environmental performance, as well as encourage critical thinking and impact-based decision-making. Additionally, they note that the application of ex-ante LCA to an emerging technology brings a "systematic rigour and discipline" to an otherwise ambiguous situation. A drawback of ex-ante LCA for product designers is that it is much more complex than the often used 'simplified' LCA. Ex-ante LCA is a lot more sophisticated but entails complex elements such as future scope definition and elaborate data collection. Also, ex-ante LCA methodology still faces challenges. For example, the availability of representative LCI data for the future scenario (van der Giesen et al., 2020). Ex-ante LCA would most definitely be advantageous to use for designers as all products modelled have a development time which should be considered in the modelling.

More research has gone into the semi-quantitative implementation of Life Cycle Assessment (LCA) and development of new methods to combine with it. For example, a number of case studies in the literature have successfully combined Quality Function Deployment for Environment (QFDE or ECQFD) with LCA (Masui, 2013; Sakao et al., 2004; Vinodh & Rathod, 2010). Vinodh & Rathod (2010) found that 80% of personnel accepted the combination of QFDE and LCA to ensure sustainable product design. Rathod et al. (2011) successfully integrated ECQFD and LCA into the automotive industry, allowing for the calculation of the reusing and remanufacturing potential per component or material. However, as highlighted by Devanathan et al. (2009), QFD-based tools have the risk of biased identification of design targets due to subjective scoring. Devanathan et al. (2010) added a function impact matrix to the process of LCA, which is a qualitative scoring system similar to that of QFDE.

Ng & Tang (2022) developed a combination of LCA with Cuckoo search, a search algorithm, to support design decision-making in the initial design stage. In the combined method, an optimal set of design parameters are explored by using different sets of design constraints. Therewith, early LCA implementation can be achieved.

Additionally, Technology Readiness Levels (TRLs) (Table 10) have been introduced to the LCA field. TRL is a way of expressing the readiness or advancement of a certain technology during its development towards market implementation. TRLs first emerged by NASA in 1989 whereafter it was adopted by the European commission (European Commission, 2014) and standardized by ISO (Héder, 2017). TRL implementation for LCA was first introduced by Gavankar et al. (2015). The paper says relative impact is likely to be reduced with development in TRL, due to upscaling of processes. The paper proposes to implement TRL and scale of production in the description of unit process data of databases to be more transparent on the data quality. They warn for the interpretation of LCI data from bench, pilot or small-scale operations. This is because of the large efficiency differences and thus most likely environmental impact with upscaled processes. To conclude, TRLs are currently used for marking processes and databases.

Table 10: Description of technology readiness levels (European Commission, 2014).

TRL 1 – Basic principles observed and reported
TRL 2 – Technology concept formulated
TRL 3 – Experimental proof of concept
TRL 4 – Technology validated in lab
TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – System prototype demonstration in operational environment
TRL 8 – System complete and qualified
TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Recently, there has been developments towards implementation of TRLs in the performance of LCA. A workflow has been developed that uses LCA and Risk Assessment on each consecutive Technology Readiness Level (TRL) while developing a new product or technology (Subramanian, 2021). The focus is on "Safe by Design", which pays attention to the safe use of chemicals involved in material and product design. The first question is whether the product has an incumbent/comparable product or not. If there is no comparable product, the only option is to use green chemistry principles instead of an LCA model, as there is no data to use. The second choice is regarding the environmental impact performance of the new product, the consideration here is based on a qualitative tool (LICARA Innovation Scanner) developed by Nederlandse Organisatie voor Toegepast-natuurwetenschappelijk Onderzoek (TNO). Concluding from this paper, an LCA is effective only for products that have an incumbent product and in combination with a qualitative environmental assessment. Another important takeaway from this research is that they claim, from TRL 4 (Technology validated in lab), a quantitative LCA is possible.

Amongst others, Collado-Ruiz & Ostad-Ahmad-Ghorabi (2013) evaluated the suitability of existing LCAs of product families in the early stages of product design. They identified several drawbacks to performing an LCA in the design process: it is too time-consuming, complex for non-experts, information is unavailable in early-stage design, models are different than those during the original design process and there is a high degree of uncertainty. Also, as they claim, it provokes fixation and limits creativity, and Thevenot & Simpson (2007) proposed approaches to systematically select product groups based on function or mass customization, respectively. It is noted that this method is only suitable for widely represented products since it allows for a fair average to be calculated. This means it is not suitable for revolutionary product system solutions. Additionally, this approach is static and does not account for burden shifts in impact categories (as described in Chapter 2). Furthermore, assumptions regarding manufacturing, geographical location, and use conditions are product and context specific, yet generalized in this method.

A prominent paper in the adaption, more specifically simplification, of LCA is that of Beemsterboer et al. (2020). It performs a review and categorization of simplification practices in the LCA literature. The aim is to make simplification techniques more tangible and transparent for LCA practitioners. The theory proposes that LCA simplification can be split into five categories: Exclusion, Inventory Data Substitution, Qualitative Expert Judgement, Standardization, and Automation. All categories and their relevance to inexperienced designers are discussed below.

Exclusion strategies are commonly used in LCA practices to reduce the complexity of the **inventory** model and the number of impact categories. Horizontal exclusion involves excluding LC stages, modules (e.g. transport to end-user), while vertical exclusion involves excluding processes, such as the 1% cut-off rule. This can help reduce the amount of data required. Depending on the purpose of the study, processes, stages or modules can be less relevant or out of control of the practitioner. This for example can be with designers that cannot change a certain producer due to business restrictions. There are of course risks to exclusion because prior to the study it is difficult to know what process, module or stage is irrelevant. This can be tested by screening the system at superficial level or experiment with different exclusion patterns.

Exclusion of **impact categories** focuses on reducing the number of impact categories for the practitioner to interpret the results more easily and easier communicate with non-experts. For homogeneous product systems, it is reported that 5 categories might be sufficient but for more complex product systems any exclusion is risky. Time saving from impact category exclusion is proven to be limited. Deciding what categories to use makes the study more complex as well. The paper concludes: ‘While common practice in LCA, exclusion strategies may introduce inaccuracies into the results and promote burden-shifting within the product system or between impact categories.

All in all, careful consideration should be taken when deciding which processes, modules, stages, and impact categories to include in a study.

Inventory data **substitution** involves using sources other than primary data to obtain information about a product system. This is often necessary when the sponsoring company is not able to provide the data, when the product system is in development (ex-ante) or is considered revolutionary. This is especially relevant when the product is complicated. Examples of data substitution include calculations, industry and patent literature, other studies, and databases such as ecoinvent. Although databases can be a convenient source of data, it is important to be aware that the processes used by the data provider may not always be consistent with the goal and scope of the current study. An alternative way to substitute output flows is to use stoichiometric calculations. Practitioners should be mindful of the accuracy of their decisions when selecting appropriate data substitutes.

In many parts of the LCA process **qualitative expert judgement** is consulted. According to the ISO14044 (ISO, 2006) this shows in the representativeness of data, the consistency and the reproducibility. A central simplification method regarding qualitative research is the Environmentally Responsible Product Assessment (ERPA) matrix. The ERPA matrix is 5x5 cells and each cell covers a number between 1 and 4 describing hotspots in environmental stressors for each LC stage. These types of matrices are sometimes combined with analytical hierarchy process (AHP) and Delphi panels.

Standardization is not often considered a simplification, but by Beemsterboer et al. (2020) it is regarded as a way to add structure and guidance to methodological decisions making it therewith a simplification. The ISO 14040:2006 and ISO 14044:2006 are the most used standardizations, but there are more guidelines such as those of the European Commission Joint research Centre (European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2010), Product Category Rules (PCRs) and Environmental Footprint initiative. Additionally, standardized LCA tools help practitioners by simplified modelling and data work by structuring.

Upcoming is also **automation** in LCA partitioning. This can be divided in computational automation and data integration strategies. An example is modular LCA, where individual stages are calculated first before adding it all together. Parametric models are used to compare a multitude of alternatives in short periods of time. A distinction is made between top-down and bottom-up parametrization, where a bottom-up parametrization reduces the configurations and top-down increases the configurations. Another example of **computational** LCA is the question list from Sustainability Quick Check for Biofuels that generates an LCA based on the answers of the question list and prior LCA's. 'At a more advanced level, neural network or response surface methods enable learning from existing LCAs for similar products to predict impacts (Chen and Chien (2004) Chen and Liau (2001)'. In the 1990 the LCA community started working on automated transfer of inventory data SPINE, SPOLD, ILCD and Ecospold formats were developed. Product system data can be transferred from computer-aided design (CAD) programs. The Global LCA Data network (GLAD) was set-up. Also, connections between material databases and emission databases are established. There are even LCA plug-in tools for design software developed. Automation has the advantages of increasing numbers of LCA alternatives and scenarios that can be tested or decreases the time that is spend by the practitioner. Automation is primarily suitable for assessing relatively similar product systems and less so for alternatives with radical design changes.

Many articles from the literature review, work with, or propose LCA to be automized (11 out of 54). This can be done in ways, described in the last paragraph. Yet expert interviews revealed that with performing LCA in conscious steps, the designer is stimulated to rethink design choices. It is harder for the designer to learn interpreting LCA results without having any knowledge of the LCA process. Going through the process can largely increase his/her awareness and knowledge on sustainability matters. This, in turn helps a lot with effectiveness of LCA for inexperienced designers.

Another manner to use LCA as an inexperienced designer is by outsourcing the LCA study to an expert team in the company or external. The designer then must properly interpret the results for effective environmental design decision-making. An example on this is found during the industry interview. At the beginning of the project, a carbon reduction target (30-50%) and a circularity target (reuse, recycling and longevity for company X) is set. At the first milestone, after ideation, experts from the sustainability team are invited for a review meeting. The design team is then consulted on the sustainability of their subjects. Also, quick qualitative environmental assessment tools (based on a scoring system) and sustainability guidelines are provided. They experience designers to need more

visual aid, relative numbers, equivalents and examples. Also, when an LCA software is provided, they freeze. After, when the chosen design is developed more into a CAD model, the sustainability team starts setting up the real carbon footprint model. The carbon footprint model increasingly refines accuracy until the actual mass production. So, the product development from zero to mass production is followed fully and influenced by the sustainability expert. Then, when needed, an external legally approved LCA can be performed.
From the industry interviews it became clear that they found having a separate expert team on sustainability (+-30 people) is more effective than the implementation of environmental assessment in the design team. They perceive themselves as a link between different departments such as supply chain management, design, engineering etc. For this particular industry it works very well to have a separate sustainability expert team that can focus fully on sustainability and continuously feedback the design teams but also packaging, supply chain etc. For not all industry sectors this is possible, for example when the company is much smaller or has less money. It is therefore important to keep researching the most effective implementation of LCA in the design team as well. For future research, this could be an interesting comparison, to see what strategy is more effective, LCA internally or external from the design team.

In conclusion, current LCA developments in literature demonstrate many attempts to make LCA suitable for (inexperienced) designers. First, the use of ex-ante LCA in the design process could provide designers with more useful results, as there is more design freedom and understanding of future contexts. However, the implementation of projected goal and scope, inventory data and impact assessment can be complex and may not be worth the extra effort in early-stage design.

Additionally, LCA is not often used in solitary. The use of qualitative (scoring) methods (e.g. ECQFD or function impact matrix) to support LCA in early design phases could be useful as it reduces time and capability/complexity incoherence. But there is a large disadvantage, namely the integration of subjective scoring without quantitative measurements and context considerations brings biases and uncertainty of results.

Also, the use of TRLs in LCA implementation for designers could be beneficial by having recognizable elements and thus make understanding better. Additionally, the implementation of TRLs in unit process description (databases) would add to the quality of LCAs because they can be more internally consistent regarding technology use.

Finally, simplifications are very relevant for LCA use by inexperienced designers as simplification can reduce time needed, complexity of LCA and thus increase comprehension. A significant drawback is the increased uncertainty of the LCA process and results (Beemsterboer et al., 2020). Simplifications that are especially relevant to this study are exclusion of unit processes, substitution of secondary data and potentially qualitative expert judgement for advice in early-stage implementation.

Development in LCA-software tools

There is an abundance of tools to apply LCA in practice, all have their own specialty, some focus on textiles, some are open source, some address multifunctionality, some have visual results outcome. Also, importing characterization families is different per LCA software. An overview of the difference and focus of all software tools is found in appendix G.

<u>Functional properties</u>

Some functional properties of LCA software tools are discussed below.

First, some tools (e.g. Simapro, CMLCA) have the option to increase complexity of the tool, namely by clarifying your background (e.g. student, professional, expert). This is a useful build-in, but the simplest option is not as simple as a simplified LCA calculator such as IDEMAT, so there is only a limited range of increasing complexity. Then, it should be considered that using a fixed tool that requires a lot, makes designers often feel restricted and limited in creativity (Lofthouse, 2006; Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2013; Liikkanen & Perttula, 2010; Millet et al., 2007; Purcell & Gero, 1996; Sousa & Wallace, 2006).

Second, there is some difference in whether the goal and scope are explicitly written down in the tool or it is integrated in the modelling. This is something important for an educational tool where attention goes to learning LCA structure as well, besides the modelling. For example, in activity browser, the functional unit is only really represented as a reference flow and not noted by itself.

Third, most tools that have been analyzed import databases into the calculation tool, for IDEMAT and Ecolizer this is different, there is a build-in self-composed database. Generally, those build-in databases are simpler and more aggregated than imported databases such as ecoinvent. This might be helpful for designers in the early phases of their design but carry more inherent uncertainty. Also, aggregated data is less location and context specific (Suppipat et al., 2023). This is concerning for designers as most designs are very context specific.

Interestingly, for most data visualizations, there is no build-in visualization of uncertainty. IDEMAT and CMLCA are the exception, here the graph fades to a lighter color visualizing unpredictability. The drawback is that uncertainty has to be manually put in and determined by the practitioner.

Fourth, the options for impact categories differ largely, in some tools they are build-in (Activity Browser, IDEMAT, OpenCLA, Granta EduPack). For other tools they are importable (SimaPro, CMLCA), so there is a much larger variety possible. Results are sometimes displayed in pre-fixed graphs, and sometimes tables of results are provided so that you can do graphing by yourself. Usually, at least the contribution of life cycle stage and/or contribution of components is provided in a bar chart. Sometimes, this is something you have to construct yourself (CMLCA) or it is provided in a Sankey diagram (Activity Browser). In SimaPro it is possible to browse between graph types as well as a Sankey diagrams.

Fifth, as Suppipat et al. (2023) claims, there are issues regarding the first-time usability of tools. There is very little descriptive instruction and tool training in the tools assessed. This is also lacking in the IDEMAT tool.

Sixth, the requirement for detailed material selection is too soon in many tools and this is observed in the IDEMAT tool during empirical research. In the early stages of design, the actual material is often unknown, but the material type can be estimated. Tools could anticipate to that notion.

