Using data and expertise from LCA for EPD reporting to inform sustainable product development

Establishing a design tool and framework

UNIVERSITY OF TWENTE.

aalberts integrated piping systems

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Industrial Design Engineering

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Abstract

As environmental consciousness grows among companies, many are undertaking Life Cycle Assessments (LCAs) for Environmental Product Declaration (EPD) reporting. These reveal insights into their product's environmental impacts and offer a prime opportunity for sustainable product development. However, limited knowledge on the topic of sustainability within firms creates obstacles to fully capitalising on this potential. This thesis aims to explore the integration of LCA and EPD data and expertise into sustainable product development, within the construction products industry.

A literature study points out that LCA data is currently mostly used to evaluate the environmental impacts of a finished product, but that the greatest improvement potential can be achieved when the environmental impact of a product is studied during the early stages of product development. Due to the complexity of typical LCA studies and the uncertainties during early design, a combined approach is suggested. LCA data from existing products can be used to inform the focus point of a design tool, where LCAs with a limited range of options or lifecycle phases can be used during the development process of a product to evaluate the options that are considered. The available literature fails to bridge the knowledge gap that companies face in implementing sustainable business development. Therefore, the thesis focusses on providing a comprehensive practical guide.

Based on the situation at Aalberts Integrated Piping Systems, a design tool was developed. This tool presents for every step of the decision-making process of the material choice how the environmental aspect can be considered, by suggesting several quick-LCAs to assess the sustainability of the options in consideration. The focus on the material decision derives from a study of the current product development process at Aalberts IPS and the results from the LCAs that are performed of the product portfolio for EPD reporting.

A framework was developed to allow companies other than Aalberts IPS to develop a design tool tailored to their situation. It consists of a decision-tree, suggesting what type of design tool could be used, and a detailed step-by-step guide of what aspects of the situation need to be studied and how the design tool can be adapted to the company's needs. The process of developing the design tool for Aalberts IPS is used as a starting point for the development of the framework. Additionally, a review is performed of how contexts within companies can vary within the construction products industry, and what that means for what the design tool would need to look like in that context.

The usability of the design tool has been evaluated by interviewing stakeholders involved in the product development process at Aalberts IPS. It was considered easy to use and a useful contribution to the product development process. Where this first evaluation step provided great insights, further testing is recommended to fully establish the potential of the tool. It is advised to further study the outcomes of using the design tool within Aalberts IPS, and to evaluate if the outcomes of using the design tool result in more sustainable products than in the current practice.

An evaluation of the framework is performed based on two case-studies of contexts within the construction products industry. It was found that the structured nature of the framework provides a sense of confidence that all relevant aspects are considered. Where the framework is intended to be used by the sustainability managers of a company, the case-studies were performed by the author of the report. Further testing is recommended to evaluate whether the framework is effective in guiding sustainability managers to develop a framework fit for their situation.

Glossary

AIPS, Aalberts IPS	Aalberts Integrated Piping Systems	The company where the graduation assignment took place. See Section 1.3.
	Construction Product	“Item manufactured or processed for incorporation in construction works.” (CEN, 2019, p. 9)
CEN	European Committee for Standardisation	An organisation that provides a platform for the development of European standards, bringing together the national standardisation bodies of 34 European countries. (CEN, n.d.)
EMS	Environmental Management System	A framework that helps an organisation achieve its environmental goals through consistent review, evaluation, and improvement of its environmental performance.
EoL	End-of-life	The end of a product’s useful life, encompassing disposal, reuse, recycling or recovery processes. (EPLCA, 2018)
EPD	Environmental Product Declaration	A structured way to present the environmental data of a product, based on LCA calculations and additional information.
IAM	Impact Assessment Method	A method that specifies how to perform an LCA. (See Section 2.2)
ISO	International Standardisation Organisation	An internationally acknowledged organisation that develops and publishes standards, covering a broad range of topics.
KPI	Key Performance Index	A quantifiable measure of the performance of a firm over time.
LCA	Life-Cycle Assessment	“A tool to assess the potential environmental impacts and resources used throughout a product’s life cycle, i.e. from raw material acquisition, via production and use stages, to waste management.” (Hauschild et al., 2018, p. 18)
NPI	New Product Introduction	The development of a new product, as opposed to redesign or product improvements.
PCR	Product Category Rules	“A set of specific rules, requirements and guidelines for developing environmental product declarations for one or more product categories.” In ISO 14022 (ISO, 2022, p. 6)
PEF	Product Environmental Footprint	“A Life Cycle Assessment (LCA) based method to quantify the relevant environmental impacts of products (goods or services).” (EPLCA, 2018)
SDG	Sustainable Development Goals	A comprehensive overview of focus points for sustainable development, developed by the United Nations in 2015. (United Nations, 2018)

Introduction

This chapter introduces the topic of sustainable development using the data and expertise acquired for performing Life Cycle Assessments for Environmental Product Declaration reporting. First, a description of the problem is provided, placing the current study in the context of existing literature. Next, a company profile is provided of Aalberts IPS, where the graduation assignment is placed. This is followed by the specification of the objective and research questions. Lastly, the scope and methodology of the research are presented.

1.1. Problem definition

As the world is becoming more aware of the detrimental effects that the current production and consumption practices have on the environment, it becomes evident that ‘business-as-usual’ no longer is a viable option. The industrial sector in particular requires a different approach, as up to 29,4% of the global greenhouse emissions can be attributed to this sector (Climate Watch, 2020). Additionally, it plays a significant part in other environmental impacts (European Environment Agency, 2020). Industry therefore has an important role to play in the reduction of global environmental effects.

For some companies the situation is alarming enough to drive them to implement more sustainable business practices. A study by Purwandani and Michaud (2021) found that for 60% of business owners that implement green business practices, internal motivation was the main driver. Others indicate that stakeholder requirements can be decisive upon implementing changes toward sustainable business (Li & Sarkis, 2021).

However, 51% of all companies indicate that they will not go beyond compliance to environmental regulations (OECD, 2018). To ensure these companies change toward sustainable business practices as well, governments are implementing a multitude of regulations. The need for this was agreed upon in the Paris Agreement (United Nations, 2015) and the Sustainable Development Goals (United Nations, 2018). These are translated into regulations for specific industries and regions. Examples within the European Union are the Green Deal, containing specific targets and requirements for the industrial sector (European Commission, 2019); the Corporate Sustainability Reporting Directive, requiring companies to report their sustainable business efforts (European Parliament, 2022); and the Directive on Green Claims, requiring companies to ground their statements regarding sustainable business practices (European Commission, 2023). Besides, legislations are enacted requiring companies to establish Environmental Product Declarations (EPDs). In such declaration, the environmental impact of a product is calculated and published in a standardised way. They are already required for products used in the construction industry in France (Ministère de la Transition Écologique, 2022), for the production or import of chemicals in Norway (Klima- og miljødepartementet, 2015) and make applying for sustainable building certification easier (BREEAM, 2017; LEED, n.d.). The European Union is also considering specification of products’ environmental footprint in a Digital Product Passport, which makes use of principles similar to an EPD (European Commission, 2022).

Product design is an important strategy for reducing the company’s environmental impact (Govindan & Hasanagic, 2018; Li & Sarkis, 2021). However, there are still many barriers that need to be addressed before eco-design is broadly implemented. Lack of market demand, complex regulations and costs are perceived as barriers for implementing eco-design (Lambrecht Ipsen et al., 2021; Li & Sarkis, 2021). Besides, companies do not always have the adequate knowledge and skill.

Life Cycle Assessment (LCA) is proposed as a tool to overcome the knowledge barrier (Lambrecht Ipsen et al., 2021). Where performing an LCA requires expert knowledge, it does provide an extensive insight in what aspects of the product contribute to the environmental effects of the problem, defining where the focus of the design team should lie in order for the product to become more sustainable. For companies that are already performing LCA for EPD reporting, this provides a great opportunity, as the investments have already been done.

Performing LCAs in the early stages of the product development process has the greatest potential to reduce the environmental impact of the product (Hetherington et al., 2013; Vinodh & Rathod, 2010). In those phases, the greater design freedom results in a paradoxical effect on the integration of LCA in the design process. The greater design freedom ensures a greater environmental improvement potential, but also creates a greater uncertainty for LCAs performed in this stage (Bhander et al., 2003).

Currently, LCA is mostly used retrospectively, meaning that the analysis is performed after the product has been in use for an extended period of time, ensuring the availability of empirical data (van der Giesen et al., 2020). Where this can reveal unanticipated insights into the environmental aspects of the products and can inform focus points for product design (Broberg & Christensen, 1999), it is not able to provide insight into avoidable environmental impacts. Therefore, a combination of retrospective and prospective LCA is most effective in informing design decisions (Millet et al., 2007; Roberts et al., 2020).

In the early stages of a product development process, when the design of the product is not yet defined, retrospective LCA can be used of products that are similar to the product under development. Whenever concepts have been developed, these can be compared using prospective LCA. However, as the typical procedure of performing an LCA is very time-consuming and detailed, it is suggested to perform a simplified prospective LCA (Roberts et al., 2022). These quick-LCAs can cover a limited scope or a limited set of options. The outcomes of these LCAs have a higher uncertainty than traditional LCAs and should therefore be treated with care (Roberts et al., 2022).

Where current literature suggests where in the product development process LCA can be used, a comprehensive guide on how to implement the data and expertise of performing LCAs into the product development process in a specific company context is lacking. As companies are currently facing knowledge barriers in the implementation of sustainable product development, such a guide could greatly increase the adoption of sustainable product development. This thesis aims to develop such a guide for companies to incorporate the data and expertise from LCA for EPD reporting into their product development process to reduce the environmental impact of their products.

1.2. Company profile

The graduation assignment is performed within the company of Aalberts Integrated Piping Systems (IPS) in Hilversum, the Netherlands. Aalberts IPS provides piping systems in valve, connection, fastening and piping technology, for all types of distribution of liquids and gases. Their production facility is characterised by a high level of automation and a focus on quality. Some examples of fittings and valves in their product portfolio can be found in *Figure 1.1*, other products that Aalberts IPS supplies are tubes and installation tools. The full range of products can be found in their website (Aalberts IPS, n.d.-b).

Figure 1.1. *Selection of fittings and valves from Aalberts IPS' product portfolio (Aalberts IPS, n.d.-b)*

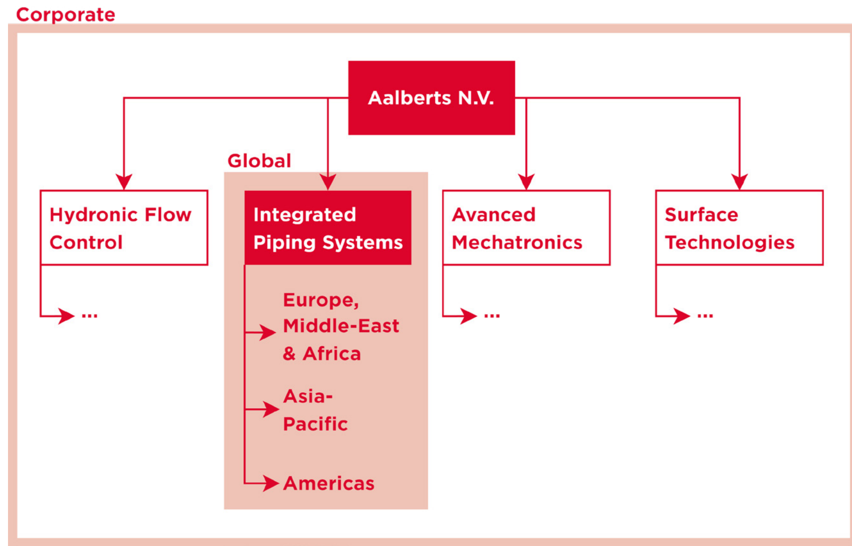


Figure 1.2. *Diagram of the organisational structure of Aalberts*

Currently they have performed Life Cycle Analyses of their product portfolio in order to publish Environmental Product Declarations, demonstrating their commitment to the demand from supply-chain stakeholders. They have expressed an interest to use this knowledge for the reduction of the environmental footprint of their products. The current sustainability goals and practices can be found on the company website (Aalberts, n.d.). The assignment takes place under the department of product development within Aalberts IPS.