Last, it is seen, just as in the empirical research, that for many tools computational skills are necessary (Suppipat et al., 2023). This can be a barrier for designers inexperienced with LCA to perform a proper LCA.

Interfaces and interaction

In general, what is interesting to see is that there is a large variety in the interfaces, user interaction and therefore usability of the tools. The structural/lay-out difference in calculation tools lead to different focus points that are presented to the user. For example, when the default screen is the database/data input then focus will be on the life cycle inventory and less attention goes to goal and scope definition. Some tools attempt to facilitate the integration of multiple Life Cycle Assessment (LCA) steps on a single user interface, potentially allowing for a more iterative approach to LCA. This could be beneficial, as it would allow for easier modifications to be made to the Goal and Scope, simultaneously to the inventory data. This is done for example in Activity Browser (Brightway). CMLCA uses the ISO standard structure of LCA namely, goal and scope, inventory, impact assessment and interpretation. This is very useful when learning the LCA phases and to easily switch between phases. Furthermore, CMLCA is a very complete and rigorous software. Appendix I, displays some examples of the tools default screens. The screens of Activity browser, OpenLCA and Simapro are adaptable to your preferences as well. It is possible to drop and drag modules in the screen. This is a useful interaction once you are familiar with the functions.

Regarding tool interaction and appearance, designers prefer visual presentation tools. This is especially important to fully grasp the dynamics between design parameters (Bernstein et al., 2010; Lofthouse, 2006). Secondly, scientific language is difficult for designers (Suppipat et al., 2023). The fundamental knowledge of scientific terms, especially related to impact categories is an issue.

Visualization of uncertainty is only done in IDEMAT by fading out the graph. This is interesting, as uncertainty is of high importance for the interpretation and yet fully left to the practitioner.

<u>Accessibility</u>

There are quite some free calculation tools available, but most of them e.g. IDEMAT, Ecolizer, OpenLCA, Activity Browser also provide less functionalities. For example, database import is more difficult because of the specific format, or the interface and interaction is not as optimized as for other paid tools.

In conclusion, there is a great variety of tools to apply LCA in practice, with different levels of complexity, user interaction and visual representation. Each tool has its own specialty, so the choice of the tool depends on the user and the context. What can be learned from existing calculation tools is the functionalities can be broad but should not overwhelm the practitioner. Also, flexibility of functionalities is a benefit and very well implemented in the popular SimaPro software. With this, also interaction properties can be improved, for example by customization to LCA goal. For interfaces, a lot of visual representation is preferred, examples and minimal scientific language. The default screen of software tools is also important as it gives the user a point of attention.

4.3.3 Application context

User group description

The tool is designed in the context of the IDE faculty. It will therefore be mostly applicable to student designers at the IDE faculty who first encounter LCA. However, the tool should be applicable to designers with no LCA knowledge in industry as well. The discussion will cover barriers and drivers for the tool may provide a model for wider industrial adoption of similar principles, as well as the integration into alternative software programs. The user group is assumed to have basic Excel skills, calculation skills and basic understanding of the English language. For the students in the IDE faculty these parameters are measured by entry levels of the study program. The age of the user group is irrelevant.

Incumbent tool of context

The currently used, IDEMAT calculation tool in the IDE faculty in Delft, is shortly introduced in chapter 2.4. A description of functionalities is given in this chapter. In the top left of the tool (Figure 5), the user is asked to fill in purpose, boundaries, functional unit and impact unit. This would generally belong to the 'Goal and scope' phase of a full LCA (ISO, 2006a).

Next the inventory phase is depicted. Four Life Cycle Phases are distinguished (Materials and manufacturing, Transport, Use and End-of-Life) in which the user is ought to fill in unit process data. The columns show what data is needed, Eco-intensity (impacts/kg), Mass per item (kg), Items per functional unit (#), Uncertainty (%) and notes. The uncertainty is expected to be estimated by the practitioner, guidance is given as: 'Uncertainty rubric: 10% for database perfect match, 30% for plausible substitution, 100% for wild guess'.

What is provided then, as impact assessment are the impacts per input row. To the right of these unit process tables, two graphs are provided: impact by component and impact by life cycle stage. These are automatically generated by filling in the rows in the inventory table. The graphs are part of the Impact Assessment phase.

Interpretation throughout these phases is not facilitated by the Excel sheet. Also missing are the inventory results showing substances that contribute from each process to the total impact before going through characterization by impact family. This characterization is seen in a different Excel sheet provided on ecocostsvalue.com/data. This is never shared with the students, neither is it easy to find or referenced. Also, it is possible to see the calculations, as Excel is transparent in this matter.

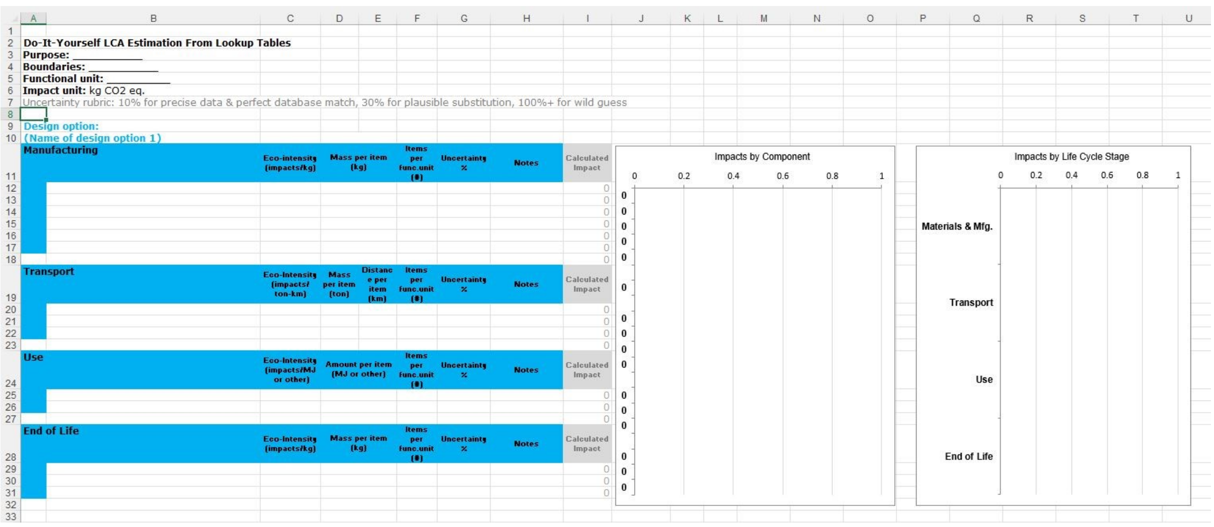

Figure 13: Screenshot of the existing IDEMAT LCA calculation tool

In the unit process background database 6 categories are distinguished: materials, energy, transport, processing, waste treatment and food. Three main impact categories are used; Total Eco-costs (Euro), Carbon footprint (kg CO2 eq), 'ReCiPe2016' (Pt). All single-score indicators have been weight by the Sustainable Impact Metrics Foundation (SIMF) (Sustainability Impact Metrics, n.d.). The 'ReCiPe2016' is weighted with the endpoints of the family of impact categories, ReCiPe (Huijbregts et al., 2016). The Eco-costs single score category is prominent in the tool as well as in the IDE education. As described in the tool: 'The endpoint weighting factors are based on subjective public opinions in Germany, France, Italy, Spain, Poland, UK'. In general, eco-costs represent the amount of money that is needed to prevent the emission. The 'eco-costs' of one kilogram of CO2 can be determined by comparing the cost of constructing a wind turbine to that of another energy source. The extra costs of the windmill are then assigned to the one kilogram of CO2 that was prevented from entering the atmosphere by using the wind turbine instead of the other energy source. A sensitive subject here is what do we use as 'other energy source' because that decision will largely determine the cost difference.

Also, calculating prevention costs brings implications on the temporal scope of technologies, their costs and effectiveness of emission prevention will vary largely over time. For example, the construction of a windmill will likely decrease over time as technology enhances. Also, prevention of emissions is an abstract term and can be interpreted in many ways. On the website, preventing CO_2-eq is done through using renewable energy sources. But what happens here, could cause an impact shift, which is then not accounted for. If we take the same example, with the construction of a wind turbine opposed to gas mining for energy gain, CO2 impacts might be avoided but the impact of critical raw material mining for the wind turbine will increase. The impacts have shifted.

4.3.4 List of design requirements

The design requirements for the tool origin from several sources. The first category is that of context parameters; current tool developments in literature, limitations from the current Excel sheet and, as based on the research question, fundamental LCA elements (Table 11). The fundamental elements are identified based on the LCA handbook (Guinée et al., 2002). A second category design requirements origins from the observed problems, problem clusters and themes gained in empirical research at the IDE faculty in Delft (Table 12). Figure 14 depicts the construction of design requirements.

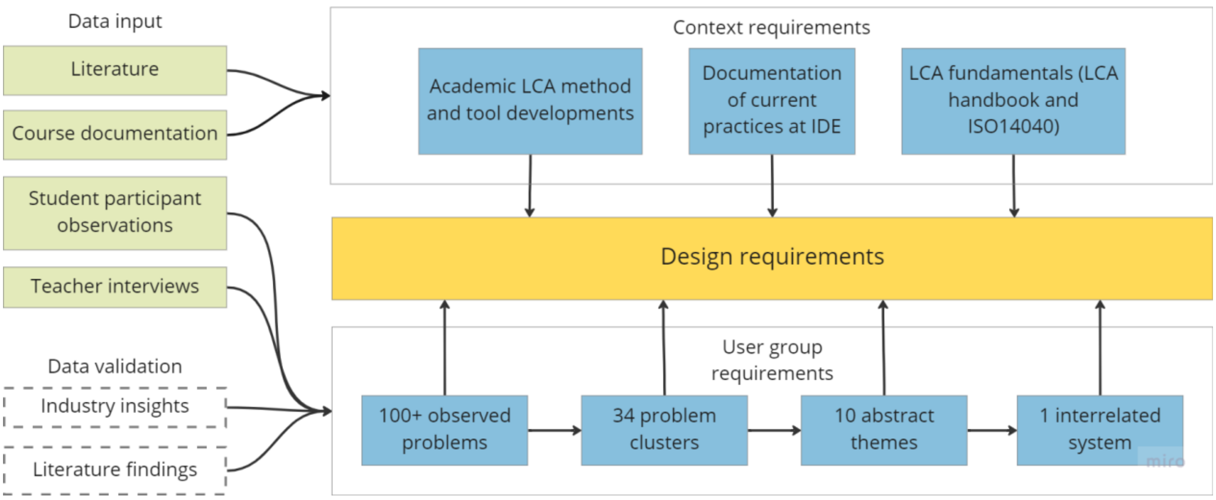

Figure 14: Construction of design requirements

Context requirements

Table 11 shows the context design requirements.

Table 11: Context design requirements

Design requirements (Functional, interaction, accessibility)	Source
1. Functional: The following fundamental LCA elements should all be included in the tool. The goal and scope phase: • LCA goal definition, LCA scope definition, function, functional unit, alternatives, and reference flows. The inventory analysis: • System flow diagram, system boundaries (incl. cut-offs description), multifunctionality, data collection and unit processes. The impact assessment: • (classification, characterization, normalization, grouping and weighing is not (consciously) performed) The interpretation: • Continuous interpretation of assumptions and sources • Contribution analysis (processes/components and LC phases) • Sensitivity analysis, scenario development or uncertainty analysis • Completeness check and consistency check • Conclusion and recommendations	The LCA handbook (Guinée et al., 2002)
2. Interaction: The tool should be based on the current version of IDEMAT ("Idemat Excel files," n.d.) in Excel.	Education module
3. Interaction: The tool should use visual aid, guidance, examples and minimal scientific language.	(Lofthouse, 2006; Suppipat et al., 2023)
4. Functional: The tool be available to use in early design stage	(Villares et al., 2017)
5. Functional: When simplification is applied, uncertainty check, sensitivity analyses should be (easily) provided	(Beemsterboer et al., 2020)
6. Functional: Simplification should be provided through inventory data submission, horizontal exclusion and expert consultation.	(Beemsterboer et al., 2020)
7. Functional: The tool should be a comprehensive platform of LCA elements (e.g. the database is and will be build-in)	(Lofthouse, 2006)
8. Functional: The tool should guide in making well informed assumptions.	(van der Giesen et al., 2020)
9. Interaction: LCA ISO phases should be very clear in the tool	Education module
10. Accessibility: The tool should preferably be free to use for all	Education module
11. Complexity of the tool should be well balanced with (expected) capabilities of the user.	(Lofthouse, 2006; Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2013; Liikkanen & Perttula, 2010; Millet et al., 2007; Purcell & Gero, 1996; Sousa & Wallace, 2006).
12. For the pilot test: Impact category should cover only one category namely climate change as it is most easy to	Benjamin Sprecher

understand for students and used in industry.	

User group requirements

It is expected from the scenario development that an improved LCA calculation tool will foremost influence three themes in the power of an inexperienced designer: comprehension of LCA, time for LCA and capabilities of the designer. The relevant problem clusters and design requirements are therefore ordered accordingly (Table 12). Note, not all insights from the empirical research could be implemented in the new tool due to Excel and time limitations.

Table 12: User group design requirements

Problem clusters from the theme: comprehension of LCA	Design requirements	Source
Students have trouble understanding a functional unit and system boundaries	13. The tool should have an easy build-up of difficult terms.	Student participant observations and teacher interviews
Multifunctionality is a difficult concept, modelling choices often not connected to multifunctionality and IDEMAT is not transparent about multifunctionality while with circularity rising, this is an important LCA element.	14. The tool should give guidance in recognizing multifunctionality	Student participant observations
Input of data from a transparent database helps for understanding of impacts by students	15. The tool should have a transparent database	Teacher interviews
The uncertainty visualized as fading works well for interpretation by students.	16. Result graphs in the tool should visualize uncertainty by graph fades.	Student participant observations
As the current IDEMAT tool provides materials and manufacturing together, there is confusion on whether unit processes already entail manufacturing or not.	17. The tool should have a clear separation of LC phases	Student participant observations
	18. The database should have clear description of unit processes	
Students do not recognize LCA elements, even though they are very similar to design elements.	19. The tool should integrate design tasks for recognition	Student participant observations
Units of process flows, and impact categories are unknown and therefore also understanding lacks.	20. The tool should be explanatory and conscious about units of process flows and impact categories.	Student participant observations
Problem clusters from the theme: Time for LCA	**Design requirement**	**Source**
Data preparation and input is one of the most time-consuming parts of LCA	21. The tool should provide quick look-up of unit processes	Student participant observations and literature (Suppipat et al., 2021; Beemsterboer et al.,
	22. The tool should stimulate simplification through	

	qualitative expert judgement 23. The tool should limit the time needed for data input	2020; Jusselme et al., 2018)
Student designers indicate to want to spend as little time as possible on making an LCA. Also, in industry the limited time is confirmed.	24. The tool should provide simplification through unit process exclusion and substitution of secondary processes	Literature (Beemsterboer et al., 2020)
(Time, motivation and mindset) Student designers are often fulfilled when they have their first results, they do not make a robustness assessment, consistency checks, completeness checks etc. (This, while sensitivity analysis and scenario testing matches very well to the fuzzy front-end of a design process)	25. The tool should make sensitivity analysis and scenario testing less time consuming and approachable, starting before they see graph results, not after. 26. The tool should provide guidance in completeness and consistency check.	Student participant observations
Time stress leads to ignoring LCA structure or skipping steps	27. The tool should facilitate a clear LCA structure and steps should be sequential.	Student participant observations
	28. The tool should prevent students to skip LCA steps	Student participant observations and teacher interviews
Problem clusters from the theme: Capabilities	**Design requirement**	**Source**
Students tend to get a little helpless and panicked when they cannot find certain data (e.g. life-time or manufacturing processes)	29. Tool should facilitate a low threshold in making assumption (will lead also to better repeatability)	Student participant observations, literature (van der Giesen et al., 2020)
Students are hesitant in making assumptions (which increases time spent and frustration)	30. Sensitivity analysis should be made easy to make designers more resolute in decisions.	Student participant observations, literature (Beemsterboer et al., 2020)
Many questions regard Excel and calculation practicalities	31. The tool should match a student's skills regarding Excel and calculation	Student participant observations
Students are generally happy and surprised by the results but not super curious to dive into the reason behind the outcomes. When graphs are made, the duty is done.	32. The tool should increase the comprehension of LCA complexity and stimulate nuanced interpretation of results.	Student participant observations and teacher interviews.

The user group design requirements are summarizing and prioritized. This results in the following main problems and design requirements as seen in

Table 13.

Table 13: Main problem clusters and design requirements

	Problems from empirical research	Design requirement	Source
1	Miscomprehension is often caused by not understanding LCA terms and the LCA structure being a misfit to design cycle. Panic due to capability/complexity incoherence is often due to complex requirements at too early stage and abstraction of product parameters.	The tool should provide a better fit to the design process.	Student participant observations, teacher interviews
2	Data collection brings most questions for students and data collection takes most time. LCA is often performed at a late design stage due to data requirements. Also, panic occurs when data problems occur.	The tool should provide early LCA implementation through simple unit process requirement and guidance in data collection.	Student participant observations, teacher interviews
3	Robustness assessment (e.g. through sensitivity testing) is not done in the course and could be very beneficial for designers to be less hesitant in making assumptions. Scenario development could be beneficial as, in early-stage design, there are often several design variations.	The tool should make sensitivity analysis or scenario testing easy and stimulated (through automatically filled-in unit process tables).	Teacher interviews, course documentation

4.3.5 Concept presentation

In appendix F, the improved simplified LCA tool is provided. In the tables below, all design requirements and their corresponding tool implementations are described. The structure is again based on context design requirements and the themes comprehension of LCA, time for LCA and capabilities (Table 14).

Table 14: Tool implementation of design requirements

Context design requirements	Tool implementation
1. Functional: The following fundamental LCA elements should all be included in the tool. The goal and scope phase: • LCA goal definition, LCA scope definition, function, functional unit, alternatives, and reference flows. The inventory analysis: • System flow diagram, system boundaries (incl. cut-offs description), multifunctionality, data collection and unit processes. The impact assessment: • (classification, characterization,	All elements have a place in the Excel sheet, where it is either asked to answer a question or fill in a datapoint.

normalization, grouping and weighing is not (consciously) performed) <u>The interpretation</u>: • Continuous interpretation of assumptions and sources • Contribution analysis (processes/components and LC phases) • Sensitivity check or scenarios development • Completeness check and consistency check at the end • Conclusion and recommendations	
2. Interaction: The tool should be based on the current version of IDEMAT (2022) in Excel.	It uses the software, Excel. The new tool also uses the unit process table as a basis and the graph style with fades to indicate uncertainty.
3. Interaction: The tool should use visual aid, guidance, examples and minimal scientific language.	LCA structure is visualized in the introduction, a visual example of a system drawing is given, for the whole goal and scope phase an example is given. Regarding scientific language, many LCA terms are replaced or supplemented by design terms (e.g. alternative/concept). Also, all LCA phases have a different color and are consistently implemented.
4. Functional: The tool be available to use in early design stage	Data requirements are made easy, it is possible to calculate results from input of material category only. Also, the use of scenarios per alternative is useful for because often there are several design options.
5. Functional: When simplification is applied, uncertainty check, sensitivity analysis should be provided	In the interpretation tab, many guiding questions are asked to reflect on uncertainty and sensitivity.
6. Functional: Simplification should be provided through inventory data submission, horizontal exclusion and expert consultation.	Data submission is done by using the IDEMAT database. Horizontal exclusion is voluntary by the practitioner. Expert consultation is advised at certain steps in the inventory phase.
7. Functional: The tool should be a comprehensive platform of LCA elements	The database is and will be build-in and all ISO LCA phases are addressed, so there will be no need to switch platforms except when e.g. lifetime data is needed from internet or company documentation.
8. Functional: The tool should guide in making well informed assumptions.	Two columns in the inventory phase are dedicated to assumptions and sources. Notes explain the way to make assumptions. Also, per step guidance is given on how to make proxies etc.
9. Interaction: LCA ISO phases should be very clear in the tool	The tool divides Excel tabs per ISO LCA phase. Each phase has a different color which is consistent throughout the tool.
10. Accessibility: The tool should preferably be free to use for all.	The tool is recommended to be freely available. The only obstacle is providing an open database.
11. Complexity of the tool should be well balanced with (expected) capabilities of the user.	*This will be discussed more detailed in the 'Capabilities' section.*

12. Impact category should cover only one category (namely climate change)	There is only one impact category input possible, and the graphs are expressed in this impact category as well.
Design requirements: Comprehension of LCA	**Implementation**
13. The tool should have an easy build-up of difficult terms.	The system flow diagram and boundaries are brought forward so that it is illustrated right from the start. Also, build up to the functional unit is done through the construction of a use-scenario including who, what, where, when and how. For many other difficult terms, examples or guidance is given.
14. The tool should give guidance in recognizing multifunctionality	In the goal and scope tab, attention is given to whether the system includes multifunctional processes. *Guidance on how to handle multifunctionality is recommended to implement in a next iteration of the tool.*
15. The tool should have a transparent database	*This is already done*
16. Contribution graphs in the tool should visualize uncertainty by graph fades.	*This is already done*
17. The tool should have a clear separation of LC phases	This is done through separation of the unit processes in; Material extraction, manufacturing, distribution, use and end-of-life.
18. The database should have clear description of unit processes	*Not implemented as it applies to the database*
19. The tool should integrate design tasks for recognition and understanding	Use scenario, ideation and whole system map are added in the goal and scope phase.
20. The tool should be explanatory and conscious about units of process flows and impact categories.	There is an explicit row with the unit of each number, to fill in by students. Also, this row has an explanation when you hover over it.
Design requirement: Time for LCA	**Implementation**
21. The tool should provide quick look-up of unit processes	This is done through keeping the database next to the calculation tools and a drop-down menu for category averages.
22. The tool should stimulate simplification through qualitative expert judgement	The tool suggests requesting for external help in some inventory analysis steps.
23. The tool should limit the time needed for data input	The tool uses automatic referencing functions in Excel sheet and dropdown menus. Also, there is the possibility to use category averages. Calculations and result visualization is based on the data with the highest resolution (category average opposed to actual data) but data can be mixed and simultaneously included in the results.
24. The tool should provide simplification through unit process exclusion and substitution of secondary processes	*This was already integrated in the incumbent tool, a database with secondary processes is used.* For process exclusion, users are free to decide what

	detail they want to go into. The tool questions help making these decisions transparent.
25. The tool should make sensitivity analysis or scenario testing less time consuming and approachable, starting before they see graph results, not after.	In the inventory, users are asked to fill in two extra unit process tables per alternative, those tables provide the chance to test sensitivity or design variations (It is left to the designers whether they want to test a scenario or the sensitivity of assumptions).
26. The tool should provide guidance in completeness and consistency check.	The interpretation tab provides questions and guidance in making a consistency and completeness check.
27. The tool should facilitate a clear LCA structure and steps should be sequential.	Excel tabs and order of assignment is split over the ISO 14040 LCA phases
28. The tool should prevent students to skip LCA steps	The tool is built up with Excel references, so if the goal and scope steps are skipped, it is not possible or a lot harder to continue to the inventory phase.
Design requirement: Capabilities	**Implementation**
29. Tool should facilitate a low threshold in making assumptions (this will also lead to better repeatability)	For all data inputs, there is an availability to write down assumptions. The threshold is lowered also because assumptions can easily be tested in the extra unit process tables.
30. Sensitivity analysis should be made easy to make designers more resolute in assumption decisions.	Sensitivity testing is implemented as an automatically filled-in table below the original unit process table, they only have to change the parameters that they want to test.
31. The tool should match a student's skills regarding Excel and calculation	Most calculations are done automatically. Small calculations such as the number of components and adding them for assembly are left for the user.
32. The tool should increase the comprehension of LCA complexity and stimulate nuanced interpretation of results.	Standard, three scenarios are given per alternative. This gives an insight into the nuances of assumptions that are made, and students consciously work with it. Also, in the impact assessment these graphs are depicted next to each other.

Again, the three main and overarching improvements are summarized in the following table (Table 15). In the table the sum of improvements is given and the benefits of implementation.

Table 15: Three main improvements of the LCA tool

	Design requirement	Sum of tool improvements	Benefits
1	The tool should provide a better fit to the design process.	Integration of design terms and actions such as ideation, 'concept', 'design variation' and drawing of a system diagram. Also, a use scenario construction to help create a functional unit and think more abstractly.	• Easier understanding of LCA terms and structure. • Better use of the method and valuable outcomes.
2	The tool should provide early LCA implementation	The tool provides the option for using category averages opposed to detailed data requirements. Drop	• A low threshold for beginning the LCA. • First understanding of LCA

	through simple unit process requirements and guidance in data collection	down menus are used to select category averages. Many Excel calculations are performed automatically, and cell referencing is implemented. Cell notes are used to guide in data collection and examples are provided.	structure. • Iterative use. • Less time intensive. • Less confusion/questions.
3	The tool should provide an easy and early application of robustness assessment (sensitivity analysis or scenario testing)	The tool automatically generates two scenario tables with which the user can decide to either test a scenario or sensitivity of parameters. (*In the final tool this is called 'design variation/sensitivity test'*)	• More insight in nuances of LCA. • More comprehension of system. • Better understanding of the sensitivity of assumptions. • Less hesitant in making assumptions. • Better fit to the design cycle by testing design variations.

4.3.6 Concept evaluation

The goal of this evaluation is to test whether the main design requirements were successfully transferred to the students. The main design requirements were as follows:

1. Better fit to design cycle by integration of design terms and actions such as ideation, system diagram drawing and use scenario construction.
2. Early LCA implementation through simple unit process requirements (category averages, drop down menus) and guidance in data collection (automatic cell calculations, explanation and examples).
3. Easy use and stimulation of robustness test (sensitivity analysis or scenario making) (through automatically filled-in unit process tables).

Appendix H, provides the tool evaluation questions and results in Excel. Results are interpretated and integrated as depicted in Table 16.

In general, both the tool structure as the LCA phases were clear (rated 4 out of 5). Regarding a better fit to the design cycle (1), creating a use scenario before constructing the functional unit was considered useful (rated 4.2 out of 5). Drawing the system and system boundaries was also quite useful (rated 3.7 out of 5), the ideation step was considered a little less useful (3.3 out of 5). Overall, the fit of the simplified LCA tool to the design cycle was graded 3.8 out of 5. Some people indicated to really like the way that it starts from simplified to more specific data needs and that it takes a reasonable amount of time compared to the outcomes. Students liked that it is quite easy to adapt early input later in the process. Other students still have difficulties with the amount of data needed and the estimations that need to be made. Also, some students gave the fit to design a 2 (out of 5) because of the inability to cover 'interaction' design and service design. These examples suggest that students have not learned what the possibilities of LCA are. It is thus caused by gaps in education.

Regarding the early LCA implementation (2), some students indicate to use the tool after detailing and embodiment, but at least half of the students expresses to use it iteratively during the design process, starting from early ideation phase. This is an improvement, compared to the prior LCA tool.

In general, people were clear on how the inventory phase was structured. Some people referred to terms being unclear such as how to define uncertainty, how the category averages work and the fact that you can select with a drop-down menu instead of filling in. Many people liked to have the category averages as a possibility, the reactions were very positive. One person indicated to get lazy from using category average and not wanting to fill in the 'actual' data. In total, the usefulness of category average was rated 3.9 out of 5.

The guidance in red instruction notes was helpful eventually, but many people indicate to have a hard time finding them. There are some people who want to have more examples as in the goal and scope phase. Uncertainty and End-of-life determination were indicated as a difficult step from the inventory phase.

Overall, students indicate that it is hard to get into the mindset of making assumptions and estimations. This is feedback that was given at the original tool analysis as well. They indicate that the tool is a bit overwhelming to perceive at first, there are many fields to fill in. But after starting, it was easier and more approachable to fill in estimations and averages.

On average, most people were moderately clear on what sensitivity test or scenario test (3) means and what the value was for them. They were unanimously positive about the usefulness of scenarios for their (hypothetical) design continuation, as they can test different design variations or the sensitivity of their assumptions. The functionality, however, was more difficult. For some people the automatic referencing in Excel got incorrect (by dragging cells), as a result the scenario or sensitivity tables were hard or impossible to fill in. The table was for some people a bit hidden as it is scrolling down. Additionally, quite some people want to have more examples in the inventory and interpretation phase. Some people were asking for a full unit process table example in the Excel sheet.

The hardest part for students to understand was interpretation of the graphs and interpretation questions at the end. Hardest to perform was making assumptions regarding data input and uncertainty. There were also again some comments on the faulty automatic referencing in the scenario tables making it time consuming and not useful.

In Table 16, a summary is given of the tool evaluation results. In the second column improvements to the tool are provided. The results are split over the three main design requirements.

Table 16: Interpreted results of survey evaluation of the simplified LCA tool at the IDE faculty in Delft

Interpreted result	Improvements to the tool
Better fit to design cycle by integration of design terms and actions such as ideate, system diagram, use scenario etc.	
It is not clear that all use scenario elements are building up to the functional unit.	For the functional unit, explanations are brought to the front opposed to in hidden notes.
Use scenario was useful and system drawing was useful, ideation a bit less	*No action*
Fit to design cycle is sometimes rated a 2 out of 5 because people think user interaction design and services cannot be modeled.	*This is considered an education shortcoming.*
Early LCA implementation through simple unit process requirements (category averages) and guidance in data collection (explanation, structured and transparent database).	