Aalberts Integrated Piping Systems is part of a larger network of businesses under the name of Aalberts N.V. The overarching group, referred to as the corporate level, spans across industries. This allows for sharing of best practices and steers sustainable development initiatives. Apart from Integrated Piping Systems, the technologies Hydronic Flow Control, Advanced Mechatronics and Surface Technologies are represented in the group. Apart from the facility in Hilversum, Aalberts Integrated Piping Systems has multiple facilities in Europe and all over the world. The different locations of the Integrated Piping Systems technology are referred to as the global level of the organisation. An overview of the structure of the organisation is provided in *Figure 1.2*.

From this point on, 'Aalberts', 'Aalberts IPS' or 'AIPS' will be used to refer specifically to the Hilversum facility of the company. Whenever the corporate or global level are implied, this will be clearly articulated.

1.3. Objective

As follows from the problem definition formulated in *Section 1.1*, the objective of this research is to help companies develop more sustainable products, based on data and expertise acquired from performing Life Cycle Assessments (LCA) for Environmental Product Declarations (EPD). To address this aim, research questions are formulated as follows:

"How can companies in the construction products industry use the data and expertise from LCA for EPD reporting to develop more sustainable products?"*

1. *How is Life Cycle Assessment currently used to inform sustainable product design?*
2. *How can Aalberts IPS use its LCA data and expertise to inform sustainable product development?*
3. *How can the findings from literature and the case at Aalberts IPS be used to help companies in the construction products industry to use data and expertise from LCA for EPD reporting to develop more sustainable products?*

These research questions already suggest the scope that will be used throughout the thesis. More about what this scope entails and why this scope is chosen, can be found in *Section 1.4*. In the methodology as presented in *Section 1.5*, it is explained what steps are taken to answer each of the research questions, and how those steps are performed.

1.4. Scope

The main research question "How can companies in the construction products industry* use the data and expertise from LCA for EPD reporting to develop more sustainable products?" as presented in *Section 1.3*, already suggests the scope that is covered in the research. In this section, the scope will be presented in more detail, accompanied by explanations on the rationale.

The focus on companies that intend to use data and expertise from LCA for EPD reporting indicates the first limitation of the scope. The companies in question should have already performed an LCA for EPD reporting, or intend to do so. It is required that this LCA is performed in-house, because the research focusses on using data as well as expertise from performing LCAs. The knowledge on how to perform an LCA, and the critical insight that is required to evaluate the results needs to be available within the company.

Another limitation that follows from the research question is that it is aimed at the construction products industry. A construction product is defined as an "item manufactured or processed for incorporation in construction works" (e.g. buildings) in the standard EN 15804 (CEN, 2019). This standard is used for EPD reporting within Aalberts IPS, and will be used throughout the research.

Next, the research is aimed at new product introduction (NPI), and is therefore less suitable for redesigns or smaller product improvements. For new product introductions, the complete product development process is considered, where for product improvements some characteristics of the product remain unchanged. This means that some steps of the product development process are bypassed. If the design choice that appears the most relevant to consider based on the LCAs is not considered in the design process, only part of the potential of this research can be established.

1.5. Method

In this section it is explained what steps have been performed in order to answer the research question, and how they contribute to the research. To describe the approach, the structure of the sub-questions as presented in *Section 1.3* is followed.

1. *"How is LCA currently used to inform sustainable product design?"*

The first sub-question is answered by a literature review, which is presented in *Chapter 2*. The question is answered by covering the topics of sustainability in businesses in general, the use of eco-design tools in businesses and the way LCA is used to benefit the sustainability of a product. For this, the databases of Scopus and Google Scholar have been used. The articles were found by an initial search using appropriate search terms, after which the 'snowball method' has been used: the referenced articles were scanned to find new sources and search terms. Apart from the academic resources, governmental and NGO reports have been consulted.

2. *"How can Aalberts IPS use its LCA data and expertise to inform sustainable product development?"*

In order to develop a solution for sustainable product development at Aalberts Integrated Piping Systems (AIPS), an analysis, synthesis and

** Here construction products refer to products that are used for construction works (e.g. buildings), based on EN 15804 (CEN, 2019)* evaluation step were performed. In the analysis step, the situation at Aalberts IPS was studied. It was explored what the product development process currently looks like and how design decisions are taken. This was done through conversations with stakeholders involved in the product development process as well as project management. The broader context of Aalberts and its commitment to sustainability was studied by looking into their key performance indices based on their annual reports. Next, the environmental impact of the current portfolio of Aalberts IPS was studied by analysing the LCA results. These results were calculated using the Ecochain software, where additional detail was acquired through calculations using Excel. To understand the context of performing an LCA within Aalberts, a study was done on a product range that had not yet been evaluated. Most of the data for this was already available within the company. For the data that was not available, tests were performed. In *Appendix E* the experience of performing the LCA is discussed, comparing it to previous experience of performing LCAs.

The synthesis step of developing the design tool combined the findings from the analysis step. It was evaluated where quick-LCAs would be useful and formulated in what way the design choices could be steered to have less environmental impact. This was then presented in form of a design tool, providing structured guidance to the product developers of when and how the environmental aspect of the product can be considered during its development.

The design tool was evaluated by performing interviews with the stakeholders involved in the product development process. An initial version of the design tool was presented and questions were posed about the usability and usefulness. The interviews were semi-structured, allowing for input from the stakeholders outside the framed questions. More details about who were interviewed and the questions that were asked can be found in *Appendix F*. The findings from the interviews were used to develop an improved version of the design tool.

More about the process of analysis and synthesis, and how each step contributed to the solution can be found in *Section 3.2*. The evaluation step is covered in *Section 3.3*.

3. *"How can the findings from literature and the case at Aalberts IPS be used to help companies in the construction products industry to use data and expertise from LCA for EPD reporting to develop more sustainable products?"*

For developing guidance to implement sustainable product development practices for companies other than Aalberts IPS, the same distinction into the steps analysis, synthesis and evaluation is used. The steps that are taken to develop the design tool for Aalberts IPS are taken as a starting point, from here it is evaluated what a design tool could look like in other

situations using thought experiments. An overview of lifecycle phases and design attributes was made, following the structure defined in EN 15804 (CEN, 2019). For each lifecycle phase and design attribute it was considered what a scenario would look like in order to have the greatest environmental impact there. This resulted in a list of possible design tools, fit for a range of scenarios.

The overview of design tools and scenarios was then used to develop a framework. In this framework it is described what steps need to be performed in order to develop a design tool tailored to the company's situation. This is largely based on the steps that were performed for the Aalberts IPS design tool, while accounting for the differences in approach that are required based on the different situations the framework is developed for. Additionally, a decision-tree is developed for accessible identification of the type of design tool fitting for the company's situation and needs. This structure is based on earlier evaluation of the lifecycle phases and design attributes that require a design tool.

The framework has been evaluated by performing the steps for two cases of companies within the construction products industry, other than Aalberts IPS. They are based on EPD reports from The International EPD System (n.d.) and additional academic literature. Additionally, the structure of the framework was followed for the case of Aalberts IPS, which provided insight in the process of design tool development according to the framework within a company context.

How the outcomes of the described method contributed to the framework that was developed, is covered in *Section 4.3* (analysis and synthesis) and *Section 4.4* (evaluation).

2 Theory

Within the companies that fall within the scope of the research, multiple stakeholders are involved. These cover firstly the sustainability manager, who will be in charge of developing the design tool; the product developers, who will use the design tool during the design process; and the LCA expert performing the LCA analyses before and during the use of the design tool. Each stakeholder has a different background of knowledge on the topics of LCA and sustainability. This chapter aims to establish a baseline of background knowledge across all readers that is required to understand the further discussions in the report.

The chapter covers a general introduction on the topic of sustainability within the corporate context (*Section 2.1*) and explains the purpose and procedures of performing a Life Cycle Assessment (*Section 2.2*). Next, it describes an Environmental Product Declaration and how this is performed for the construction products industry (*Section 2.3*). Lastly, a review is provided of using eco-design practices to incorporate the environmental concerns into the product design, and what role Life Cycle Assessment can play in that process (*Section 2.4*).

2.1. Sustainability

The terms 'environment', 'sustainability' and 'climate change' have established a widespread presence in current societal discussions in politics, businesses and media. These followed from an increasing awareness of pollution and depleting resources during the 1960s and 1970s, and have been a widely adopted in political discussions after several international conventions during the 1980s and 1990s (Caradonna, 2018). The report "Our Common Future" by the Brundtland Commission has proven pivotal for the approach to sustainable development. This report defines the term sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs", and established the need for action to move toward a sustainable society (Brundtland et al., 1987). In 1994 the term 'Triple Bottom Line' was added to the vocabulary on the topic, stating that business practices can only be truly sustainable if the economic, societal and environmental concerns are addressed (Elkington, 2004).

Sustainability concerns have permeated the corporate world and companies are increasingly recognising the need for sustainable business practices. There is a multitude of tools that companies can use to implement sustainable changes within the firm. Two of the most prevalent are discussed below. Another approach that is often used is eco-design, this will be further discussed in *Section 2.4*.

The most widely adopted tool is the Environmental Management System (EMS) as presented in the ISO 14001 standard (ISO, 2015). This standard specifies all that needs to be considered to establish an EMS, from setting environmental targets and translating them to practices in the firm, to specifying how the environmental performance will be evaluated. Within the 14000 series, the International Standardisation Organisation (ISO) provides an extensive range of tools that support companies in their efforts to reduce their environmental impact. Throughout the report, multiple standards from this series are used. An overview of the standards that are used in the report, and how they relate to each other can be found in *Appendix A*.

Apart from the ISO norms, the Sustainable Development Goals developed by the United Nations are indispensable in helping companies reduce their environmental impacts. The 17 goals provide clarity on what aspects a company can focus its efforts towards. The SDGs are supported with additional explanation targeted at businesses (United Nations, n.d.).