The notes, indicated in red are first ignored, because it is not very visible (with red triangles)	For some terms, explanations are brought to the front again, and more tips to look for notes is given.
The distinction between automatic cells, selecting cells and fill-in is not clear (some students copy data to a cell that is calculated, which messes up the calculation).	This distinction is clarified by using light blue color for automatic cells, a border for selecting cells and empty for fill-in. Also, at the top bar, it is now clarified what should be done in the cell.
The second column is empty, and it was unclear what to fill in here.	The column is merged with the next one so that there is no misunderstanding.
Students indicate to want more examples in the inventory phase.	Another tab is given with a full unit process table example.
Easy implementation of robustness test (sensitivity or scenario testing)	
The term 'scenario' in the inventory phase was very unclear and confused with use scenario (from the goal and scope phase).	The term scenario is replaced by 'design variation' (therewith it is clear that it is not a different alternative/concept but a variation to the concept) in the note it is described what is the difference between design variation test and sensitivity analysis.
It is unclear that it is needed to make different 'scenarios' as the table is hidden below the original inventory table.	At the top of the inventory tab students are asked to provide the design variations already with a reasoning why. This reason is referred to again in the impact assessment as a reminder why they were testing certain design variations. Also, an overview graph of the environmental impacts is given at the top. *In future development, the graph should have proper labelling to distinguish automatic generated data and manually input data.*
The scenario tables show some Excel limitations, mainly when dragging cells in the first table, the scenario tables get malfunctional.	*No action, Excel functional limitation. Can be fixed with different software or more advanced excel skills (e.g. cell lock).*
Other feedback (outside of research scope)	
Students indicate that it might be nice to know that there are more impact categories than Carbon footprint.	A note at the impact assessment is added, to reflect on what categorie they use and what there are available, what the value is etc.
It is unclear how to decide on uncertainty	The uncertainty choice is guided by Ecoinvent uncertainty pedigree matrix: reliability, completeness, temporal, geographical and further technological correlation (Ciroth et al., 2016).
Interpretation questions were difficult for students to fill in.	More guidance is given in the notes. *Even though this is not the main goal of this improvements and therefore not elaborated upon.*

To summarize this chapter, after the decision to test intervention 3 from the theoretic research phase, an improved LCA tool for the IDE faculty has been developed and tested.

At this point the following research question can be addressed: *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?*

To answer the above research questions and complete this chapter intervention 3, an improved LCA tool for the IDE faculty, has been developed. The tool solves some of the main problems that students at the IDE faculty encounter while performing LCA.

It can be concluded that an improved LCA tool has successfully manifested some of the main theoretical findings. The effectiveness of main improvements has been evaluation at the IDE faculty in Delft among master students. The main improvements include a better fit to design cycle by integration of design terms and actions, early LCA implementation through simple unit process requirements and guidance in data collection and easy use and stimulation of sensitivity analysis and scenario making are tested. Overall, a better fit to the design cycle was mainly achieved by an easy buildup of difficult terms and substitution by design terms such as 'concept' and 'design variation' (opposed to 'alternative' and 'scenario or sensitivity test'). The fit to the design cycle was overall rated as 3.8 out of 5. There is a small limitation found in educational practices in conveying LCA's value for interaction designs and service design (students are still doubtful about this). Furthermore, using category averages has shifted the use of the simplified LCA tool to earlier implementation and iterative use. The usefulness is rated 3.9 out of 5 and it is mentioned as the reason why iterative use is possible. However, for many students it is still hard to get into the mindset of making assumptions about unknown data in early design stages. This could be good to study again, although it has improved by making it easy to do sensitivity testing and design variation testing. Students were unanimously positive about the functionality of several automatically filled in unit process tables. In general, students indicate the interpretation phase as being hardest to understand and perform.

4.3.7 Tool limitations

The main tool improvements are 1) a better fit to design cycle by integration of design terms and actions, 2) early LCA implementation through simple unit process requirements and guidance in data collection, and 3) easy and early implementation of robustness assessment (sensitivity analysis and scenario making).

Choosing an improved tool as system possible intervention, this LCA tool is only an example of manifestation of the research findings. Many more tool adaptions are possible as well as the development of an adapted LCA method or design method based on academic LCA methodology. The disadvantage of having only an adapted simplified LCA tool is that it remains a sidestep from the design process. Designers, inexperienced with LCA, still must 'leave' the design process to perform a simplified LCA. This means risks of creative limitation and disruption of the design process. It is not integrated into the 'regular' design process. Taking this sidestep requires a mindset change, which has become evident in the current study as well. There has been an attempt to make this mindset change less overwhelming by enhancing the fit between design practices and LCA performance (see chapter 4.3.5). But still, there has been feedback on the fact that quantification is needed, and a lot of parameter definitions are required (e.g. materials, manufacturing etc.). The change to an abstract mindset has been made more smoothly for instance, by slowly building up to the functional unit with a use scenario.

Besides the sidestep being mentally challenging, it means the designer has a choice to take this sidestep or not. There are many facets influencing whether this sidestep is taken. For example, education can force an (inexperienced) designer, regulation can do so too, and social factors can, more softly push a designer. Therefore, it could be more effective to have a design method or adapted LCA method that integrates LCA continuously over the design cycle. Then designers naturally run into an LCA performance during their design process.

Besides application limits, there are some functional limits to the new LCA tool. Two functional limitations regard Excel functionality, namely, the expansion of the user its system is a time intensive task and therefore avoided in the test assignment. Also, multifunctionality is brought to the consciousness of the user, but solving strategies are not discussed and presented for the user. In further research these functional limitations should be considered. Additionally, for this prototype only one impact category can be used, this is simpler for students but limits the LCA results and interpretation tremendously as not all impacts a product makes can be covered in one indicator.

There are more minor functional limits to Excel, such as the referencing of cells being disturbed when edited. The conversion to another software program is recommended at this point to solve functionality problems of Excel and enhance user interaction and experience.

Also, the current data of category averages is based on averaging process groups of the IDEMAT database. This is only for the prototype to test its functionality. Research should go into methods to average material (or other process) groups, as it is apparent that material impacts within a group differ largely.

Because the tool aim was to manifest research findings, which were mainly functional design requirements, there has been little attention going into aesthetic performance of the tool. However, aesthetic performance can have influence on a designer's motivation and mindset. It could therefore be an interesting parameter to keep in mind for future iterations on the tool and possible conversion to another software program. The same goes for database limitations such as the effort it takes to go back and forward between the database and inventory tab to copy processes. Those limitations are not solved in the tool as the study focus is on 'LCA method and tool' improvement, but improvements to the database could have influence on the general tool useability that are evaluated. It should therefore be considered in further tool development iterations.

5 Discussion

Designers carry a large responsibility regarding the environmental impact of products, services and systems. The quantitative, holistic, and context-specific environmental assessment method, LCA has the potential to support designers make environmentally sustainable design decisions. However, the effective use of the method fundamentals by designers has been falling short. This study has improved the knowledge on what problems inexperienced designers run into while performing LCA. Also, it gives an example of one intervention that can help enhance the way inexperienced designers use LCA.

This study has aimed to determine w*hat is needed to enable design students, particularly at the Industrial Design faculty in Delft, without prior experience in Life Cycle Assessment to effectively incorporate the fundamentals of the LCA method into their design practices?* To answer this question, three sub-questions were answered:

1. *What are the problems that design students experience when performing LCA for the first time?*
2. *What are the relations between the identified problems and what effect could possible interventions to the system have?*
3. *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?*

A case study is conducted at the IDE faculty in Delft. During the study, students and teachers are interviewed and observed. The observed problems are clustered into problem clusters and abstracted into themes. These themes are then depicted in a system causal loop diagram. Possible interventions are drafted based on external influence on the system. Finally, an improved LCA calculation tool is introduced to demonstrate the most important research findings. The tool is evaluated with master students at the IDE faculty.

This chapter discusses the research results (5.1), the constraints of research results (5.2), the limitations of methods (5.3) and the scientific and societal importance of research findings (0).

5.1 Research results

Overall, the research results consist of (1) a system model containing problems and themes inexperienced designers encounter while performing LCA and (2) an implementation of theoretic findings in an Excel LCA tool.

In the first phase of this research a system model is developed compiling the first research questions: *What are the problems that design students experience when performing LCA for the first time?* This system model encapsulates the problems that student designers encounter represented in themes of the reasons why they occur. The identified themes are a designers' mindset, motivation, time for LCA, capabilities and comprehension of LCA. They will shortly be addressed below.

A designer's **mindset** can directly influence the effectiveness of LCA method by having the mindset more aligned with uncertainties, enable abstract thinking and quantitative result interpretation. A positive mindset can also apply a designers' holistic perspective for the better and raise its interest in sustainability. In case designers become more familiar with quantitative methods, interpretation will become more accurate and nuanced. Also, trust in the application of LCA might increase. Careful interpretation must be done considering uncertainties, trade-offs, nuances and other complexities. So, the designer's mindset can be beneficial but also very counterproductive to LCA performance.

Motivation can have an indirect influence on the effectiveness of LCA as a method for designers through the increased time for LCA, improving capabilities and comprehension of LCA. Problems building up to the motivation themes are, amongst others, the fact that only 50% shows up in class, students indicate to want to spend only 3 hours or half a day on LCA and students go for the easiest and fastest option regarding data input and result interpretation. Motivation can be enhanced through external intervention such as regulations (or company policies) and an improved mindset.

Time for LCA is a very central node in the system and influences the comprehension of LCA, designer capabilities and motivation. It therefore also influenced the effectiveness of LCA use for designers. Directly, a lack of time causes a rush through the method possibly going over phases too fast or neglect them completely. This is seen during student observations with skipping parts of the goal and scope phase such as functional unit, system boundaries, goal definition and multifunctionality. The largest most time-consuming step is considered the data collection. Therefore, the external theme of data quality and quantity is very entangled with time for the LCA method.

Then there are the designer **capabilities**. In the IDE case study, it is seen that discrepancy of a designers' capabilities and the method or tool complexity, can result in overwhelmed students. It is seen that students sometimes get upset when too much knowledge or data is requested by the LCA tool or method. Literature confirms that this capability/complexity discrepancy can cause fixation (Liikkanen & Perttula, 2010; Millet et al., 2007; Purcell & Gero, 1996; Sousa & Wallace, 2006) and limit creativity (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2013; Lofthouse, 2006). Fixation appears during the design process and causes stagnation. However, it can also appear during interpretation and lead to adhering to one solution neglecting the complexity and nuances of LCA results. In empirical research is found that when graphs are made, students feel the duty is done. Rarely robustness assessments, sensitivity analysis, scenario testing or research into the cause of outcomes is conducted.

Lastly, the **comprehension of LCA method** might have most effect on the effectiveness of LCA, especially an adverse effect when the comprehension is insufficient. Below a certain threshold, LCA results are not representable if the method is applied incorrectly. Misunderstanding, as results from the empirical research, appears in all LCA phases. In the goal and scope phase, mostly functional unit and system boundaries are not understood correctly. The inventory phase and data collection, as discussed earlier, can be unclear regarding proxy processes, making assumptions, determination of the use phase and uncertainty estimation. In addition, multifunctionality and end-of-life determination are a very difficult subjects to inexperienced designers. The end-of-life is difficult in relation to drawing system boundaries. 'Does the impact of recycling belong to this or the next product's lifetime? How do you integrate that in the functional unit?' those are some examples of the questions. Understanding when to implement LCA in the design process is still unclear and there is no easy recognition of elements that bridge both processes (LCA and design). Then, for the interpretation there are questions about impact category meaning, how to handle uncertainties and how quantitative numbers are in relative proportion to each other.

The second sub-question concerns: *What are the relations between the identified problems and what effect could possible interventions to the system have?*

The themes show interrelations of which time for LCA is the most interrelated theme, being connected to motivation, capabilities, and comprehension. Besides themes in the power of designers, there are themes influencing from outside. These themes include social factors, regulations and company policies, data quality and quantity, LCA method and tools and LCA education. The themes are interrelated with the internal themes. In this matter, LCA method and tools is the most connected external theme influencing time for LCA, capabilities and comprehension of LCA. LCA education is related to capabilities and comprehension. The strength of these interrelations have not been tested in this study.

The development of a system of themes helps understand the dynamics between problems. By knowing the dynamics of the system, it is possible to understand the systemic effect of changes or interventions. For example, when regulations regarding product environmental impact change, the designers time for LCA and motivation might change. However, these theories also need to be tested and scrutinized in real-life practices. Concluding, this system model could be a start to further explore interventions and improvements of the system and its themes.

Possible interventions to the system are described and the most feasible intervention to test within this research is chosen, namely LCA tool improvement. This intervention could influence the designer's comprehension of LCA, the time for LCA and the capability/complexity coherence. This Intervention is tested by improving the LCA tool used at the IDE faculty. This fits within the research resources; time, IDE location and researcher skills.

Overall, the improved tool aims center around the themes of a designers' capabilities, comprehension and time for LCA. Three main improvements are highlighted below.

The first overarching improvement is a better fit to design cycle and is achieved by integration of design terms and actions. For instance, ideation is stimulated, a design method being 'Whole system mapping' is integrated as addition to the LCA flowchart. Also, there are questions building a use scenario for the designer to slowly construct the functional unit. The use scenario consists of questions who, what, where, when and how the function is fulfilled. Also, some LCA terms are supplemented by design terms such as 'Alternative/concept', 'Sensitivity analysis/Design variation'. By these measures, it is expected that inexperienced designers better understand LCA terms and find it easier to perform certain LCA steps. Also, it is expected that getting into product and system abstraction becomes easier. This measure is expected to improve the themes; time for LCA, capability/complexity coherence, comprehension and possibly a designers' mindset.

The second overarching improvement is the tool providing early LCA implementation through simple unit process requirements with category averages and data collection guidance. Guidance is given though notes in the cells when you hover over them, suggestions for external help and there is structure in ISO LCA phases. The unit process requirements are more smoothly increasing as it is possible to first make an LCA with category averages selected from a drop-down menu. The threshold for this kind of modelling is considered very low. Later, the designer can make an LCA with the actual input data. Calculations and result visualization is based on the data with the highest resolution, but data can be mixed and simultaneously included in the results. Also, many calculations are automized and the amount of data input is minimized. For example, when the title of a material is put in correctly, the tool automatically finds the corresponding environmental impact indicator value. Also, titles of alternatives and variations are automatically referenced over all ISO LCA phases in the different tabs, lowering the repetition for the user. These measures create a low threshold for beginning the LCA in early design phases and stimulate iterative use. As a result, less time is spent, and confusion or questions regarding data collection are minimized. The theme time for LCA and the capability/complexity discrepancy is expected to be improved.

The third overarching improvement is the tool allowing for easy and early implementation of robustness assessment (sensitivity analysis or scenario making). This is done through automatically filled in unit process tables in Excel. The designer only needs to edit the parameter that they want to test or the design variation they want to make. For early LCA use it is beneficial that design variations can be easily tested. This creates a better fit to the design process. Most importantly, the extra unit process tables can provide the designer with more insight into both the nuances and complexities of LCA results. Also, it creates a lower threshold for making assumptions as they can easily be tested. This measure is expected to improve mainly the time for LCA and comprehension of LCA.

Besides these main tool characteristics, there are many minor improvements made compared to the initial LCA tool used at the IDE faculty. For instance, the tool includes visual aid by the LCA phases being color-coded. Category impact results are visualized in graphs increasing detail. There is an overview graph, a contribution graph per LC phase and per unit process.

Overall, in the tool evaluation, the fit to the design cycle was rated 3.8 out of 5. The usefulness of having category averages was rated 3.9 out of 5. Having extra, automatically filled in, unit process tables to make a sensitivity analysis or design variations was unanimously evaluated positive. The student designers were happy to test several design variations or the sensitivity of their data input. These results show a positive stance towards the tool improvements and suggest a better integration of the LCA method into design practices. Hence, this could be a good basis to further develop an LCA tool based on the theoretic findings from this research and test its effect in a broader scope.

5.2 Constraints of research results

This section will discuss the boundaries that the research results.

To begin with, there are some boundaries to the generalizability. The research group is made up of student designers inexperienced with LCA. So, the results of this research also only apply for design students in the IDE faculty. In industry there are expected to be many designers with little or no prior LCA experience as well. University is a general learning environment whereas in industry it might not be as common to learn new methods and tools. This may possibly constrain the speed of learning the functionalities of the LCA tool in industry practices and consequently constrain the effective LCA implementation.

The study focused on the research group of inexperienced designers. Its applicability to more experienced designers could be tested further. It is expected that more experienced designers can make use of the tool, while they may find guidance and examples redundant. Furthermore, such designers may require more advanced LCA functionalities as they continue to refine their LCA skills. As such, it may be recommended to either enhance this tool or use it as a steppingstone before transitioning to more advanced LCA software. The main advantage of this LCA tool is that it is comprehensive in terms of fundamental method elements and clearly displays the phases of LCA in a repeated manner. This makes the transition to more advanced LCA software tools smooth.

Research has been in the Netherlands, a fairly stable, knowledgeable and economically developed country. This leads to possible biases in the sample group such as little interference from financial problems, political instability, technological limitations (e.g. no computer available) and the benefit of knowledgeable support from surroundings. In the system model this concerns almost all external themes. Most importantly it concerns the social factors, LCA education and regulation and company policies as those are country specific. Data quality and quantity in LCA methods and tools are generally worldwide accessible, although largely depending on financial aid. Also, there are cultural difference with a target group in the Netherlands opposed to other countries. For example, directness in communication can possibly lead to more transparency and critical questions during the courses. The researcher being participant in the research observations has contributed to the openness of questions as well, as there is less hierarchy opposed to when questions are asked from a pedestal or distant figure. This likely has been a benefit for data collection and supports research quality because questions are answered more openly.

The quality of education has influence on generalizability as well. Design education at the TU Delft is ranked 11th in Art and design by the QS World University Subjects Rankings 2021 (*QS World University Rankings for Art & Design 2021*, 2021). This could influence the results in a way that the theme 'LCA education' has a more positive effect on the system. It therefore also has a positive impact on the designer's comprehension and capabilities. In a more average system (e.g. in a different country), the design and LCA education could be worse.

Assessing generalization would be a good step for further research.

The decision is made to assess the intervention that is feasible with this research scope, namely the improvement of LCA method or tool. An improved LCA tool is only one piece of the puzzle; for a complete solution, it is necessary to explore and implement other interventions to the system as well.

As found in the system model, mainly designers' capabilities, comprehension and time for LCA are affected by the improved tool. Yet, the motivation and mindset are not necessarily affected. How could these themes also be stimulated? Looking at the system model, regulations and social factors can play a role in this matter. For example, social factors may include the study association awareness activities. The faculty organization can play a big role in this as well, namely by integrating the concepts of Design for Sustainability more spread out over the study program to gain awareness and familiarity. This can enhance familiarity with quantitative research as well. Besides the study influence, initiatives such as 'extinction rebellion', a climate activist group, can socially influence students as they see it is gaining popularity and urgency.

As only one intervention is tested (intervention 3), it is good to address the possible influence of other interventions (1,2,4) as well. The improvement of regulation or company policies might have powerful influence on the system as it consists of strict rules, which designers would have difficulty avoiding. Also, it influences the time for LCA which is a very central node in the system. Then, the improvement of data quality and quantity could have had influence on the time for LCA mainly. It is only one theme, but in practice, time for LCA and especially time spent on data collection has demonstrated to be one of the biggest problems. So, the improvement of data quality and quantity could have a powerful influence, but it takes a lot of time and effort to improve. Lastly, the improvement of LCA education can have influence on the comprehension of LCA and designer capabilities. The power of influence of this theme, should be tested in practice. The LCA method and tools can take over some of those educational practices as is done in the improved LCA tool. It is probable that the most effective approach would be to implement interventions from multiple external inputs, such as data quality and quantity, education and regulations, at the same time.

5.3 Limitations of methods

Overall, the rigor in interpretive research can be described by 4 parameters; dependability, credibility, confirmability and transferability (Bhattacherjee et al., 2019). In short, the research is dependable if two (or more) researchers assessing the same phenomenon end at the same conclusions. This is not established in the current study as it is performed and evaluated by only one researcher, it should thus be scrutinized in future research. The credibility of this should also be proven by independent researchers and is not yet done. Regarding confirmability in this study, the participants can confirm the conclusions, as is done in the tool evaluation. This strengthens the confirmability. Still, more researchers and participants should add to the confirmability. Finally, the transferability refers to external validity. Transferability of this study can be improved as research has been based on a IDE faculty case study. No external tests, such as in different context and with different research samples have been performed.

Before going into individual method limitations, it is good to assess the relationship between methods compiling this research. There is a consistency in all research methods being qualitative in nature (apart from a few supporting literature studies). This could be strengthened by adding a quantitative research method, for example a larger research sample would be beneficial. In the research methods there is a mix of primary and secondary data of which the secondary data is only used to validate and support primary data. Moving forward, limitations to individual methods are addressed per research question.

1) *What are the problems that design students experience when performing LCA for the first time?*

To address this research question, two methods have been used; teacher interviews and student participant observations.

In the teacher interviews some data issues have been found. First, there is likely a social desirability bias, as being critical of sustainability is prone to damage someone's social image. Especially now that the majority (64%) of public opinion believe action should be taken to avoid climate change (Flynn et al., 2021). Furthermore, the semi-structured nature of the interviews has likely led to interviewer bias, with follow-up questions potentially steering the subject. Additionally, the interviews were manually summarized by the interviewer, which could lead to researcher biases. Sampling bias is also possible, as the sample consists of those teachers who voluntarily applied and may be more motivated than others. Finally, there is a possibility of recall bias, as some teachers have not taught LCA in over a year.

A sampling bias is also found. The participation rate in class was only 50% and it is expected that motivation is higher for those students attending. Thus, the sample was comprised of relatively motivated students, which could lead to results that are more positive than reality.

These potential sources of biases have been considered when interpreting the data and results.

2) *What are the relations between the identified problems and what effect could possible interventions to the system have?*

For this research question, thematic clustering and system modeling are used. Observed problems are clustered into problem clusters and themes thereafter. This is a highly interpretive practice; the researchers' perception is the basis for finding clusters. Also, abstraction of the clusters is a subjective practice. To limit researcher biases, the clusters have been proposed to several peers and university thesis supervisors. Also, the process of clustering has been iterative and so after more insights and data analysis the clustering and system model is reviewed. Still, the method is prone to researcher biases.

Additionally, in the system model, there are two themes (social factors and regulation and company policies) that do not result from empirical research but are added individually to make the system more comprehensive. The themes are based on logic reasoning and researcher experience. Validity should be proven in further research.

3) *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?*

This last sub-question has been answered based on design methods namely, context description, problem definition and construction of design requirements. Then, an idea generation and concept development has taken place to eventually present a final concept. The final concept is evaluated through an assignment at the IDE faculty for Master students and questions in an online survey are filled out.

There are limitations to the concept development as design decisions are taken by the researcher only. The researcher has sole responsibility for designing the tool and interpreting the problems based on prior empirical and literature research. It should be considered that this concept is one way to operationalize main theoretic findings, design variations are certainly possible and could be as effective. In the concept evaluation, the successfulness of design decisions is tested. This iteration should be the first of many. Also, design with a bigger and more interdisciplinary team would be helpful for the success of this LCA tool.

Tool evaluation data is limited by the fact that only a simple assignment is given to the participants. There has been no test of the tool with more detailed or complicated products. Also, a sample limitation is present as the Master course where evaluation took place is a voluntary course and so, mostly students with a positive motivation towards environmental assessment are present. Additionally, the sample size is limited as only 20 students have tested the improved tool.

Additionally, in the tool evaluation only the three main improvements are tested, smaller design requirements could be tested in future research if needed. Also, sensitivity and scenario testing as a design requirement are evaluated together. In future research they should be tested separately as they both have a slightly different value to the LCA practice and design process. Namely, sensitivity analysis would help designers to be less hesitant in assumptions/decision-making and testing the robustness of their LCA. While scenario making or design variation testing changes more parameters and can test different concepts, making it easy to use in the ideation phase of design and fit design practices better. In the current evaluation, the extra unit process tables are mainly used for scenario testing, and some use it for sensitivity testing. The value of sensitivity testing in relation to making assumptions should be tested in future research. Also, Excel limitations in this first prototype might have influenced the experience of designers towards robustness assessment in a negative manner as the scenario table was sometimes not referencing correctly. This, resulting from the survey, has led to some frustration when filling in the assignment.

In the tool evaluation there is no strict division between independent and dependent variables. The dependent variable is not isolated as the test has been in its context, meaning there can be more influences on the results. For example, teaching changed and could have influenced the results.

There has been no zero measurement of the initial tool, with the same questions, to compare the improved tool with. This was due to limited time with the sample group as course objectives have priority. As a result, it is hard to determine whether the improved tool has actually caused more effective implementation of LCA fundamentals into their design process.

The tool has not been compared to other often used LCA calculation tools as described in chapter 4.3.2. Testing the difference in effectiveness for designers could add to the strength of the conclusion. It could prove that the main improvements have added to the effective incorporation of LCA fundamentals into design practices.

5.4 The scientific and societal relevance of research findings

The following paragraph addresses what the position of this study is in a broader scientific and social context.

The first part of this study identifies what problems designers, with no prior LCA experience, encounter while performing an LCA. This contributes to the understanding of the problems between designers and their LCA performance. There are many aspects to this relationship as defined in problem clusters discussed in section 4.1.1. The problem clusters, abstracted as themes, show interrelations, for instance the influence of time on capabilities and comprehension. The system relations can contribute to the scientific field unraveling problem patterns. For instance, existing attempts to improve the way designers use LCA, could be mapped out in this system to better understand their influence. However, as this is a theoretical system, interventions should be tested in practice to confirm or refuse hypothetical system dynamics. Another implementation of the theoretical system is for designers themselves to map out what kind of problems they run into and give an initial idea how they could overcome these problems. For example, a designer runs into time related problems, the designer could think of intervening in company policies, search for better LCA tools, methods or refine their own capabilities. The system diagram is then used as way to become conscious about types of problems and get inspired for solutions.

As read in the context description and background methods, the method of LCA is gaining popularity in literature and is broadly adapted to different contexts, different applications, and method combinations. For example, there has been many attempts to combine LCA with qualitative methods (e.g. quality function deployment, function impact matrix) for design and many adaptions to simplify LCA. The theoretical findings of interrelated themes would contribute to this by being able to understand the influence of all these adaptations and interventions for designers.

The second part of this study manifests theoretical findings into an LCA tool. This part contributes scientifically mostly by testing theoretical findings. In literature context it adds another tool to help calculate LCA, based on solid theoretical findings in a specific target group. On a broader, more societal level, this study contributes to the better handling of resources, through more responsible design. More responsible product design can be achieved by effective use of LCA while designing. In this research a step is made to improve the effective use of the LCA method for inexperienced designers.

In the end, more interventions and involvement of stakeholders are needed to enable the full incorporation of LCA for inexperienced designers. As addressed earlier, the other possible interventions (regulations, data quality and quantity and education) should be implemented and tested. For this, many more stakeholders are needed besides those in the study field of Industrial Ecology and Industrial Design Engineering. For improved regulations, governmental institutions are needed. For improvement of data quality and quantity, research institutes and producing companies are needed to collaborate. Finally, also product buyers or consumers are needed, to stimulate governments or commercial companies to prove their environmental impact. Eventually, this will stimulate the designer to measure the impact of their design and make decisions accordingly.

6 Conclusions

In this research, a case study at the Faculty of Industrial Design Engineering at Delft University of Technology has aimed to answer the following research question: *What is needed to enable student designers, particularly at the Industrial Design faculty in Delft, without prior experience in Life Cycle Assessment to effectively incorporate the fundamentals of the LCA method into their design practices?*

From teacher interviews and student participant observations at the IDE student faculty, 34 overarching problems have been identified to answer the first sub-question: *What are the problems that design students experience when performing LCA for the first time?* The problems are validated and supported by literature findings. Based on the problem clusters a thematic analysis was conducted, leading to 5 overarching themes; mindset, motivation, time for LCA, capabilities and comprehension. Additionally, there are 5 external themes; social factors, regulations or company policies, data quality and quantity, LCA method and tool and LCA education. A system model of these themes showed relations and dependencies between themes, answering the second sub-question: *What are the relations between the identified problems and what effect could possible interventions to the system have?* The most interrelated internal theme is that of time for LCA, influencing a designers' motivation, capabilities and comprehension of LCA.

Possible interventions have been drafted based on the system of themes. This is done to answer the final sub-question: *How can one intervention, chosen based on research feasibility, be implemented in the context of IDE education?* The possible intervention drafts have shown that improving the LCA tool will influence the time for LCA, comprehension of LCA and capabilities through coherence with complexity. This intervention is most feasible for this research as it has a limited temporal scope and possibilities at the IDE faculty. LCA method and tool influence on the system is broad, the strength of influence is not yet proven. As research was based on IDE faculty practices, theoretic findings are manifested in an improved simplified LCA tool.