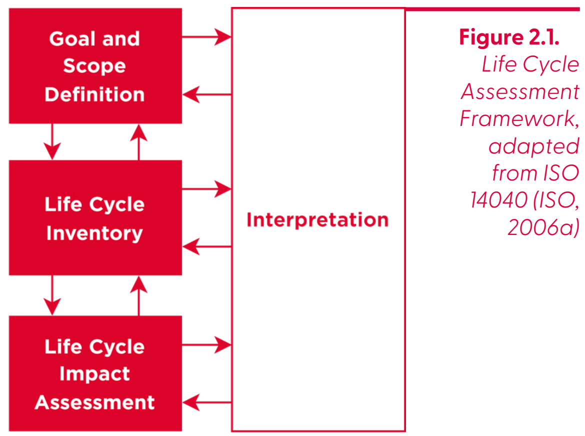


Figure 2.1. *Life Cycle Assessment Framework, adapted from ISO 14040 (ISO, 2006a)*

2.2. Life Cycle Assessment

Life Cycle Assessment (LCA) is a valuable tool to assess the environmental impact of a product over its entire lifecycle.* The methodology has been solidified in the ISO 14040 and 14044 norms (ISO, 2006a; ISO, 2006b) and has been used in a great variety of applications. From informing government's policies, to aiding firms in product design or informing consumers about the sustainability of their purchases. Below, the steps of performing an LCA are discussed.

2.2.1. Process

The process of performing an LCA is described in the LCA framework, as presented in ISO 14040 (ISO, 2006a).** It consists of the four steps Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation, as shown in *Figure 2.1.* Each step will be shortly introduced below. The explanations are roughly based on the book by Hauschild et al. (2018), the LCA practitioners guide in ISO 14044 (ISO, 2006b) and the International Reference Life Cycle Data System (JRC-EIS, 2010). These works can be consulted for further explanations of the proceedings of performing a Life Cycle Assessment.

Goal and scope definition

The LCA starts with a clear definition of the goal and scope of the study. The following aspects are covered:

- Application: It is described what the study aims to achieve, whom the LCA is performed for and who has initiated the study;
- Impact assessment method: An appropriate Impact Assessment Method (IAM) is selected, fit for the product and target group;
- Temporal and geographical validity: The results of the LCA study will not be applicable indefinitely, and not for every region. Therefore, the temporal and geographical validity of the study need to be defined;
- Functional unit: A quantification is made of how much of a product's function or service will be used in the analysis. This allows for comparison of products that perform a different amount of a function during their lifespan;
- Scope, system boundaries: It is defined what will be included in the study, and what will not. What product will be studied in the LCA? What level of detail will be considered? What lifecycle phases are considered?

**Within the context of LCA (and this thesis) the product's lifecycle phases refer to the stages one physical product goes through from creation to disposal. This differs from the definition that is used in the study of Product Lifecycle Management (PLM), where the lifecycle phases refer to the steps from a product idea to a fully mature product.*

***More about how the ISO standards relate to each other can be found in Appendix A.*

Inventory analysis

In this step, data is collected about all phases of the product's lifecycle. This encompasses the materials that are extracted, the emissions that take place during the manufacturing and use phase, and the waste that is produced during the product's lifespan. The result of the inventory analysis should be a complete list of resource extractions and emissions that are caused by the lifespan of the product. As extensive testing is required to determine the emissions of all processes involved in the lifecycle of a product, and not all data is within the reach of a company, databases can be used. These translate data that is more readily available into approximations of resource extractions and emissions. For example, it is hard to determine how much carbon dioxide is emitted due to the use of electricity at the manufacturing site, but it is known how much electricity is used. The database then provides a translation between the required amounts of electricity and the emissions that are caused by this electricity use.

Impact assessment

During the impact assessment steps, the translation is made from resource extractions and emissions to the effects they cause to the environment. For the impact category of climate change that means that the amounts of carbon dioxide and other greenhouse gas emissions is translated into the total amount of global warming they cause. This is done in the following steps:

- Classification: It is defined what impact categories are affected by the extraction or emission of each of the substances.
- Characterisation: All extractions and emissions are multiplied by a characterisation factor, quantifying how much they contribute to an effect in each of the impact categories. For example, ammonia causes more global warming per unit than carbon dioxide. This is accounted for by their characterisation factors. The result of the characterisation phase is a calculated impact of the product on each of the impact categories, each expressed in their own reference unit.
- Normalisation: A normalisation step is performed to express all impact categories in the same unit, allowing the comparison of impacts across categories. This is done by dividing each impact category by a norm. Different methods for normalisation are available, which are discussed in *Box I*.
- Weighting: Not all environmental indicators are equally relevant to the studied situation, or within the temporal context. Currently, climate change is the focus point of societal discussions on sustainability, where in the 1980's ozone depletion was considered more relevant. This can be accounted for by using weighting factors, multiplying each normalised result by a factor quantifying the severity of each of the impact categories in relation to each other, the weighting factor. The weighted scores can then be added to each other into a final

Box I: *Methods for normalisation and weighting*

There are multiple approaches available to normalising the characterised results from the LCA-study, and subsequently assigning weights. This box explains these different methods, where *Box II* explains how it can be determined which method is suitable for a specific situation. For normalisation two general approaches can be used (Pizzol et al., 2016):

- Internal normalisation: For this approach, a benchmark product is used as the norm. This means that the environmental impact of all products is compared to the product that is set as the norm. To do so, the normalisation factor for each of the environmental impact categories is set to be the environmental impact of the benchmark product.
- External normalisation: Here, the impacts of the products are scaled to the 'total inputs and outputs for a given area that may be global, regional, national or local' (ISO, 2006b, p. 21). This can then be used as a total or per capita number, and is often expressed in 'person year' equivalents. Scaling the impacts of a product along an external norm provides an insight into the magnitude of the impacts of the product. For example, where a plant supplying power to thousands of people over the course of multiple years can be expected to have an impact of multiple 'person year' equivalents, only a smaller portion would be anticipated for a simple pencil.

For weighting, a multitude of methods is available. A non-comprehensive overview is presented below, based on Hauschild et al. (2018) and Pizzol et al. (2016):

- Distance to target: This method quantifies the degree in which a political or scientifical target is met. The target that requires most attention to be reached therefore acquires the highest weighting factor.
- Monetary: The environmental effects are quantified through financial evaluation. This can be done with a social assessment of 'willingness to pay'. For this it is assessed how much people are generally willing to pay for the qualities addressed in an environmental impact indicator. For example, the travel costs that are permitted for a walk in the fresh air of nature provide insight into the societal importance of the particulate matter impact category. Another method of financial quantification is by assessing the costs associated with prevention or repair of the environmental damage that is expressed in the impact category.
- Multi-criteria analysis: Criteria are drafted that are considered relevant to assess the weight of the impact categories. Each impact category then receives a score on a predetermined scale for each of the criteria. The total weight of each of the impact categories is determined by adding the scores for each criteria.
- Panel: For this method, the expert opinion of several stakeholders is combined into a weighting score. Every stakeholder determines the relevance of each of the impact categories and quantifies this into a score. The total weight is then determined by calculating the average of the scores assigned by each of the stakeholders. The panel method allows for incorporating a wide variety of environmental concerns, as represented by the variety of expertise in the stakeholder panel. ■

Box II. *Assessing validity of normalisation and weighting methods*

Not all normalisation or weighting methods are suitable for every situation. In this box, it is presented what should be considered in order to select the suitable normalisation and weighting method. Additionally, reasoning is provided for the selection of the normalisation and weighting method used in this thesis. *Box IV* and *V* further explain how the methods are used.

The method of normalisation that is preferred in most cases, is external normalisation. This allows the practitioner to compare the products to each other and prepare the values for weighting, as well as providing an insight into the magnitude of the impact.

In cases where an external norm is not available, internal normalisation can be used. Additionally, it can be used in cases where a first calculation with the external normalisation factors shows a high focus on some of the impact categories. Such results, showing one or two impact categories with >90% of the environmental impact often fail to display the differences between products or other focus points beside the impact categories with the large impact. In such cases, internal normalisation can be helpful. Still, great care must be taken in using the conclusions from the results calculated using this method. They should only be used for the comparison of products and impact categories. The conclusion that these impact categories are crucial to consider in improvements toward sustainability must be taken into account in all following steps.

For the LCA calculations at Aalberts IPS, internal normalisation is used. The products in Aalberts IPS' portfolio are made of metal, resulting in a high focus on the resource extraction and ecotoxicity impact category. Across the different products, these two impact categories add up to an average of 95% of the total impact, meaning that the impact of all other categories becomes negligible. Using internal normalisation better highlights the differences between the impact categories, as can be seen in *Figure 2.2*.

The methods of distance to target and monetary weighting require extensive research to determine accurate values. These are therefore better substantiated, and can be applied in a broad scope of contexts. However, the time invested into calculating the appropriate weighting factors is unlikely to be worthwhile if the weighting factors are used within only one company. The panel weighting method is preferred when a wide range of stakeholders with opposing values needs to be considered. This method results in a nuanced weighting set. Multi-criteria analysis can be combined with a panel method, asking all stakeholders to grade the sub-criteria. However, if no panel is available, the multi-criteria analysis can still provide a structured approach to grading the relevance of impact categories. ■

indicator score. This allows for direct comparison of the total impact of one product to another. There are multiple standard sets of weighting factors available, for example in the Product Environmental Footprint (EPLCA, 2018). However, a weighting set can also be developed for the purpose of the study. For this, multiple methods are available, as presented in *Box I*.

Impact assessment methods
In an Impact Assessment Method (IAM), it is specified how the steps of classification, characterisation and optionally normalisation and weighting are to be performed. It presents a method to determine the characterisation, normalisation and weighting factors, and typically presents a predetermined set of values for each. The results are presented in a selection of environmental impact categories. The impact assessment method that is selected for the LCA calculations greatly influences the outcomes of the LCA. In each of the step of the impact assessment process, the IAM defines how the input values are translated into an environmental impact. Therefore, choosing a different IAM can result in different conclusions.

There are multiple Impact Assessment Methods available, covering a wide temporal and geographical scope. Examples are the EcoIndicator 95 and 99 developed for the European continent (Goedkoop, 1995; Goedkoop & Sprinsma, 2000), as well as the ReCiPe (Huijbregts et al., 2016) and Product and Organisational Environmental Footprint methods (EPLCA, 2018) covering the same region. The Eco-Cost Indicator is developed in congruency with Dutch policy (Stichting National Environmental Database, 2020). Other geographical regions are covered by the LIME method in Japan (Inaba & Itsubo, 2018) and a method for the United States is developed by Bare et al. (2006). The EN 15804 standard is the impact assessment method that is used for the calculations in this thesis (CEN, 2019). Apart from the calculation methods that are typically specified in an IAM, this standard provides a broader guidance of performing the LCA as is discussed in more detail in *Section 2.3*.

Impact categories
The effects of the product's lifespan on the environment are expressed in impact categories. A wide range of impact categories covers the great variety of environmental impacts a product causes. Where the current public debate is often solely focussing on the effects of a product on climate change, its effects in other effects, such as the formation of smog or depletion of the ozone layer should not be overlooked. Each impact assessment method presents the environmental impact in a unique set of impact categories. Hence, it is not feasible to present a comprehensive list of impact categories. A selection is presented below, based on the ReCiPe (Huijbregts et al., 2016) and Product Environmental Footprint (EPLCA, 2018) methods:

- Climate change: The emission of greenhouse gases (such as carbon dioxide) that leads to global warming and climate change.
- Ozone depletion: The emission of substances (such as chlorofluorocarbons) that damage the ozone layer, leading to damage to human health because of higher amounts of UV radiation.
- Acidification: The emission of gases (such as nitrogen oxides and sulphur oxides), that lead to acidification of soil or water, causing loss of biodiversity.
- Eutrophication: The excessive enrichment of freshwater, oceans or soil with nutrients, causing a loss of biodiversity.
- Photochemical ozone formation: The emission of substances (such as nitrogen oxides) that causes formation of ozone, resulting in summer smog and respiratory inflammation.
- Resource use (minerals and metals): Using minerals and metals means that more of them need to be extracted from the earth. This leads to scarcity and makes mining more difficult and harmful for the environment.
- Resource use (fossils): Using fossil fuels means that more of them need to be extracted from the earth. This leads to scarcity and makes extraction more difficult and harmful for the environment.
- Water use: Water is needed for humans, animals and ecosystems. Using water for making products means that it is no longer available for those other purposes.
- Particulate matter: The emission of aerosols, causing respiratory inflammation and diseases.
- Ionising radiation: Damage to human health and ecosystems due to radioactive particles.
- Ecotoxicity: The impact that toxic substances emitted to the environment have on organisms.
- Human toxicity (cancer): Chemicals can enter the human body and cause health risks, for instance cancer.
- Human toxicity (non-cancer): This category covers the health risk caused by chemicals, other than carcinogenic effects.
- Land use: The occupation of surfaces of land for the purpose of making products, and therefore taking it away from nature.

2.3. Environmental Product Declaration

An Environmental Product Declaration (EPD) is a structured way to present the environmental data of a product, based on LCA calculations and additional information. The goal of the environmental declarations is that through transparent and verifiable declarations of the products' environmental impact, an informed comparison can be made between alternatives. Where great efforts have been made to standardise what should be declared in the EPDs, variation still remains. Therefore, the results presented in an EPD cannot be directly compared. However, the transparent documentation of what is left in or out of consideration gives insight into what can and cannot be compared.

The procedures of calculating and presenting the environmental impact of products is declared in Product Category Rules (PCR). ISO 14025 (ISO, 2010) provides a general description of what should be specified in a PCR programme, and a what an EPD entails. In ISO 14027 more detailed guidance is provided to developing a PCR programme (ISO, 2017). Both standards refer to the ISO 14040 series on how to perform an LCA (ISO, 2006a).*

Product category rules for construction products (EN 15804)
For construction products, the product category rules are set in the EN 15804 standard (CEN, 2019). It specifies how the scope of the LCA should be defined: what lifecycle phases should be considered, how the functional unit needs to be declared, and in what impact categories the outcomes should be presented. Additionally, it specifies how the scope, assumptions and results of the LCA study should be presented and how the report can be externally verified.

The standard specifies what lifecycle stages should be declared in different situations. The lifecycle phases are referred to as modules, as is shown in the overview in *Figure 2.2*. The standard specifies for each module when it should be declared, and what data should be provided. The structure and terminology of the modules will be used throughout the report.

In a typical LCA study, a functional unit is defined to compare the environmental performance of alternatives based on the same function (see *Section 2.2.1*). However, in EPD reporting this is not always possible. As the comparison of EPDs is performed outside of the scope of one EPD report, it is unclear what the required function for the comparison will be. Therefore, whenever a product's function can be considered ambiguous, a 'declared unit' may be specified. Instead of the function of a product, this refers to the amount of a product and may be specified in terms of e.g. number of pieces, mass or length.

The standard also specifies what environmental impact indicators should be declared and what is optional to declare. The impact categories listed in *Section 2.2.1* cover the majority of the environmental indicators that are specified in the norm. Additional indicators cover more details of the climate change and resource use impact categories.

In order to compare the results from EPDs in different studies, a clear understanding of the scope and procedures of the studies is required. This needs to be presented in the project report, along with the results from the

**More about how the ISO standards relate to each other can be found in Appendix A.*

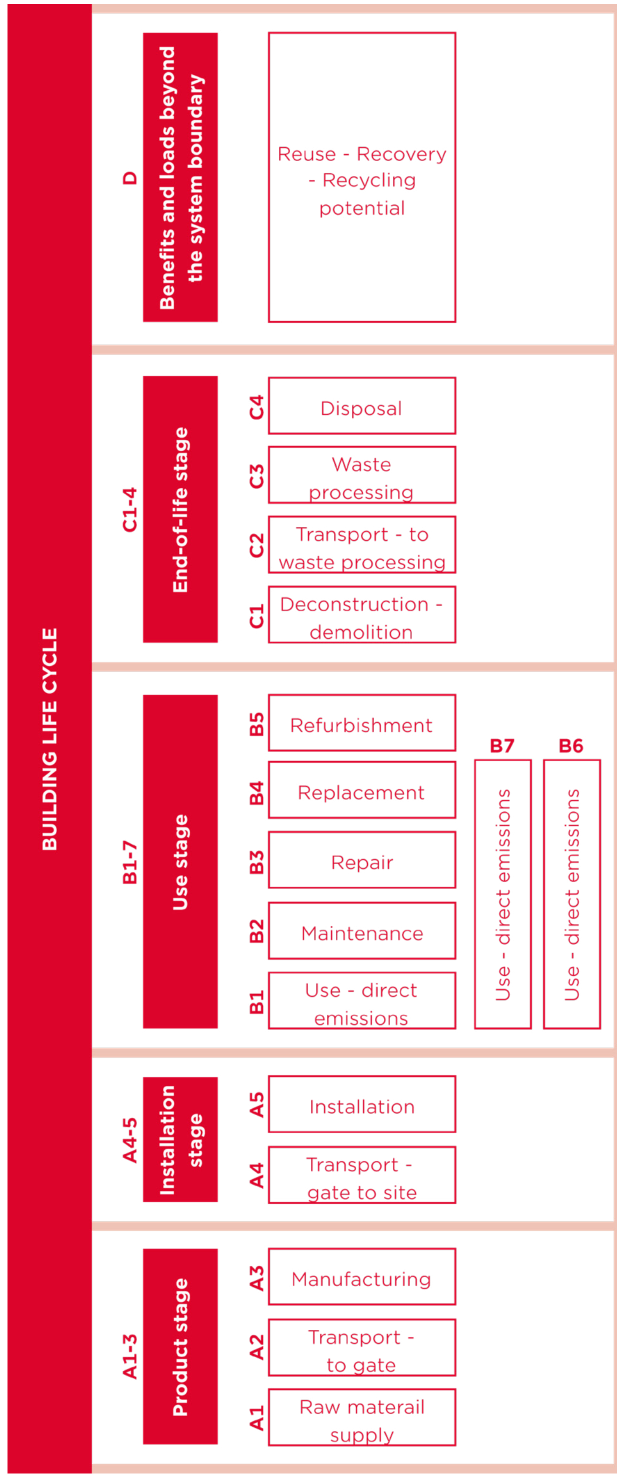


Figure 2.2. *Lifecycle phases as according to the structure of modules in EN 15804. Adapted from CEN (2019).*

EPD study. In this report, the scope should be transparently declared, along with a critical review of assumptions and the validity of the used data. This report provides the basis for external verification, providing the reader with the affirmation that the procedures and results are sound.

2.4. Eco-design

One of the many ways for businesses to reduce their environmental impact is through product design that minimizes its burden on the environment. Many terms exist that describe this process, including 'sustainable product development', 'design for sustainability', 'green design' or 'eco-design'. In the ISO 14006 standard, the term eco-design has been explained and a general procedure of implementing eco-design alongside the Environmental Management System (as covered in ISO 14001) is specified.*

The eco-design process combines two core activities: environmental assessment and environmental improvement (Vallet et al., 2013). A multitude of tools is available for eco-design, aimed at the different core activities within eco-design. These tools provide a sense of confidence and comprehensiveness for the designers, as it limits the risk of forgetting significant elements (Åkermark, 2003).

Life Cycle Assessment (LCA) is a valuable tool for the environmental assessment activity of eco-design. It is able to provide an insight into what lifecycle stages or design parameters have a great influence in the overall environmental impact of a product. This allows the design team to focus their attention on improving these aspects of the product's design.

For the environmental improvement activity, techniques are used that are currently used in typical product development. Examples are brainstorming, morphological charts and concept diversion and conversion techniques as used in the 'double diamond' method by Kochanowska and Gagliardi (2022). For these steps, eco-design tools are available that can be divided into three categories (Knight & Jenkins, 2009). Guidelines providing a broad support across the whole product development process, checklists presenting in-depth explanations for a narrow scope and analytical tools providing guidance of when and how systemic analysis can be performed.

**More about how the ISO standards relate to each other can be found in Appendix A.*

3 Design tool

In this chapter the design tool is presented that has been developed for Aalberts Integrated Piping Systems, to incorporate the environmental impact of products during their development using Life Cycle Assessment. First the design tool is presented and it is described how it can be used (*Section 3.1*), then it is described how the design tool has been developed (*Section 3.2*).

3.1. Using the design tool

The design tool is intended to be used by the product development team. *Section 3.1.1* explains how they can use it to develop more sustainable products. The design tool requires quick-LCAs that are performed by an LCA expert. In *Section 3.1.2* the procedure for these LCA calculations is defined.

3.1.1. Product development

The explanation of the design tool in this section resembles the user guide that is presented to Aalberts, as shown in *Appendix B*, where the following section provides a more detailed explanation. Additional reasoning behind what is included in the design tool is provided in *Section 3.2.4*.

Overview of design tool
The design tool consists of two sides and the design guide presented in *Appendix B*, each presenting a different level of detail. This distinction is made for easy retrieval of required information. The front of the design tool (*Figure 3.1*) provides only the essential information, without the clutter of additional explanations. Whenever clarifications are required, these can be easily found on the back of the design tool (*Figure 3.2*). The guide is intended for the first use, providing an explanation of how the design guide should be read and some background information that is required for the interpretation of the LCA results.

The design tool proposes to consider the environmental impact of the material during the product development process in four steps, based on the steps in which the decision for the material of the product is defined within Aalberts IPS. First the material of the main body is defined by choosing the alloy family, followed up by the definition of the specific alloy that is used. The same distinction into alloy family and specific alloy is made for the evaluation of the material of the subpart.

The term 'alloy family' refers to the general distinction into categories of alloys, such as carbon steel, stainless steel, brass or copper. This definition is based on the report by UNEP (2011). The 'specific alloy' step dives into differences within the alloy family. For example the difference between the commonly used grades of 304 and 316 of stainless steel, but also if the alloy composition is tailored specifically to the requirements of the product.