Literature findings are the basis for the context design requirements, while theoretic findings from empirical research construct the user group design requirements. Ultimately, three main improvements can be underlined. First, a better fit to design cycle is achieved by integration of design terms and actions such as ideation, the terms 'concept' and 'design variation', the use of a use scenario to build a functional unit and the drawing of a low threshold system diagram. This provides easier understanding of LCA terms and structure, better use of the method and thus more valuable outcomes. Second, the tool provides early LCA implementation through simple unit process requirements with category averages and guidance in data collection using notes and automatic calculations. This creates a low threshold for beginning the LCA and stimulates iterative use. Eventually this will cause less time spent and confusion/questions. Third, the tool provided easy and early implementation of robustness assessment (sensitivity analysis or scenario making) through automatically filled in unit process tables. This measure gives the designer more insight in the nuances and complexities of LCA results. Also, there is more comprehension of system and better understanding of the sensitivity of assumptions. This can lead to less hesitance in making assumptions and a better fit to the design cycle by testing design variations.

Besides these main improvements there has been many small improvements which can be read in chapter 4.3.5.

Evaluation of the tool at the IDE faculty among master students, has concluded that the main theoretic findings have been successfully implemented, though further improvements and iterations can be beneficial. Category averages and the easy availability of sensitivity or scenario testing have been rewarding in making the tool usable in early design phases and more iterative. Additionally, the request for a use scenario has contributed to a more accurate construction of a functional unit, though other educational factors may have also had an influence. Overall, fit to the design cycle was rated 3.8 out of 5 and the usefulness of category averages was rated 3.9 out of 5. The value of an automatically filled in robustness test was unanimously positively evaluated. Most student designers would use it for testing design variations or the sensitivity of their assumptions.

There are, however, some constraints to the research. Namely, the research sample is limited to a few classes at the IDE faculty in Delft. Therefore, generalization of the theory and tool to broader design practices needs further research. Also, research has been of qualitative nature and performed by only one researcher causing a possible researcher bias in research phases such as the problem clustering. Additionally, evaluation of the tool has been with no zero measurement, meaning the design aims can be verified but no hard proof has been gained regarding the relative improvement of the tool compared to the initial LCA tool or other external LCA tools. Also, the manifestation of findings in a new LCA tool is merely one way to address the student problems. It is expected that a better integration into design practices is possible with an adapted LCA method and improved education. Thus, further research is recommended go into the development of an integrated and continuous design method addressing LCA. Also, other interventions as defined earlier (regulations, data quality and quantity and LCA education improvement) should be elaborated upon and tested in practice.

However, despite its limitations this study provides a system model representing student problems and a pilot intervention to *enable student designers, particularly at the industrial design faculty in Delft, without prior experience in Life Cycle Assessment to effectively incorporate the fundamentals of the LCA method into their design practices.* This case study research found that the problems students run into when performing LCA can be split over 5 themes in their power. Those themes influence the effectiveness of LCA implementation by designers. The themes are a designers' mindset, motivation, time for LCA, capabilities and comprehension. To enable designers and positively influence these themes, the LCA tool can be improved and added to the system. The tool has three main improvements, namely 1) a better fit to design cycle by integration of design terms and actions, 2) early LCA implementation through simple unit process requirements and guidance in data collection, and 3) easy and early implementation of robustness assessment (sensitivity analysis or scenario making). By incorporating these main improvements into an LCA tool, the improved tool has been positively received by students. The main improvements theoretically helps the designer's capability/complexity coherence, comprehension, and time for LCA leading to a more effective use of the LCA method. To test all benefits of the new tool, more elaborate pilot testing needs to be done.

This research serves as a foundation to investigate potential interventions or strategies necessary to incorporate the fundamentals of LCA into design practices. In doing so, it is contributing to evidence-based sustainable design engineering.

7 Recommendations

This chapter suggests new research directions, based on research findings. Some of the research directions are introduced in the discussion chapter.

- The improved tool will provide merely part of the solution. An improved LCA tool is only part of a bigger system and so it is recommended to enable other parts of the system as well. Going forward, **more interventions should be developed and evaluated in future studies**. For example, the influence of better education could be tested. This is expected to have a big influence as well, as it largely influences the comprehension of LCA. Besides, the data quality and quantity improvement could have a large influence as most student questions were regarding data collection. Literature claims, designers encounter a lack of data that fits their exact needs (Beemsterboer et al., 2020; Jusselme et al., 2018). Designers need data more custom to their design practices (e.g. aggregated data) and easier to access (Lofthouse, 2006). Information quality and quantity is intrinsically connected to the effectiveness of LCA, provided that the method is properly implemented (sufficient comprehension, time and mindset). Testing the influence of regulations would be a long stretching research as it is expected to see changes only after a few months or years. But it would be worth testing the influence.

- There are a few recommendations related to the user group. Research should be conducted **to determine the extent to which the system model and tool can be applied to a wider range of design practices**. For example, further study should be conducted to assess the tool's usefulness for designers who are already familiar with LCA. It would be beneficial to research the difference in problems that designers inexperienced with LCA and experienced with LCA encounter.

- Based on the research findings, **there could be a difference between LCA use in distinct design sectors**. Therefore, different design sectors could be compared. For instance, are there differences between LCA use in the automotive industry compared to kitchen appliances. Also, culturally different design practices would be interesting. A cross country comparison for example, would be interesting to see if differences appear.

- Another recommended research direction is **to test the tool, not only in different contexts but also compared to other LCA tools**. In this study, the relative performance of the improved LCA tool compared to the initial tool or other LCA software tools has not been assessed.

- It would be good **to research the difference in effectiveness between designers performing an LCA themselves opposed to outsourcing an LCA to an external team**. An early research decision was to investigate the way designers themselves perform LCA opposed to outsourcing it to an external team. This decision was made based on the expectation that it is more effective when designers themselves do the LCA. Doing the LCA allows for a deeper understanding of the process and results, the trade-offs and assumptions that need to be made. These procedures are beneficial for the thought process during design. With a better comprehension of the complexities of LCA, designers can interpret the results more accurately and creatively incorporate them into the design. However, in practice often designers outsource the performance of LCA and literature claims it could be more effective if LCA performance is left to an expert (in the design team or outside) (Millet et al., 2007).

Designers are then responsible to correctly interpret and integrate LCA results into their design. This can be a challenge as well. As the method is not performed by the designer anymore, understanding of complexity, trade-offs and nuances is expected to worsen.

- Another research direction could be to explore LCA to be a more integral part of design practices. For instance, it could be researched **how effective it would be to integrate design parameters such as mechanical properties one tool**. This is a recommendation resulting from the tool evaluation at the IDE faculty and the research papers by Bovea & Pérez-Belis (2012) and Karana et al. (2008). Applying this, designers could compare design variations on more parameters such as strength, stiffness, conduction, texture etc. and make a more holistic decision. To stretch that thought further, it would be interesting to see if it is possible to input design conditions such as the dimensions, strength, function, lifetime and environmental performance. As a result, design options are provided by the tool and compared. There are currently developments in the use of artificial intelligence for making product design in 3D modeling programs. The program asks for a product description and generates a multitude of design variations. It would be interesting to include environmental impact as a parameter in these situations.

  Another direction to make LCA more integral is **to research the possibility of LCA being translated into a design method**. This evolves from the finding that an improved LCA tool still requires the designer to take a sidestep from their design process. Integrating the LCA method could be based on Life Cycle Thinking (LCT) principles to start with, because LCA itself is an assessment method. It would be interesting to see what would happen if a design method would be fully based on the LCA structure and elements. The determination of function and functional unit could then be the start of your design process. Along the way, ideation is done to generate alternatives, flowcharts are drawn to consider the whole system. Every LCA step would be adding to the design of a product (system). LCA or LCT would act as a guidebook to design practices, opposed to the other way around as is currently the case. The LCA and design method would be fully entangled. A fully integrated design/LCA method together with a more systemic approach, addressing other influential factors (e.g. themes), is expected to be very effective for environmental evidence-based decision-making in design.

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Supplementary material

A. IDE education module

In this section additional information on the education module on DfS from the Industrial Design Engineering (IDE) faculty is given. This includes calculation rules of the IDEMAT fast track LCA tool and the LCA assignment as given in the course.

General Calculation rules LCA tool

The next paragraph is directly extracted from https://www.ecocostsvalue.com/lca/idemat-calculation-rules/

"IDEMAT is in compliance with ISO 14040, 14044, EN15804, and the ILCD Handbook ("General guide for Life Cycle Assessment – Detailed guidance"), and has the following Calculation Rules:

'cut-off" at the end-of-life (according to EN15804, and similar to Ecoinvent 'multifunctionality cut-off by classification'), where there is no carry over from the old product system to the new product system; 'system expansion" is only applied when materials are combusted in reality, applying combustion efficiencies as they are in the real combustion systems.

For the system boundary a 2% cut-off criterion is applied

application of (carefully selected) case studies, or averages of groups of production systems, rather than statistical data

the LCIs have the 'unit' approach, only the 'remaining background processes' have the 'system' approach (the disadvantage of the system approach is that LCIs become rapidly outdated, because of the fast changing electricity mix)

electricity data are based on measured emissions (for Europe the E-PRTR data, for the USA the eGRID data), being fundamentally different from most other LCI databases, for further explanation of this issue see https://www.ecocostsvalue.com/lca/electricity-in-lca/

Electricity data on 373 countries and regions are available at https://www.ecocostsvalue.com/data/

end-of-life credits for combustion with heat recovery (according to ISO 14044 section 4.3.3.1) as well as end-of-life credits for upcycling of metals and plastics (section D in EN15804) are provided in an extra set of generic LCIs, to facilitate LCA practitioners with practical data that are readily available for C2C calculations (in most cases, it is quite laborious to find or calculate the data on combustion energy and recycling).

The dataset in OpenLCA does not apply multifunctionality: unit processes have been divided in two sub-processes where applicable

for easy understanding and transparency in OpenLCA, two sets of 'original, not normalized, LCIs' give the direct data from literature

for plastics and transport fuels, the 'embodied fossil fuels' are provided in the LCIs ('oil & gas in materials' and 'oil & gas in transport fuels') to cope with EN15804 requirements, and to cope with double counting issues in ISO 14044, section 4.4.2.2.3, in the eco-costs system (i.e. avoiding the double counting of fossil fuels in 'fossil resource use' and CO2 in 'climate change') the IDEMAT datasets in Simapro and in OpenLCA have been developed for calculations in the eco-costs single category system, as well as CML, ReCiPe, CED, TRACI and EF 3. Take care with other category systems, since names of substances might be different

to enable correct eco-costs calculations EI 'unit' datasets, extra LCI data lines ('Ecoinvent Eco-costs corrections') have been added; this is necessary to cope with the double counting issue of fossil fuels and CO2 emissions, as mentioned in the previous issue 9

Note 1. The consequence of 1) and 6) is, that the further application starting from the sorted waste materials are free of the eco-burden of the previous product life. The new product life that starts with recycling of that waste, starts with zero eco-burden. (in OpenLCA this is effectuated with a zero mass flow, rather than creation a long list of dummy materials for 'urban mining').

The recycling credit equals the eco-burden of the 'secondary material' minus eco-burden of the 'primary material', both cradle-to-gate, where the cradle of the secondary material is the stockpile of waste. Only the part of virgin material at the system input is counted (when 100% of the material at the input is secondary, there is no recycling credit, to avoid double-counting).

Note 2. The IDEMAT system adheres to the basic principle of the IPCC that the so called 'short cycle' CO2, i.e. biogenic CO2, is not counted in LCA, unless the product last longer than 100 years, See also LCA of wood. The detailed calculation rules for biobased plastic are given at (Biotechnology Industry org, 2010).

The fact that biogenic CO2 emissions are not counted, as opposed to fossil-based CO2 emissions, has much impact on calculations of combustion at end-of-life: biobased waste materials have a rather big end-of-life credit for combustion with heat recovery, in contrast with fossil based waste materials.

Note 3. With regard to point 6). The end-of-life credits for combustion with heat recovery (according to ISO 14044 section 4.3.3.1), IDEMAT takes into account the fact that municipal waste incineration has only 55% efficiency of the efficiency of co-burning in electrical power plants (45% of the heat is lost, and therefore not part of the heat recovery). The result is that combustion of fossil-based plastics (e.g. from packaging) in a municipal heat incinerator has a severe impact (eco-costs debit). The shift towards bioplastics, like PLA helps to mitigate this CO2 emission problem.

"

LCA modeling assignment
This is a direct copy from the course reader
"
STEP 1: DECIDE ON YOUR SCOPE (BOUNDARIES) AND FUNCTIONAL UNITS
TIME: 10-30 MINUTES
Choose your goal – every LCA needs a goal to quickly estimate priorities for eco-design.
Choose your scope — the boundaries of what you will and won't consider in your analyses. Ideally you would choose everything in your Whole System Map, but you might exclude things out of your control, or too peripheral to the system. Choose the functional units for your analysis (e.g. environmental impact per hour of operation, or impact per kilo of food cooled, etc.). If you consider multiple scenarios, this must be consistent between them all.
Note: Choose the functional unit well, because it affects your final conclusions. A comparison of a disposable paper coffee cup and a ceramic mug would favor the disposable cup if the functional unit were environmental impact per cup, because one paper cup requires less material and energy and produces less waste. However, a comparison would favor the ceramic mug if the unit were environmental impact per liter of coffee drunk, because the mug's impacts get amortized away over dozens or hundreds of liters of coffee drunk.

STEP 2: LIST YOUR INVENTORY
TIME: 1-5 HOURS
Make a table of your invention's Bill of Materials (BOM) and manufacturing methods as best you can: how many grams of this material, formed with what manufacturing method, how many pounds of that material, everything.
Also include an estimate of energy use during product lifetime, transportation from the manufacturing site to end consumer, and disposal scenario—everything that was within the boundaries you set above. For example, you can use a table for a common refrigerator from the Resources section "Life Cycle Inventory Data for a Refrigerator".
If your business is a service, make a table of the energy use, transportation, and other things that will be caused by people using your service and performing it.

STEP 3: CALCULATE IMPACTS AND CONSIDER SCENARIOS FOR SENSITIVITY ANALYSIS
TIME: 1-3 HOURS
Enter all of the data above into the LCA calculator template spreadsheet (see "Resources" section), or use LCA software like Ecolizer, SustainableMinds, SimaPro, or GaBi.
You may not know which materials to choose from the LCA software database or lookup table (for example, there are several kinds of steel, which have very different impacts). You can try to look up these materials online, using Google searches or material databases (see "Greener Materials" in "Resources" section) , or you can just guess and include a large uncertainty or run multiple scenarios for best-case and worst-case alternatives.