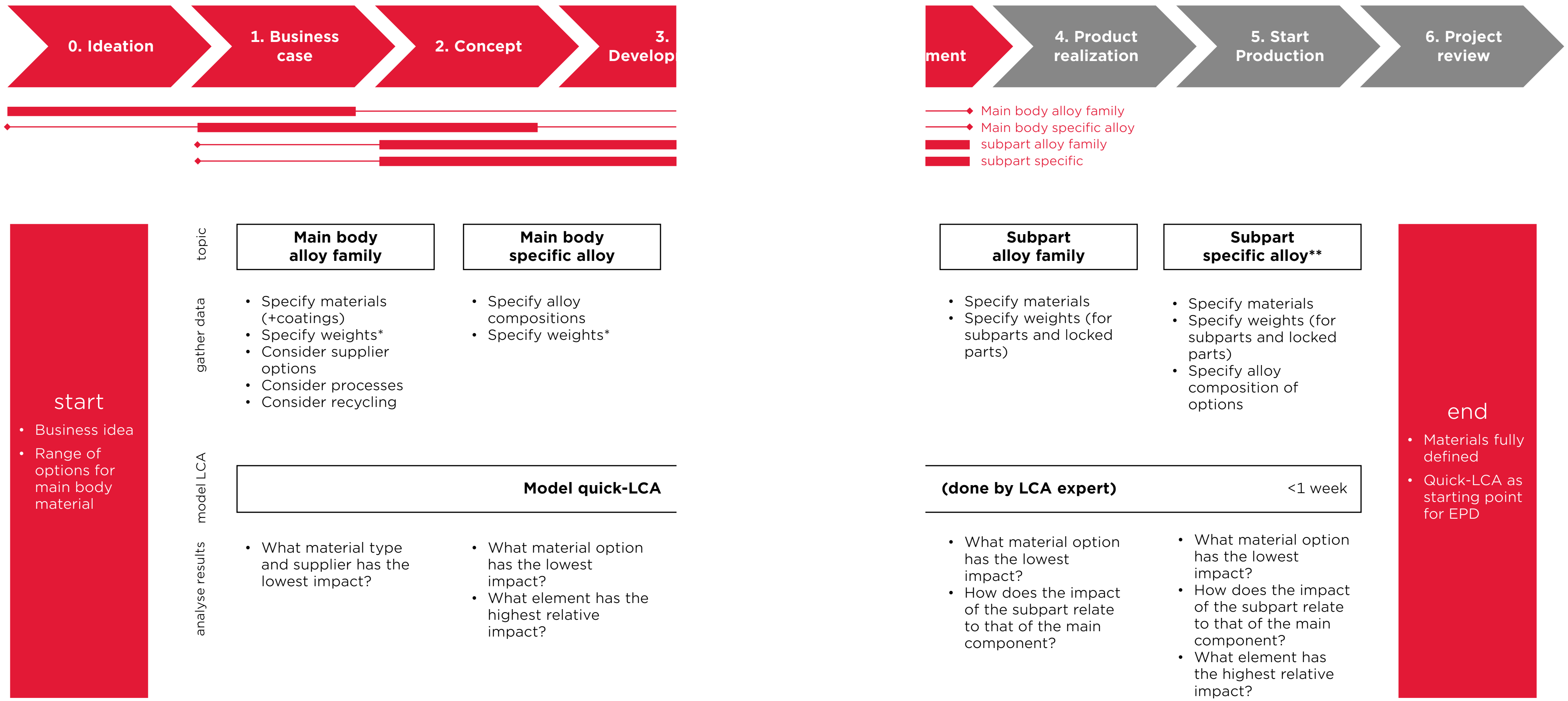
Per decision topic, two general steps are performed by the product development team. First the materials in consideration are specified, so that the LCA expert can model a comparison. The tasks of the LCA expert should be performed within one week, so the product development team can continue with the development of the product. The next step is to interpret the results, providing answers to the questions posed.

Below, an overview is provided of the two sides of the design tool. Next, the steps that require some more explanation are presented.

Front
On the front side of the design tool, the steps of the product development at Aalberts IPS are shown, with a time range in which the different decisions take place. It can be seen that all decisions should be solidified at the end of the third phase: 'development'. However, the main body alloy family and specific alloy are preferably considered in the earlier phases. Only after the ideation phase, the subpart alloy family and specific alloy consideration starts, with their focus in the concept and development phase. The centre of the design tool presents the steps that should be taken by the product development team. These are explained in more detail on the back of the design tool. The red bars framing the centre present the start- and end conditions of the design tool. They represent what is necessary to start using the design tool, and what the results would be after using it.

The steps of the subparts material need to be repeated for every subpart under consideration. That way only one variable is changed at the time, reducing complexity in the comparison.

Design tool LCA in product development



* only if differences in weight are expected for material options
** only if the difference between subpart options is significant

Figure 3.1.
Front of design tool for Aalberts Integrated Piping Systems

Design tool LCA in product development

gather data

Main body alloy family

- **Specify materials**: Specify general material or alloy type of all options. Also include coatings if that is required for the material.
- **Specify weights**: If a different weight is expected for different material types, use this here. Also specify weights of coatings.
- **Consider supplier options**: Do suppliers provide multiple (sustainability) grades of the same materials?
- **Consider processes**: If different materials require a different (energy-intensive) process, the LCA expert should be informed.
- **Consider recycling**: If the recycling percentages differ > 50 percentage points, the LCA expert should be informed.

example

Material	Steel	Stainless steel
Weight (g)	100	100
Coating	Zinc	-
Weight (g)	0,001	-

Main body specific alloy

- **Determine alloy compositions**: Specify what elements the alloy is made of, and how much of each element is present in the alloy options.
- **Specify weights**: If a different weight is expected for different material types, use this here. Otherwise, select an easy-to-use amount, the same for all options.

Element	Option 316	Option 317
Iron	67,75	63,75
Chromium	17	19
Molybdenum	2,5	3,5
Nickel	12	13
Silicon	0,75	0,75

Subpart alloy family

- **Specify materials**: Specify the materials of the components for which the material choice is set, as well as the options for the subpart.
- **Specify weights**: Specify the weight of the components for which the material choice is locked, as well as the options for the subpart.

Component	Housing	O-ring	Grabring	Grabring
Status	Set	Set	Option 1	Option 2
Material	Steel	EPDM	Copper	Steel
Weight (g)	320	1	11	11

Only if the difference between subpart options is significant

Subpart specific alloy

- **Specify materials and weight of set components**: For the components for which the material choice is locked, specify the materials and weights.
- **Determine alloy composition of options**: Specify what elements the alloy is made of, and how much of each element is present in the alloy options. Make sure they add up to the same weight for all options, unless different performance is expected.

Component	Housing	O-ring	Grabring	Grabring
Status	Set	Set	Option 1	Option 2
Material	Steel	EPDM	C12200	C27451
Weight (g)	320	1	11	11

Element	C12200	C27451
Copper (Cu)	99,985	63
Phosphor (P)	0,015	0,15
Lead (Pb)	-	0,25
Zinc (Zn)	-	36,25
Iron (Fe)	-	0,35

Model quick-LCA (done by LCA expert)

<1 week

analyse results

Main body alloy family

- **What material option has the lowest impact?** What are the differences between the options? Make sure to compare the materials including the necessary coatings. How do the differences in LCA performance relate to performance on other criteria? If different supplier options are available, compare their environmental impact.

Main body specific alloy

- **What alloy option has the lowest impact?** What are the differences between the options? How do the differences in LCA performance relate to performance on other criteria?
- **What element has the highest relative impact?** How do the weights of the elements in the compositions relate to the impact of the elements? Is it possible to reduce the content of large contributors in the alloy?

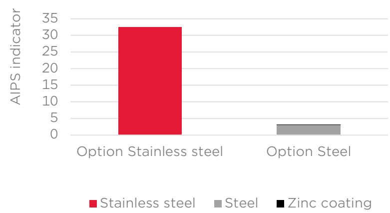
Subpart alloy family

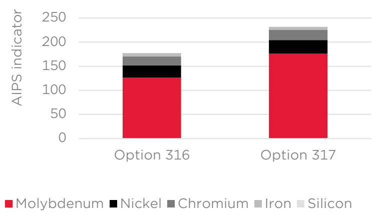
- **What material option has the lowest impact?** What are the differences between the options? How do the differences in LCA performance relate to performance on other criteria?
- **How does the impact of the subpart relate to that of the main component?** How does impact relate to other aspects, such as weight and performance? Is the impact of the subpart significant compared to the set components? (>5%)

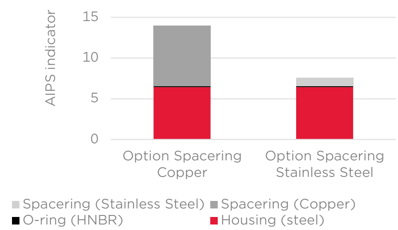
Subpart specific alloy

- **What material option has the lowest impact?** What are the differences between the options? How do the differences in LCA performance relate to performance on other criteria?
- **How does the impact of the subpart relate to that of the main component?** How does impact relate to other aspects, such as weight and performance?

example







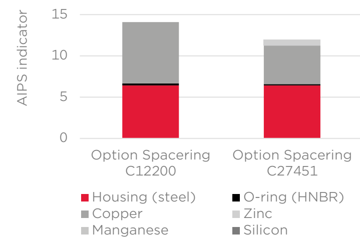


Figure 3.2.
Back of design tool for Aalberts Integrated Piping Systems

Back
The same steps that are mentioned on the front are also shown on the back, but with more detailed explanation. It also provides an example of how the gathered data in the first step should be presented to the LCA expert, and what the results could look like. The data should be presented to the LCA expert so that it is clear what the material types and weights are that will be compared. For the specific alloy comparison that means that they should be split up into the elements that make up the alloy.

The results should be interpreted by comparing the values between the different options and components. The main focus should be on the differences in values between the options, the total values are less relevant. This is a result of choosing the internal normalisation, as described in *Box III*. The total values only mean how the impacts relate to the total impact of the selected benchmark product. The values are expressed in 'AIPS indicator', of which the calculation is discussed in *Box V*.

Elaboration
Some of the steps require additional explanation. These are discussed below.

Specify materials (+coatings)
In the same step where the material options are defined, the coatings must be specified. The material of the coating, as well as the chemicals used during application of the coating are often much more harmful to the environment than the main body material.* As some materials require a coating, and others do not, the comparison of impact of material options is only representative when the coatings are considered.

Specify weights
It is possible that for different material options, different weights are to be expected. This could be due to completely different designs, or if the strength or density of the material differs between options. If such a difference is expected, this should be taken into account in the comparison. If not, the same weight will be used for all options. This can be the weight as specified in the design or a round number.

Consider supplier options
Many suppliers are currently working on more sustainable materials. Therefore, it is relevant to consider these alternatives, next to the general material types. As you rely on the way that suppliers present their information, these differences cannot be implemented further into the quick-LCAs. However, they can be considered throughout the next steps. If the exact composition of the alloy is to be defined, the quick-LCAs in the 'main body specific alloy' step can still provide insight in the general differences in impact between elements and alloy compositions. The subpart LCAs will not be representative, as the comparison between the main body material and the subpart will not reflect reality.

Consider processes
Different materials can require different manufacturing processes. These processes are likely to consume different amounts of energy. This difference is not accounted for in the quick-LCAs, as they only consider the environmental effect of materials. Whenever a difference in energy consumption of factor two is expected between two material options, this should be reported to the LCA expert. They can then evaluate how this influences the conclusions that can be drawn from the quick-LCAs.

Consider recycling
If there is a big difference between the recyclability of materials, the results from the material quick-LCA should be considered with additional care. They might falsely favour a material with a low material impact that cannot be recycled over an option that is well recyclable but has a higher initial impact. Therefore, the LCA expert should be made aware if the difference in recycling percentage between two material options is more than 50 percentage points. This difference will then be considered in the evaluation of the results.

Moving from 'subpart alloy family' to 'subpart specific alloy'
If the impact of the material options for subpart alloy family is significantly lower than the impact of the main body, it is not useful to evaluate the impact of the alloys in the next step. It can then be assumed that the differences between the specific alloy will not have a significant contribution to the total impact. In other words, it is only relevant to evaluate the environmental impact of the step 'subpart specific alloy' for subparts that have >5% of the total impact.

AIPS indicator
The scores in the graphs are presented in the Aalberts Integrated Piping Systems (AIPS) indicator. The results from the LCA analysis as calculated in the Ecochain software, are presented in different environmental indicators, each with a different unit. In order to compare the values to each other and add them up into a single indicator, a normalisation and weighting step are required. This allows for incorporation of the sustainability KPI's into the LCA results. *Box IV* describes the general process of determining company-specific normalisation and weighting factors, *Box V* discusses how the normalisation and weighting factors have been developed for Aalberts IPS.

**This is visualised in Figure 3.7 on page 47.*

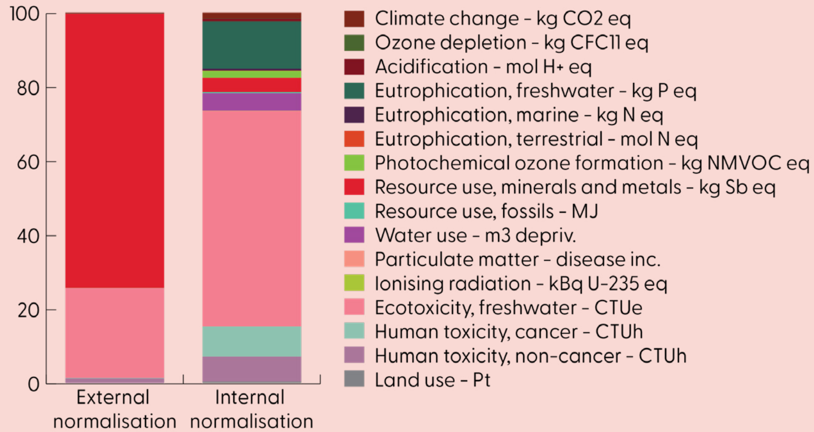
Box III.
Reasoning for selected normalisation and weighting methods

In this box, it is presented which methods are selected for normalisation and weighting in order to calculate the Aalberts IPS weighted indicator score, based on the methods presented in *Box I* and the considerations in *Box II*. *Box IV* will provide a general description of the steps that are required to calculate the normalisation and weighting factors according to the selected methods, and *Box V* presents the outcomes for Aalberts IPS as calculated according to *Box IV*.

For the LCA calculations at Aalberts IPS, internal normalisation is used. The products in Aalberts IPS' portfolio are made of metal, resulting in a high focus on the resource extraction and ecotoxicity impact category. Across the different products, these two impact categories add up to an average of 95% of the total impact, meaning that the impact of all other categories becomes negligible. Using internal normalisation better highlights the differences between the impact categories, as can be seen in *Figure 2.2*.

The panel method is selected for determining the weighting factors. This is chosen because of the wide range of stakeholders within Aalberts IPS that are relevant for sustainable product development. Using the panel method creates a more nuanced view than using the multi-criteria analysis. The distance to target and monetary weighting methods were considered too time-consuming to perform for the scope of the thesis.

Figure 3.3.
Comparison of external and internal normalisation for the environmental impact of Aalberts IPS' product 'Super', expressed in percentages



The external normalisation is calculated according to the EC-PEFC norm (EPLCA, 2018), internal normalisation is done according to the benchmark product as described in Box V. ■

Box IV.
Determining company-specific normalisation and weighting factors

In this box, the methods for normalisation and weighting that are used in the report are explained. They are based on the available methods as discussed in *Box II*. The methods as described here are used to determine the normalisation and weighting factors to use in the Aalberts IPS design tool – which is presented in *Box IV* – and can be used to determine the normalisation and weighting factors for the company as part of the framework (*Section 4.1.1*).

>

Box IV.
(continued)

Normalisation factor
A normalisation factor tailored to the company can be determined by selecting a benchmark product. It is also possible to select an available set of normalisation factors, as is described in *Box II*. To determine the normalisation factors based on a benchmark product, the following steps are performed:

- Select benchmark product: Choose a product that is representative of a large part of the portfolio with regards to design, material and weights, and also sold in large volumes.
- Calculate the environmental impact: Do this for the entire product portfolio that is under consideration, including the benchmark product. This ensures that the data from the benchmark product can be compared to the rest of the portfolio.
- Calculate the normalisation factor: The normalisation factor for each environmental impact category is equal to the impact of the total product for each of the impact categories. That way, when dividing the environmental impact by the normalisation factor, the total impact of the product should become 1.

Weighting factor
The weighting factor is calculated using the panel method. As there are still many approaches to use the panel method, it is explained below what steps are used to determine the weighting factors within the scope of this report.

- Prepare overview of environmental indicators: Determine what environmental indicators will be considered, then describe them in a way that someone without prior knowledge on sustainability and LCA can understand.
- Determine key sustainability goals: Define what sustainability goals are most relevant to the company. These might be presented in the Corporate Sustainability Reporting, or any other outing of the sustainable business goals. These insights will inform the weighting factors for the initiator of the weighting factors.
- Define panel: Consider who within the company has relevant insights about sustainability and the environmental impacts of the products. Think of sales, product development and marketing departments. Make sure to also include the initiator of the weighting factors in the panel.
- Perform interviews: Present the environmental indicators to the panel, and explain what they mean. Ask the panel members to classify the impact categories into high, medium and low importance. Next, rank the indicators classified with high and medium importance according to their individual importance. These can be individual sessions or in a group setting.
- Calculate final weights: Assign values to all categorised and ranked responses. The impact categories that were considered of high importance receive scores between 0,5 and 1 (with equal steps), the categories with medium importance between 0,05 and 0,1 (with equal steps) and the low importance impact categories receive a weight of 0,01. The final weighting factors are calculated as the average of the panel for each of the environmental indicators. ■

Box V. *Determination of AIPS indicator*

This box describes how the normalisation and weighting factors are determined for Aalberts IPS, based on the process described in *Box II*. This allows the results to be calculated towards a final AIPS indicator score.

Normalisation

For the normalisation, the benchmark product XPress Carbon 28mm, 90° bend is chosen. This is a product that is sold in large volumes, and its design is representative of the largest portion of the portfolio. The product is shown in *Figure 3.4*. The normalisation factor for each environmental indicator is set so that the sum of the total impact of the reference product is 1, see *Table 3.1*.

Figure 3.4. *XPress Carbon elbow 90°. (Aalberts IPS, n.d.-c)*

Weighting

To determine the weighting factors for the AIPS indicator, two approaches were combined. First, weighting sets available in literature were used and combined into one average score. This is then combined with the outcomes of the interviews that were performed second. People from the departments product management and sustainability management level (within IPS and on the corporate level) were interviewed. The final weighting factor could then be calculated as the average of the weighting sets found in literature and the interviews, and is presented in *Table 3.1*. What pre-existing weighting sets were considered, as well as the individual scores from the interviews can be found in *Appendix C*. An explanation of each of the impact categories can be found in *Section 2.2*.

Table 3.1. *XPress Carbon elbow 90°. (Aalberts IPS, n.d.-c)*

Environmental Indicator	Normalisation factor	Weighting factor
Climate change - kg CO2-eq	1,21E-01	1,00
Ozone depletion - kg CFC11 eq	4,58E-09	0,03
Acidification - mol H+ eq	2,10E-03	0,07
Eutrophication, freshwater - kg P eq	2,37E-07	0,02
Eutrophication, marine - kg N eq	1,61E-04	0,08
Eutrophication, terrestrial - mol N eq	8,71E-03	0,04
Photochemical ozone formation - kg NMVOC eq	1,27E-04	0,06
Resource use, minerals and metals - kg Sb eq	2,71E-04	0,74
Resource use, fossils - MJ	1,63E+00	0,21
Water use - m3 depriv.	8,99E-03	0,21
Particulate matter - disease inc.	2,08E-08	0,02
Ionising radiation - kBq U-235 eq	3,69E-03	0,01
Ecotoxicity, freshwater - CTUe	1,10E+00	0,29
Human toxicity, cancer - CTUh	1,29E-10	0,33
Human toxicity, non-cancer - CTUh	1,92E-08	0,47
Land use - Pt	1,81E+00	0,11

3.1.2. LCA expert

The LCA expert performs quick-LCAs during the product development process, based on the material options under consideration. The product development team specifies the data that can be used as input for the LCA, and will later on use the results. The LCA analysis should be performed within one week at most, ensuring that the product development process is not delayed extensively.

The general steps of performing the quick-LCAs using the Ecochain Helix software are described below, a more in-depth explanation specific to Aalberts IPS can be found in *Appendix D*. The descriptions apply to all four types of quick-LCA discussed in the design tool.

1. Entering data: The material data is presented to the LCA expert in the form of a table, defining the material type and weight of each of the options. This data is entered into the LCA software for the raw materials supply lifecycle phase, making sure to select the database entries that best reflect the desired material or element. As some elements are not frequently used separately, these can be difficult to find. All life cycle phases other than the raw materials supply are left empty.
2. Processing data: The results are calculated. Ecochain does not facilitate calculating a customised weighted indicator score. Therefore, these calculations are done manually in Excel. This Excel sheet is explained in *Appendix D*.
3. Presenting results: The weighted scores are presented in graphs so that the product developers can compare the options. The total impact of the options is shown, as well as the different parts or elements that make up the total score. This is done using Excel.
4. Assessing validity: Before the results are presented to the decision-makers, the validity of the results should be assessed. It should be evaluated how reliable the data is that was used, and how that could affect the conclusions that follow from the results. If the product developers indicated an expected large difference in manufacturing processes (≥ factor 2) or recycling percentages (≥ 50 percentage points), this is considered in this step. If the option with the highest environmental impact resulting from the quick-LCA study is also the option for which a higher environmental impact is expected for manufacturing processes or recycling, the results can still be used. However, if the opposite is true, the uncertainty is too high to use the outcomes further. Additionally, attention should be paid to the outcomes of the LCA of specific alloys. Due to the limitations of the EcoInvent database, these calculations present a higher uncertainty. If the results are too close and the uncertainty too high, the outcomes should be disregarded.

5. Evaluating results: An optional next step is to evaluate the origins of the environmental impacts. Knowing where the impacts come from can give an insight into how the impact can be reduced, other than reducing the amount of a material that is used. The impact category that contributes most to the overall environmental impact of the product is evaluated in more detail. It is studied what mechanisms cause the emissions. For example, the material copper has a large impact on the ecotoxicity impact category, which is caused by the antimicrobial nature of copper (Anjum et al., 2015). These insights can help in conversations with suppliers. Knowing what causes the largest impact can be a starting point for them to reduce the impact.

3.2. Developing the design tool

This section describes how the design tool, as presented in *Section 3.1*, has been developed. This section explains the reasoning behind what has been included, and this process will be used as a starting point for the development of the framework as described in *Chapter 4*.