You likely won't find all the right materials in the database. Make your best guess about what an equivalent proxy would be, or by assembling a proxy out of several items (e.g. you might estimate a motor with a certain amount of forged steel, copper drawn into wire, and magnets.) Your estimates may be wrong, but leaving out components means you think they have zero impact. If you include your large uncertainties in the analysis, you can see whether you need more precision, or if the impacts are small enough that it wouldn't change the final overall result.
Consider a few different scenarios, to explore where your assumptions might be wrong—particularly when you estimated materials or processes that weren't in the database. Write down best-case and worst-case values for things you're uncertain of (like energy use, or key material sizes or types). This is called "sensitivity analysis" because it shows how sensitive your results are to changes in assumptions. These may cause you to rethink your boundaries or functional unit; that's ok, even encouraged.
When you have entered all the data, you can graph the results.

STEP 4: INTERPRET RESULTS
TIME: 5-15 MINUTES
Look at the graphs for your different scenarios with different assumptions. What do you see? What parts of your system have the biggest impacts? What impacts change the most with different assumptions?
Interpreting your graphs may cause you to rethink your boundaries or functional unit; that's ok, you can redo them and make new graphs to interpret. Don't expect it to be a linear process.
Use your final interpretations to estimate your priorities for eco-design. Where should you focus your creative efforts? Where do you need to know more before moving ahead?
"

B. Teacher interviews

This section describes questions asked at the teacher interviews and results gained from the interviews. More elaborate results can be found in the Excel sheet: ***'B. Teacher interviews.xlsx'***

Interview questions

<u>Introduction/contextual</u>

1. In what way are you in touch with LCA for designers?
2. If so, in which course did you teach with LCA for designers?
3. Have you been teaching with the LCA calculator or was it conceptual?
4. When was the last time you taught with the tool?
5. Do you have a first experience that comes to mind when looking back?

<u>Core: Details LCA concept</u>

1. What is your vision on LCA for designers?
2. What would you say is the most important lesson for designers to take from the LCA concept?
3. Do you consider LCA to be important in a design process?
4. If yes, in what way do you consider LCA to be important for the design process?
5. What do you see lacking in the current way LCA is taught for designers?
6. Do you think there is something lacking in the connection between the design cycle and LCA?
7. Follow up: What do you think lacks in the connection between the design cycle and LCA?

<u>Core: Details LCA calculator</u>

1. What calculator did you use to teach and practice LCA in the course(s) you taught?
2. What was the main goal for you to use this calculator in your teaching for the students?
3. Do you think that LCA calculation fits correctly to the design cycle?
4. If yes, when do you think it would be correctly used? In what phase of the design cycle?
5. What obstacles do you see with the students using the tool?
6. What do you think about the impact categories that fit LCA for designers?

<u>Wrap up</u>

1. How do you see the future of Industrial design with LCA?
2. Do you have any last comments on the way the LCA tool is received and used in the IDE faculty?
3. Observation notes:

Results teacher interviews

Excel sheet ***'B. Teacher Interviews.xlsx'*** shows the raw notes from the literature insights, below in Table 17, problem clusters gathered from those notes are collected.

Table 17: Problem clusters gained from teacher interviews

Mindset	**The designers' holistic mindset can be a benefit for systemic thinking or a pitfall when attention is split over many design parameters.**
	Designers' creativity is limited by quantitative process and results
	Students don't want to see or engage in the complexity of LCA
	Students' interest towards sustainability is growing
Motivation	Show up for class is around 50%
Capabilities	Students in the 2nd year of IDE are not accustomed to using Excel or look up tables for making calculations. This results in conflicts while making LCA calculations.
	Teachers see students get scared and hesitant from complexity. Teachers expect that some assignments do not match their knowledge.

Comprehension	Students are not used to quantitative methods in other courses
	Interpretation of results with the proper uncertainty consideration is difficult.
	Many questions regard the functional unit
	The lack of experience is a large cause of the miscomprehension
	Drawing data from a transparent database helps with fast understanding of process impact by designers

C. Student participant observations

Questions to students

Table 18 depicts the questions that have been asked during the student participant observations. The questions are asked unstructured, during the assignments and in the breaks. Thus, the results are in the form of notes and not structured per participant.

Table 18: Questions to students as used in the participant observations.

General	**Algemeen**
Do you feel like IDEMAT LCA is a valuable tool for product design?	Vind je IDEMAT LCA een waardevolle tool voor ontwerpers?
Do you think LCA properly fits into the design process? And why?	Vind je LCA berekening passen bij het ontwerp proces? En waarom?
At what time during a design process would you use LCA?	Op welk moment tijdens je ontwerpproces zou je LCA gebruiken?
Do you think this LCA exercise fits well with the LCA theory?	Vind je de oefening goed passen bij de LCA theorie?
Would you shortly describe the design cycle/process to me?	Zou je kort de ontwerpcyclus aan mij uit kunnen leggen?
Specific	
How confident do you feel using the tool?	Hoe zelfverzekerd voel je je terwijl je de LCA tool gebruikt?
What do you find the most difficult part of this LCA exercise?	Wat vind je het lastigste deel van deze LCA oefening?
Why?	Waarom
How is it to compose a Functional Unit?	Hoe heb je je FU opgesteld?
What do you think about when deciding on system boundaries?	Hoe heb je besloten waar je systeem grenzen liggen?
If you would have to do an LCA for your own design, when in the design process would you do it?	Als je een LCA zou moeten doen voor een eigen ontwerp, wanneer zou je het doen?
What would you run into, you think?	Waar zou je tegen aan lopen?
Do you think doing an LCA during your own project would have added value?	Denk je dat het doen van een LCA meer waarde heeft tijdens je ontwerp process?
If yes, what is the added value?	Als ja, wat is de toegevoegde waarde van LCA in je ontwerpprocess?
How would you interpret the results and use for your design?	Hoe zou je de resultaten interpreteren en wat zou je gebruiken voor je ontwerp?
Have you done any robustness assessments? If yes, which and why?	Heb je sensitiviteit analyses gedaan? Zo ja welke en waarom?
How do you decide on the uncertainty of your data?	Hoe beslis je over de onzekerheid van je data?

Participant observations students

Sustainable Impact (SI) second year bachelor

Four sessions of each 2 hours are attended. During these sessions there were parallel classes, thus the teachers in other classes we also asked to note down frequently asked questions. One teacher really counted the questions as requested. The other two teacher wrote down some feedback in words.

The workshop hours consisted of a lecture (45min) and an assignment thereafter. The lecture was interactive so many questions were asked. On Wednesday the topics were related to estimation of environmental impacts versus measuring, the creation of a functional unit and the assignment of refrigerator was introduced. Friday the lecture was about comparative LCA, functional units related to that, uncertainty, 'allocation' (not multifunctionality) and an introduction of the comparative book assignment.

Questions are noted in the following categories:

- Related to interpretation of the assignment
- Related to Excel
- Related to goal and scope definition
- Related to Functional unit
- Related to flowchart and system boundaries
- Related to Data collection/ looking up
- Related to Impact categories
- Related to Interpretation of result/graph
- Other:

This according to the insights gained at teacher interviews.

Sustainable Design Strategies for Product Development (SDS)

The half-day course that I attended was meant to finish their LCA's and draw conclusions. The progress of most groups was not as far as expected, they were mostly working on functional units still and collecting data. The cases that were handed out were regarding the redesign of the system of a coffee vending machine or serving warm lunch meals. For both systems, disposable packaging is used now (a paper/plastic coffee cup and a lunch box from paper/Styrofoam/plastic). Students were requested to fill in the Eco-design strategy wheel in week 1 and construct an LCA of current practices and new design in week 2. It should be noted that in almost every group of the course there was a person from the master Industrial Ecology which also has an elaborate LCA course, this could have resulted in a knowledge advantage.

Results of participant observations

Table 19 shows the questions asked during the workshop hours, separated by ISO LCA phase. As shown, very little questions are regarding the ISO phase impact assessment as it is not consciously performed by students. Most questions that were asked were related to: Goal and scope, Functional Unit, Data collection, Impact categories, Transport and Multifunctionality. Beware, that the number of questions are solely for an indication as it is only performed by 2 teachers and some questions might have been missed.

Table 19: Counted questions during 'Sustainable Impact' course by two teachers.

ISO 14040 phase	Number of counted questions during 'Sustainable Impact'
Goal and scope definition	14
Inventory analysis	10
Impact assessment	4
Interpretation	4
Other	5

Observed problems and frequently asked questions are found in the excel sheet ***'C. Student participant observations.xslx'.*** They are categorized over the ISO LCA phases; Goal and scope definition; inventory analysis; impact assessment; interpretation. A first interpretation of insights is done by the researcher. It is questioned why the problems appear as they do. So sometimes it is expected that problems are solely due to education, sometimes general difficult terms or comprehension. Lastly, the observations and questions are categorized according to the themes as far as possible.

In Table 20, 19, 20, 21 and 22, for each theme, the observed problems that contribute to the theme are depicted.

Table 20: Observed problems contributing to the theme 'Mindset'

Mindset	Interpretation
Thinking about multifunctionality is not naturally done, it is not seen as something they have to necessarily deal with	Education but also the mindset or familiarity with expressing products in services to society, functional units and flows. The quantification or abstraction of their product is difficult.
Students are not quite sure why they are doing LCA.	General comprehension is lacking as well
Students blindly follow the impact category that is given in the assignment or if they have to decide themselves they only choose the category that is closest to their knowledge. No critical attitude towards it.	No curious mindset or motivation
Student unsure why they have to make all the assumptions, is the model still valid then.	Skepticism on LCA method. Familiarity with qualitative methods mostly during design practices.
Is it even useful to perform an LCA if there are so many uncertainties?	Scepticism

Table 21: Observed problems contributing to the theme 'Motivation'

Motivation	Interpretation
Internal consistency is not evaluated by students.	
If several numbers are given in assignment, the urge is to use all numbers in the calculation. Individually thinking about what to do is difficult	
In the lectures only on average 30/60 were present for each block. (and general pass rate is 50%)	Also, the general pass rate of the course is 50%.

Students want to spend between 3 hours and half a day on LCA	Maybe the way that they are thought maybe general motivation
Students would only do LCA if they are obliged to, or they consider it strictly necessary.	
Students tend to go for the easiest option when it comes to impact categories (e.g. single score categories)	

Table 22: Observed problems contributing to the theme 'Time for LCA'

Time for LCA	**Interpretation**
Goal and scope is not finished before going into data collection.	Value of G&S is unclear
There is an overall stress over time limitations	Result: students make rash decisions
Time lacks when only 2 hours are dedicated to LCA for lecture and practice.	Education module
Group copying all the processes including weights from an existing LCA from literature	Useful, but should be aware of consistency with redesign (Goal and scope)
Tendency to rush to data collection due to time stress	A lack of time and knowledge on LCA structure also

Table 23: Observed problems contributing to the theme 'Capabilities'

Capabilities	**Interpretation**
Students are likely to lose themselves in the numbers and consider numbers and results to be the goal of doing an LCA. The process, they want to proceed as fast as possible.	No motivation to dive into the complexity behind results
Paper incineration gives negative emission numbers (assuming that it is a database fault, because how can incineration be 'good' for the environment)	No motivation to dive into the complexity behind results
Students are generally happy and surprised by the results but not super curios to dive into the reason behind the outcomes. When graphs are made, the duty is done.	No sensitivity analysis or scenario building is done. Also not stimulated by the course. There is no capability or motivation to dive into the complexity behind LCA
Students get scared and hesitant from the complexity that does not match their knowledge.	IDEMAT is not a tool that gradually increases complexity, students are overwhelmed
Unclear how to convert certain units (e.g. tkm, MJ, KwH) and how to convert them	General technical skills are lacking
Students are unclear how to handle not knowing the lifetime or other use scenario properties	
The first class already many students lose themselves in data collection	This (uneccessarily) takes a lot of time. Could be solved by education partly
Excel skills are lacking. Many questions regarding: They do not know how to fill in a calculation, commas vs points, adding rows etc	They do not know how to fill in a calculation, commas vs points, adding rows etc. Practical software skills
Not clear what the detail of data is supposed to be	A general lack of experience will be the reason.

How do I decide between different but similar (electricity) datapoints?	Data collection
How do I determine the uncertainty of a unit process?	Data processing.
What does 'equivalent' meant?	Education
What impact categories are best to choose?	Education
How do we add rows in Excel?	Excel skills

Table 24: Observed problems contributing to the theme 'comprehension of LCA'

Comprehension of LCA	**Interpretation**
Hard to find for example the service that a refridgerator provides. This differs per person and household.	Abstraction is difficult.
It is unclear how to estimate uncertainty in the assignment	Data collection and interpretation
The objective of LCA is not always clear for students (e.g. to guide innovation process)	Possibly education, quantification (mindset in more qualitative methods and design not evaluation)
Not convinced why they need to make a functional unit (Can I not just use 1 item for each)	Educational shortcoming or difficult term to understand
Not knowing what impact category to take, choosing the one that is most understandable by the public	Commercial strategy on selecting impact category
Not clear if all alternatives go in one LCA model	Excel calculation sheet
Student unsure why they have to make all the assumptions, is the model still valid then.	Skepticism on LCA method. Familiarity with qualitative methods mostly during design practices.
Students do not start with LCA in existing literature	Might be limiting, as it can be very useful to see how it is done in literature. General unfamiliarity
Interpretation of graphs and insight on how it would change with a parameter change is difficult.	Sensitivity analysis is missing in course (educational)
	comprehension of impacts (interpretation)
Student: 'I thought LCA was only for physical products', 'How can we make an LCA for services?'	General method comprehension
Do we have to define the Goal and Scope before starting data collection? Because there might be changes later	Goal and Scope
How detailed should our data input be?	Data collection
When is a proxy good enough?	Data collection
How do we get the weight of materials that are glued together?	Data collection
Why is it that my redesign does not have a better score?	Interpretation

The impact numbers for paper incineration are negative, is that correct?	Interpretation/ multifunctionality problem
What is most important to get out of the LCA?	Interpretation
The systems of all 5 alternatives are very similar, should we put them all in one LCA?	General understanding
How do we model End of Life? How do we know where it ends up? Do we make our own estimation?	Flow chart and system boundaries
Why is transport within the boundaries?	Flowchart/system boundaries
What phase does energy use belong to?	Flowchart/system boundaries
How do I handle not knowing the life-time?	Functional unit
Can we calculate averages if we cannot decide between datapoints?	Data collection
What LC phase is energy use?	
What can we design for?	Interpretation
How do we describe the system boundaries in words?	Difficult terms
Where do we as designers have influence? What can we design for?	General value of LCA

Some of the issues mentioned in X , are also due to the lack of experience from students and cannot easily be solved by education. They need practice, which is in the current course not possible. Table 25, provides observed problems clustered under the theme education.