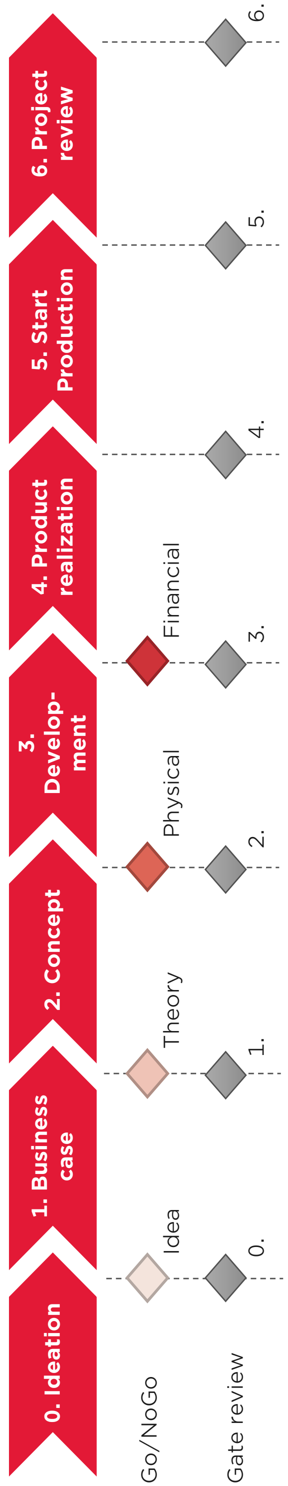
The development of the design tool followed a number of steps, as is described in the following sections. First, the data and expertise on LCA within Aalberts IPS was considered (*Section 3.2.1*). Then the product development process was studied (*Section 3.2.2*), giving an insight in when decisions are taken that are relevant for the environmental impact of the products. Then the results from LCAs of Aalberts IPS' portfolio were evaluated, to pinpoint what design choices have the largest influence on the total environmental impact of the product (*Section 3.2.3*). It is then described how the findings from the analysis steps have been combined into a design tool (*Section 3.2.4*).

3.2.1. LCA data and expertise at Aalberts IPS

Aalberts IPS has recognised the trends towards sustainability and the need for analysing their products' environmental footprint. LCAs are performed internally, which are used to publish Environmental Product Declarations (EPDs) of the products. These EPD results can be found on the website of Aalberts IPS (n.d.-a).

Aside from the LCA expertise, positions related to sustainability are filled on all levels of the organisation. On the corporate and global level,* those positions focus mostly on strategic positioning and organisational improvements. Aside from that, in the other business units within the Aalberts group there are also people working on LCAs and sustainability strategy.

An overview of the organisational structure of Aalberts can be found in Figure 1.2 on page 13



Phase	Phase activites
0. Ideation	Market demand, innovation needs, input of first ideas
1. Business case	Draft business case, rough outlines, capital expenditures reservations, Go/NoGo
2. Concept	Design prototypes, feasibility studies, finalise business case (project charter) Go/NoGo
3. Development	Order machinery, develop products and tooling
4. Product realization	Proof of manufacturing, set up production process and organisation
5. Start production	0-series, ramp up, market introduction
6. Project review	Closure and handover documentation, review process and return-of-invesments

Figure 3.5. *Stage-gate model used at Aalberts IPS, based on Cooper (1990)*

Table 3.2.
Overview of decisions, written out per product development- and lifecycle stage, based on the modules used in the EN 15804 standard (See Figure 2.2 on page 27)

Module	Variables	0 ideation/ 1 business case	2 concept	3 development
A1 Raw material extraction	**Material type**	Type of metal specified (alloy family)	Specific alloy	Specific materials of smaller components
	Weight	Rough range of diameters	Rough design and dimensions	Exact dimensions and weights
A2 Transport to gate	**Transport distance**		Suppliers are chosen based on alloy choice	
	Mode of transport			Transport modes defined
	Weight of product (see A1)			Weight of product defines impact of transport
A3 Manufacturing	**Energy consumption**	General type of machine chosen (e.g. hydraulic vs electric)	Specific machine chosen	Specific processes worked out
	Energy type (organisational decision)	Electricity contract		
A4 Transport gate to site	**Transport distance**	Defined when the target market (or country) is identified		
	Mode of transport			Transport modes defined
	Weight of product (see A1)			Weight of product defines impact of transport
C4, D Disposal and recovery	**Recovery strategy**	Type of recovery scheme		
	Material type	Material type choice influences recycling scenarios		

Note:

The overview only shows the product development phases 0 to 3. The decisions in the later phases are either iterations on decisions made in earlier phases, or are on such a high level of detail that they do not have a significant influence on the environmental impact. This is in line with statements by Millet et al. (2007). Furthermore, the ideation and business case stages are combined as the decisions made in the phases are similar, only the level of detail might vary slightly.

The lifecycle phases of installation (A5), use (B) and end-of-life (C1-3) have been excluded. There are no impacts in the installation and use phase for the products at Aalberts IPS, and the effects in the end-of-life module (C1, C2, C3 and transport of module D) are outside of the control of the company. Only the effects in the C4 module (disposal) are influenced by the recovery strategy, in terms of how much is recycled as opposed to landfilled. The use of ancillary materials and direct emissions during the manufacturing phase (A3) has been considered negligible and is thus left out of consideration.

Within the corporate level of Aalberts and the Integrated Piping Systems technology, objectives are set to reduce the environmental impact of the business practices. They focus on increasing the energy efficiency, reducing water and resource consumption, reducing waste generation and travelling consciously (Aalberts, 2022). These focus points correspond to the impact categories that received the highest weighting factors, as can be seen in *Box V on page 40*.

The LCAs are performed using the Ecochain Helix software, a web-based tool that allows the user to fill in company-based data on e.g. production amounts, product dimensions and energy consumption. It works with the EcoInvent database, where the user can select the appropriate materials, modes of transport and end-of-life treatments. When all product data has been filled in, the results can be calculated. These can easily be converted into an EPD report, but also analysed further to find the causes of emissions. Ecochain already presents the data in a number of views, but if further details need to be studied, the results can easily be converted to an Excel file.

To get a deeper understanding of LCAs at Aalberts, an LCA was performed for a product range that had not yet been evaluated. This differed from performing an LCA in the theoretical projects in previous experiences in a number of different ways. These differences are reflected on in *Appendix E*.

3.2.2. Product development process

The product development process at Aalberts IPS is modelled after the stage-gate model (Cooper, 1990), and is presented in *Figure 3.5*. It follows six stages, from ideation to project review. Each stage is rounded up at the so-called gate, where the results from the stage are evaluated. Based on this information, the choice is made whether to progress to the next stage or not. If the results are insufficient to pass the gate, improvements are made in the stage until the results are sufficient to continue. With each stage, the detail level increases and the level of uncertainty decreases.

In each phase, decisions are made about the product that influence the environmental impact. For instance, the material is selected, a machine is chosen, and the transportation distance is defined. To get an insight in how the decisions are made in the different stages of the product development process, and how these decisions influence the environmental impact of the product, an overview is made based on conversations with project management. This is presented in *Table 3.2*. The goal is to determine for which decisions a prospective LCA could provide valuable insights for improvements during the product development phase.

It can be seen that some decisions are spread across multiple product development phases. This is the case for the impacts from the material choice and weight and manufacturing, moving from a general idea to a detailed decision in the different steps. Multiple quick-LCAs can be performed to inform the decisions that together shape the final outcome.

What can also be seen is that one decision can have an influence on multiple aspects of the environmental impact, throughout different lifecycle phases. For example, the material choice influences the recycling potential, and the chosen weight influences the impact of the transportation steps. An LCA could be useful to evaluate the interplay between the different lifecycle impacts that are affected by the decision.

Another finding is that some impacts follow a logical relation, where other impacts are harder to predict based on the input data. If the travel distances are longer, the impact of the transportation is logically higher than for shorter distances. A similar relation applies for the weight of the product and the energy consumption, in both cases it is easy to understand how the environmental impact changes based on the input values. For the material choice, such a logical relation between the options does not exist. The difference between the impact of copper versus stainless steel cannot be explained by a simple relation. For such decisions, an LCA can be a valuable way to evaluate the differences between options. Other decisions for which no logical relation exists are the mode of transport, energy type and recovery strategy.

3.2.3. Results LCAs portfolio

In this section, the results will be discussed for the LCAs that have been performed of the products in Aalberts IPS' portfolio, in order to publish the first set of EPD reports. A general description of what is modelled, and the most important conclusions are explained below.

The LCAs are performed on the five product ranges that have been modelled in Ecochain. Of each product range a specific product has been selected, a similar product for each. That way the comparison is fair across the product ranges. The chosen products and their characteristics are shown in *Table 3.3*. The LCA study has been performed according to the EN 15804 standard (CEN, 2019), filling in modules for material extraction (A1), manufacturing (A3), transport (A2, A4) and end-of-life (C, D). The results are expressed in Aalberts Integrated Piping Systems (AIPS) indicator, combining the different environmental indicators in a way that best represents the relevance within Aalberts IPS. How this indicator is calculated can be found in *Box V on page 40*.

The first observation that can be made from the results, is that the materials extraction phase holds the most significant impact by a considerable margin. Across the different products, an average of 95% of the total impact is attributed to the materials (*Figure 3.6*). After that, the manufacturing (17%) and end-of-life phase (-17%)* have the largest contribution to the total impact.

The compared products each have different masses and are made of different materials, contributing to the differences in impact per product. The product Super has the largest impact in the materials phase. This can be partly attributed to its mass, as it is heavier than most other products. However, the main reason for its high impact, is its material type. Where Super is made of brass, the other products are made of stainless steel and carbon steel.

To get a better idea of the impact of the choice of material types, the impact per ton of material is displayed in *Figure 3.7*. It can be clearly seen that brass has a much larger impact per ton of material than carbon and stainless steel. The impact of carbon steel is even lower than of some polymer materials.

What should also be noted is that the zinc coating that is used on the carbon steel products, has such a large impact per ton that it could not be displayed on the same scale as the other materials. This material is only used in small amounts in the final products, reducing the overall impact of the coating. However, the impact of the coating still has a significant impact on the total product, despite the small amount that is used.

**Some of the materials are recycled, which means that the impacts of the material extraction steps can be omitted. This avoided impact is presented as a negative value, in this case resulting in an overall negative score for the end-of-life phase.*

Table 3.3. *Characteristics of products selected for LCA study*

	Type of product	Sealing element[i]	Diameter	Weight[ii] (g)	Material[ii]
Power-Press	Straight coupling	HNBR	¾”	138	Carbon steel
XPress C	Bend 90°	EPDM	18 mm	57	Carbon steel
XPress SS	Bend 90°	EPDM	18 mm	57	Stainless steel
SudoPress C	Bend 90°	EPDM	18 mm	57	Carbon steel
SudoPress SS	Bend 90°	EPDM	18 mm	57	Stainless steel
Super	Straight coupling	N/A[iii]	18 mm	115	Brass

i: Different types of rubber are used for the sealing elements (O-rings) of the fittings for different applications (see technical handbook in Aalberts IPS (2023)). ii: for the main compent. iii: no sealing element is used in the fittings of the 'Super' product range.