Table 25: External problem clusters gained from student participant observations

Education	
It is not clear that Functional unit is also useful as a story to the commissioner	Education
Confusing how the material weight of a polymaterial is determined.	Lack of LCA experience
To deal with uncertainty, sensitivity analysis is not considered an option.	Education
A large part of the lecture is about the amount of items in a functional unit	This might be confusing as that is not the only purpose of FU.
Focus on 'number of items' in functional makes students confused about the objective for functional units	education
Making a functional unit is difficult and confusing, students don't understand what an FU should consist of.	They often want to include 'environmental impacts' or just say '15 years' or an amount of items or 'We made the functional unit 3 instead of 2.5 items because you cannot have half a phone.' Comprehension of FU and abstraction of product into a service providing entity is difficult.
It is stimulated to make a 'fair and convenient' functional unit. This means fair comparison mostly and convenience is in the calculation of 3.75 shoe opposed to 4 shoes.	This could cause the unneccessary focus on convenience, as actually the modelling software will do those calculations for you. Is there a focus on manual calculation

Students do not have to describe what is left out from the analysis and what are the consequences of that	Less conscious of the sensitivity where your system boundaries are
In class they do not have to make a fowchart with system boundaries themselves, they should only decide on; cradle to gate; cradle to cradle, cradle to grave etc.	Education
Impact categories are not elaborately handled in the lectures	Interpretation
What exactly means the single score category?	Interpretation
Multifunctionality is confusing.	Is recycling counted for in this or the next process? How does a negative EoL scenario work? Interpretation and inventory
A lot of the lecture time is spend on what greenwashing is	This is not the key to LCA. Good stimulation maybe but not explanatory.
The introduction to the Excel calculation sheet is very fast, leading to many questions on functionality	Education and interaction with Excel sheet
No full example of an LCA is given in the lecture, this makes the student understand only bits	Solution should be more comprehensive
The course assumes everyone has read the reader	This is not the case, thus some confusion regarding terminology.
Students have not really thought of when to do LCA yet, it is not integrated in the course.	Educational shortcoming or unfamiliarity
In the course the word 'green' was very often used	To my perspective, especially in the context of sustainability and LCA, this is a very confusing and incorrect term.
Teachers are convinced that it is better to put 'bandage on a wound, not before'. So it is better to let students get curious and make them ask questions before providing information that they are not neccessarily waiting for.	
Students are unsure on how to decide between proxies, and how valid they are.	Lack of experience with LCA
What steps should we follow when looking for data?	Data collection
What does this graph actually show? (regarding the ecolizer aggragated average product categories) No unit of impact is given	Education
LCA method and tools	**Interpretation**
Uncertainty as a fade in the graphs was clear for students.	Visual representation of uncertainty is clear
What does ‘amount per item’ mean?	Excel functionality
Data quality and quantity	**Interpretation**
Heating ceramics is not in database	Database shortcoming
Data collection takes a lot of time in IDEMAT and missing data/proxies make it difficult	Making educated guesses is confusing and annoying according to students
Ceramic heating is not found in IDEMAT, how do we handle that?	Data
How to handle not knowing the lifetime?	Data collection
Is the location integrated in the datapoint?	database does not provide description

Below in Table 26, all problem clusters gained from student participant observations are summarized.

Table 26: Problem clusters gained from student participant observations

Mindset	**(student) designers sometimes don't see the relevance to their work, they lack curiosity and a critical mindset**
	The usefulness of LCA results with so many assumptions and uncertainties is questioned
	Some LCA terms are too abstract for designers
Motivation	Students would only do LCA if they are obliged to, or they consider it strictly necessary.
	Students want to spend between 3 hours and half a day on LCA
	Sensitivity analysis is often not considered
	If several numbers are given in assignment, the urge is to use all numbers in the calculation. Individually thinking about what to do is difficult
	Students tend to go for the easiest options (e.g. single-score for impact categories)
Time for LCA	Students want to spend between 3 hours and half a day on LCA
	Time stress leads to ignoring LCA structure (**e.g.** skipping G&S)
	Time stress leads to rushing in data collection and making unnecessary mistakes on the way (rash decisions or neglection)
	Sensitivity analysis is not often considered due to motivation and time limits
Capability/complexity	Students likely lose themselves in the data collection and quantitative numbers
	Students are generally happy and surprised by the results but not super curios to dive into the reason behind the outcomes. When graphs are made, the duty is done.
	Students tend to get a little helpless and panicked when they cannot find certain data (e.g. life-time or manufacturing processes)
	Many questions regard Excel and calculation practicalities
Comprehension	Self-determination of uncertainty of data is a conscious step but could be inaccurate.
	Students have trouble composing a functional unit and system boundaries
	Many questions concern data collection (steps, proxies, location etc)
	Multifunctionality is a difficult concept, modelling choices often not connected to multifunctionality and IDEMAT is not transparent about multifunctionality
	Interpretation of results and their relevance is difficult for students
	Students do not know when to use LCA in the design process
	Students do not recognize LCA elements, even though they are very similar to design elements.
	The meaning of impact categories is not understood

The Excel sheet: ***'C. Student participant observations'*** provides the raw observation results and clustering process.

D. Literature review

Table 27, provides an overview of the literature from the Web of Science with search query as found in section 3.3.

Table 27: Results of literature review in Web of Science

	relevance		Auto	(1)Case study (2)review (3)new method/tool	Publication Type	Authors	Article Title
1	2	application in case study		1	J	Villares, M; Isildar, A; van der Giesen, C; Guinee, J	Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste
2	2	with conjectural scenario		1	J	Villares, M; Isildar, A; Beltran, AM; Guinee, J	Applying an ex-ante life cycle perspective to metal recovery from e-waste using bioleaching
3	1	Old but early stage LCA			C	Betz, M; Schuckert, M; Herrmann, C	Life Cycle Engineering as decision making support in the electronics industry
4	2	ECO-it in thailand		2	J	Suppipat, S; Teachavorasinskun, K; Hu, AH	Challenges of Applying Simplified LCA Tools in Sustainable Design Pedagogy
5	2	DfE review		3	J	Telenko, C; O'Rourke, JM; Seepersad, CC; Webber, ME	A Compilation of Design for Environment Guidelines
6	2	screening LCA		1	J	Broeren, MLM; Molenveld, K; van den Oever, MJA; Patel, MK; Worrell, E; Shen, L	Early-stage sustainability assessment to assist with material selection: a case study for biobased printer panels
8	2	environmentally conscious quality function deployment (ECQFD)		1	J	Rathod, G; Vinodh, S; Madhyasta, UR	Integration of ECQFD and LCA for enabling sustainable product design in an electric vehicle manufacturing organisation
9	2	Quality Function Deployment for Environment (semi quantitative)		1	C	Sakao, T; Kaneko, K; Masui, K; Tsubaki, H	Analysis of the characteristics of QFDE and LCA for ecodesign support

11	2	normative decision analysis method for the sustainability-based design of products (NASDOP)		3	J	Eddy, DC; Krishnamurty, S; Grosse, IR; Wileden, JC; Lewis, KE	A normative decision analysis method for the sustainability-based design of products
14	2	configuration scheme optimization, the TOPSIS method		1	J	Zhang, L; Dong, WF; Jin, ZF; Li, XY; Ren, YQ	An integrated environmental and cost assessment method based on LCA and LCC for automobile interior and exterior trim design scheme optimization
16	2	a novel, semiquantitative ecodesign methodology		3	J	Devanathan, S; Ramanujan, D; Bernstein, WZ; Zhao, F; Ramani, K	Integration of Sustainability Into Early Design Through the Function Impact Matrix
17	1	A bit old but relevant			C	Recchioni, M; Mandorli, F; Germani, M; Faraldi, P; Polverini, D	Life-Cycle assessment simplification for modular products
21	1	screening LCA in electronic industry			C	Nissen, NF; Paeglow, S; Walachowicz, F	Requirements and solutions for a practicable ecological product assessment
24	2	New method early design stage		3	C	Devanathan, S; Koushik, P; Zhao, F; Ramani, K	INTEGRATION OF SUSTAINABILITY INTO EARLY DESIGN THROUGH WORKING KNOWLEDGE MODEL AND VISUAL TOOLS
	11		2				

Table 28, provides the results of the literature review from Scopus.

Table 28: Literature review results from Scopus

	Unique	**Relevance**	**Description**		(1)Case study (2)review (3)new method/tool	**Authors**	**title**
13	2	2	review on DfS tools, focus on social…		2	Ahmad S., Wong K.Y., Tseng M.L., Wong W.P.,	Sustainable product design and development: A review of tools, applications and research prospects

22	2	1	Focus on material selection			Eddy D.C., Krishnamurty S., Grosse I.R., Wileden J.C., Lewis K.E.,	A predictive modelling-based material selection method for sustainable product design
26	2	2	Original QFDE method paper		3	Masui K.,	Environmental quality function deployment for sustainable products
27	2	2	LCA simplification, semi-quantitative		1	Collado-Ruiz D., Ostad-Ahmad-Ghorabi H.,	Estimating Environmental Behavior Without Performing a Life Cycle Assessment
30	2	2	LCA as a sustainability design strategy		1	De Coster R.J., Bateman R.J., Plant A.V.C.,	Sustainable design strategies for electronics products utilising life cycle assessment (LCA)
31	2	2	Survey on eco-design tools (among which LCA)			Bernstein W.Z., Ramanujan D., Devanathan S., Zhao F., Sutherland J., Ramani K.,	Function impact matrix for sustainable concept generation: A designer's perspective
32	2	2	iterative use of LCA in design		1,3	Jeong M.-G., Suh H.-W., Morrison J.R.,	A framework for stepwise life cycle assessment during product design with case-based reasoning
35	2	2	exergetic approach		3	Medyna G., Cpatanéa E., Millet D.,	Comparative study of environmental evaluation assessment using exergetic LCA implemented in existing software and a novel exergetic approach during the early design phase
37	2	2	Semi-quantitative design tool		3	Devanathan S., Koushik P., Zhao F., Ramani K.,	Integration of sustainability into early design through working knowledge model and visual tools
38	2	1	Parametric approach to LCA iterations, a bit old	1		Ostad-Ahmad-Ghorabi H., Bey N., Wimmer W.,	Parametric ecodesign - An integrative approach for implementing ecodesign into decisive early design stages
39	2	1	a set of DfE principles, qualitative			Telenko C., Seepersad C.C., Webber M.E.,	A compilation of Design for Environment principles and guidelines
41	2	2	Semi-quantitative design tool		3	Dewulf W., Willems B., Duflou J.R.,	Estimating the environmental profile of early design concepts

48	2	2	Early stage LCA in automotive industry		1	Saur K., Eyerer P., Hesselbach J.,	LCA as decision making support in the automotive R & D
		10		9			

E. Comparison of LCA software tools

In Table 29, a comparison between popular LCA tools with characteristics is given.

Table 29: Comparison of existing, popular LCA tools based on ISO LCA phases and general characteristics

	Interface	Usability	Goal and scope definition	Functional unit	Life Cycle stages	Transportation modelling	Recycling modelling	Data input	Data precision	End-of-life modelling	Inventory tables	Hotspot analysis	Alternative comparison	Result visualisation	impact categories	Uncertainty visualisation	Access	Suitability for Designers
Granta EduPack Ecoaudit	Quite intuitive, in steps	Explanation as you go	Implemented in use section	Not explicitly noted	Material, manufacturing, end of life, transport, use	13 transportation types,	Yes, simple (0%, typical, 100%)	From Granta database	Very precise: material classification on the member level.	Landfill, downcycling, recycling, remanufacture, reuse, none	not given	Yes, per life cycle stage	Yes	Barcharts, fixed	Embodied energy Carbon footprint	None	Paid	Useability good but functionalities largely lacking.
IDEMAT	Very functional, partly in steps	Lectures and assignment description	A line in Excel for: purpose and boundaries	a line in Excel, guidance in assignment	Manufacturing, transport, use, end of life	Mass per item and distance per item	Limited to database availability	From Idemat (A mix of EcoInvent and literature)	Very precise: material classification on the member level.	Limited to availability in idemat	not given	Yes, per component	Yes	Impact by component and impact by life cycle stage in **barcharts, fixed**	Total eco-costs (eur), Carbon footprint (kg CO2 eq), ReCiPe 2016 endpoint(Pt)	Fading graph	Open, Online	Useability good but functionalities largely lacking.
Simapro	Very formal but visual in a flowschart right away.	Elaborate, two types of tutorials	Written elaborately in window.Naam, datum, auteur, comment, LCA type, goal, reason, commissioner, stakeholders, practitioner, Functional unit, reference flow, alternative scenarios.	Given on the goal and scope page.	All, in flowchart visually	In databases	Possible, limited to database	Any database that is convertable to AB	Depending on database	possible, depending on database	Given	Yes,	Yes	Default in table, opportunity to change many factors and adaptable clickable graph types, Table gives absolute numbers graph contributions. Normalisation on endpoint categories. Weighing is done as well even single impact score sankey diagram as well.	Default ReCiPe endpoint, many more available	None	Paid	Very elaborate, thorough but too complex. All options are given for interpretation and modelling, but maybe too many.
OpenLCA	Not very intuitive	Extensive manual online	Project set-up page,	Not explicit	All, not in flowchart	In database	Possible, limited to database	From databases, many available in format .	Depending on database	Depending on database	Given	yes	Yes	Many possibilities, even LCC charts	Around 20 options but not importable	unknown	Open, online	Quite complete but not very intuitive, not very visual(with flowcharts etc)
Activity Browser	Formal but visual as well	Limited, only tutorials on youtube not integrated	Not explicit, in model	Not explicit, in model	All, in table and after calculation in flowchart.	limited to database	Possible, limited to database	Any database that is convertable to AB	Depending on database	possible, depending on database	Given	Yes, In a barchart and a sankey diagram	Yes	Barcharts, sankey diagrams, tables, dynamic	Pre-programed in AB, extensive	None	Open, anaconda programmed	Open access, but limited guidance. Visual approach is helpful
CMLCA	Very formal and practical	Non intuitive, split in phases of ISO standards but not visual in flowchart etc.	explicitely defined in different window	Not explicit, in model	All	limited to database	Possible, limited to database	From databases, many available in format .	Depending on database	possible, depending on database	Given	yes	yes	Some possibility in charts and exports to Excel	Constructed by yourself, many possibilities	None	Open, online	Not intuitive, too complex for designers.

F. Improved LCA tool

The Excel sheet ***'F. Improved LCA tool - prototype 1'*** provides the first prototype of the tool as used in the evaluation at the ECAM course.

The Excel sheet ***'F. Improved LCA tool - prototype 2'*** provides the final prototype of the improved LCA tool.

G. Tool evaluation

The Excel sheet ***'G. ECAM LCA assignment'*** provides the assignment that is given to ECAM students for tool evaluation.

The Excel sheet ***'G. Improved LCA tool evaluation'*** provides the raw survey results from evaluation at the ECAM course.