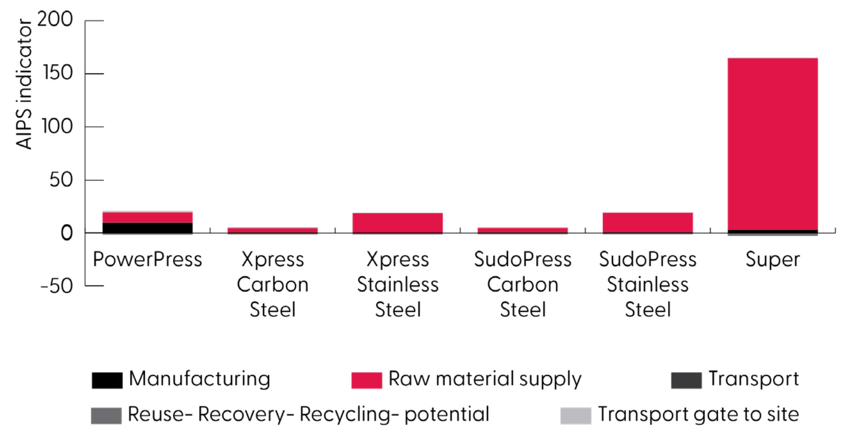


Figure 3.6. *Environmental impact of lifecycle phases for different products, expressed in AIPS indicator*

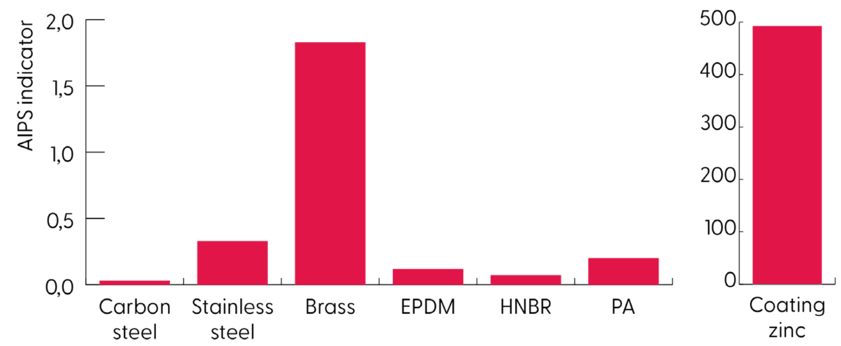


Figure 3.7. *Environmental impact per ton of the material, expressed in AIPS indicator per ton - the impact of the coating is shown on the right.*

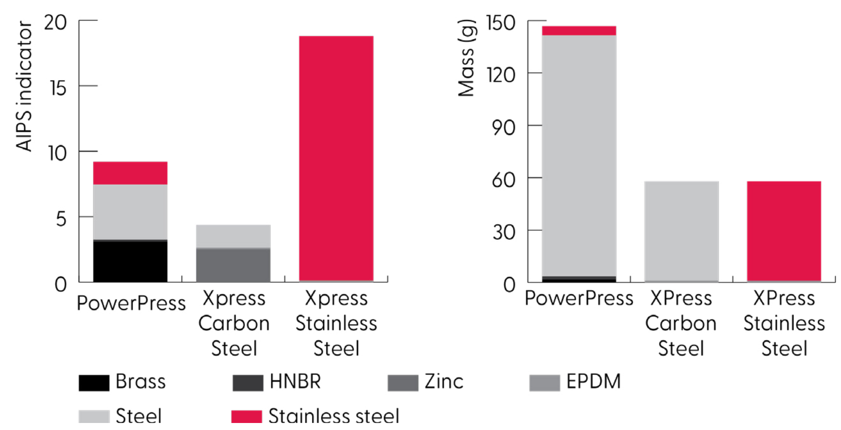


Figure 3.8. *Environmental impact of materials for different products, expressed in AIPS indicator (left), product composition in mass per material (right).*

In *Figure 3.8* it can be seen that for the XPress Carbon Steel product, the weight of the coating is only 0,01% of the total product, where the impact is 58%. However, the combination of steel and coating for the XPress Carbon product still has an impact below that of the XPress Stainless Steel product.

Similar to the coatings, it can be concluded that small components can have a significant environmental impact to the total product. In *Figure 3.8*, the brass component in the PowerPress product contributes to 1% of the weight, but 34% of the total impact. For the stainless steel component of the Power Press that is 4% and 19% respectively. The main body of the product, with the largest mass (stainless steel, 93%) only has a relatively small impact (46%).

The most important conclusions that can be drawn from the results of the LCA of the current portfolio at Aalberts IPS are that the products' environmental impacts are mostly caused in the materials extraction phase, and that smaller components can still greatly influence the total impact of the products.

With this in mind, it is most beneficial to focus the attention of the product development on the material choice when looking for reduction of the environmental footprint. This should not only be considered for the main component of the product; great care must also be taken when defining the materials of smaller components.

3.2.4. Combining into design tool

From both analyses it can be concluded that for Aalberts IPS the most relevant decision to consider is the material choice. The LCA shows that the materials extraction phase has by far the largest impact, so the biggest improvements with regards to the products' sustainability can be made here. This impact is defined by the decisions for material choice as well as material weight. The impact of material weight follows a logical relation and is therefore less interesting to consider. Therefore, the material choice is used as the focus of the design tool.

The results from the LCA also show that the interplay between impacts of the different lifecycle phases is irrelevant to consider. As the materials' impact is so large compared to the other lifecycle phases, the effects of

Table 3.4. *Recycling percentages of elements often used in by Aalberts IPS.*

Element	Recycling percentage[i]
Chromium (Cr)	87-93%
Manganese (Mn)	53%
Iron (Fe)	52-90%
Nickel (Ni)	57-63%
Copper (Cu)	43-53%

[i]The recycling percentage represents the percentage of the metal reaching the end-of-life stage that enters the scrap market, as found in UNEP (2011)

a change that affects both the material extraction phase and another phase, will only make a significant difference to the impact in the materials phase.

As discussed in *Section 3.2.2*, the material choice consists of multiple steps. In *Table 3.2 on page 44*, three steps are pointed out, but upon closer investigation the decision was taken in the following four steps:

- Main body – alloy family
- Main body – specific alloy
- Subpart – alloy family
- Subpart – specific alloy

These steps were used to structure the design tool. For each of these steps, it is described what LCAs can be performed to provide insight into the environmental impact of the options for the decision. Besides, additional points of attention are mentioned for each of the steps. In cases where the material options are not metals, the distinction into 'alloy family' and 'specific alloy' can still refer to the different levels of detail of the material decision. The first level of detail then refers to the general material type such as rubber or plastic, followed by a comparison between the different types of the chosen material, for example polypropylene or polyethylene.

In the design tool, there are three instances where a factor defines how to proceed. The reasoning behind the values of the factors is discussed below. However, it should be noted that these values are not soundly substantiated and therefore require further testing before use. This is discussed further in *Section 5.2.2*.

For the step 'consider processes' it is specified that if different manufacturing processes are required for different materials, an estimation of required energy consumption must be made. If this is expected to vary more than a factor two between options, the results must be considered with care. This factor is chosen based on the results of the LCA from Aalberts IPS' current portfolio. From *Figure 3.6 on page 43* it can be seen that for PowerPress, the impact in the raw materials phase is 70%, compared to an impact of 35% in the manufacturing stage.* Doubling the energy consumption makes that the manufacturing and materials stage have an equal impact. In such a case the LCA expert will need to critically evaluate the validity of the outcomes. Within the LCAs of the current portfolio, the PowerPress has a large share in the manufacturing process compared to the other products. It is therefore expected that this factor two is large enough to cover the differences in other future situations.

**Some of the materials are recycled, which means that the impacts of the material extraction steps can be omitted. This avoided impact is presented as a negative value, in this case resulting in an overall negative score for the end-of-life phase. This explains that the percentages add up to >100%.*

Great differences in recyclability are accounted for in the step 'consider recycling'. It states that if the difference in recycling percentage between two material options is more than 50 percentage points, the results of the LCA do not accurately represent reality. This number is chosen to account for the impacts of the disposal and recycling processes that are not accounted for in the current LCA calculations. It is estimated that the 50 percentage points difference covers the variation between the environmental impacts of end-of-life processes. Besides, the types of metal that are often used in the portfolio of Aalberts IPS are within the range of 50 percentage points difference to each other, see *Table 3.4*. This provides a confidence that the conclusions from the LCA favour the option that is indeed the most sustainable.

Moving from the step 'subpart alloy family' to 'subpart specific alloy', it should be evaluated if the subpart has an impact that is larger than 5% of the total impact of the product. This number is chosen because within the chosen alloy family, limited variability is expected within the chosen alloy family. Therefore, it is considered unlikely that if the alloy family is less than 5% of the total, differences between specific alloy options end up having a significant differences in the total product's environmental impact. The time that would be spent on evaluating the impacts in the next step are unlikely to provide useful insights.

3.3. Evaluation

A first version of the design tool – as presented in *Appendix F* – has been verified by presenting it to stakeholders within the company that are involved in the product development process. The changes that were made are discussed below, and incorporated into the design tool that has been presented in *Section 3.1*.

The design tool was received with an overall positive response. It provided a clear overview of what could be done during the product development process and it was appreciated that it followed the same structure of the product development process that they were already familiar with.

The first suggestion regarded the structure of the design tool in relation to the product development process. In the first version, each step of the design tool was performed in one step of the decision-making process. However, it proved more realistic to present each step along a timeframe of the development, spanning across multiple phases. The timeframe describes when the topic is first considered, and when a final decision needs to be made. This better represents the differences between the development processes of different products.

Another suggestion was to include a short manual to explain the general idea behind the design tool, how it should be used, and some additional

explanation on topics that were not immediately understood by the stakeholders during the verification sessions. Most notably, an explanation of the calculations behind the AIPS indicator was requested, as this allowed for better understanding of the results from the quick-LCAs. This guide can be found in *Appendix B*.

Next, the start and end conditions were added to the design tool. In other words, the state that is required before the design tool can be used, and the end result after performing the steps is described. Including this in the design tool makes sure that the expectations are clear before it is first used.

Furthermore, a small step was added to consider supplier options in the early development phases. That way the efforts by suppliers to produce more sustainable materials are taken into account. It is important to consider this early in the product development process, so the material properties can be verified to meet the requirements.

A suggestion that was repeatedly mentioned was to include the recycling potential in the LCAs for the material choice. That way, the comparison between materials with different material impacts and recycling potential can be fairly made. Therefore, the step 'consider recycling' was added. This accounts for situations where big differences in recyclability are present.

4 Framework

In *Chapter 3*, it has been explained how the design tool was developed for Aalberts IPS, and how it can be used to consider their environmental impact during the product development process. In this chapter, the scope of the application is broadened. It is explored how other companies can develop a design tool with the same purpose as the Aalberts IPS design tool, fitting to the company's situation. This is presented as a framework. In *Section 4.1* it is described how companies can use it. Two case studies, exemplifying the use of the framework are provided in *Section 4.2*. *Section 4.3* provides more explanation on how the framework has been developed, and in *Section 4.4* an evaluation of the validity of the framework based on the case studies is presented.

4.1. Using the framework

This section describes how companies can use the framework to develop a design tool to incorporate the sustainability concerns during the product development process. The steps that are performed to develop the design tool are explained in *Section 4.1.1*, the decision tree that is used in one of the steps of the framework is presented in *Section 4.1.2*.

4.1.1. Step-by-step-guide

This section describes the steps that are required to develop a design tool fitting for a specific company's situation. These steps are visualised in *Figure 4.1*.

The figure describes the steps involving the definition of the design tool, from analysing the LCA data, following the

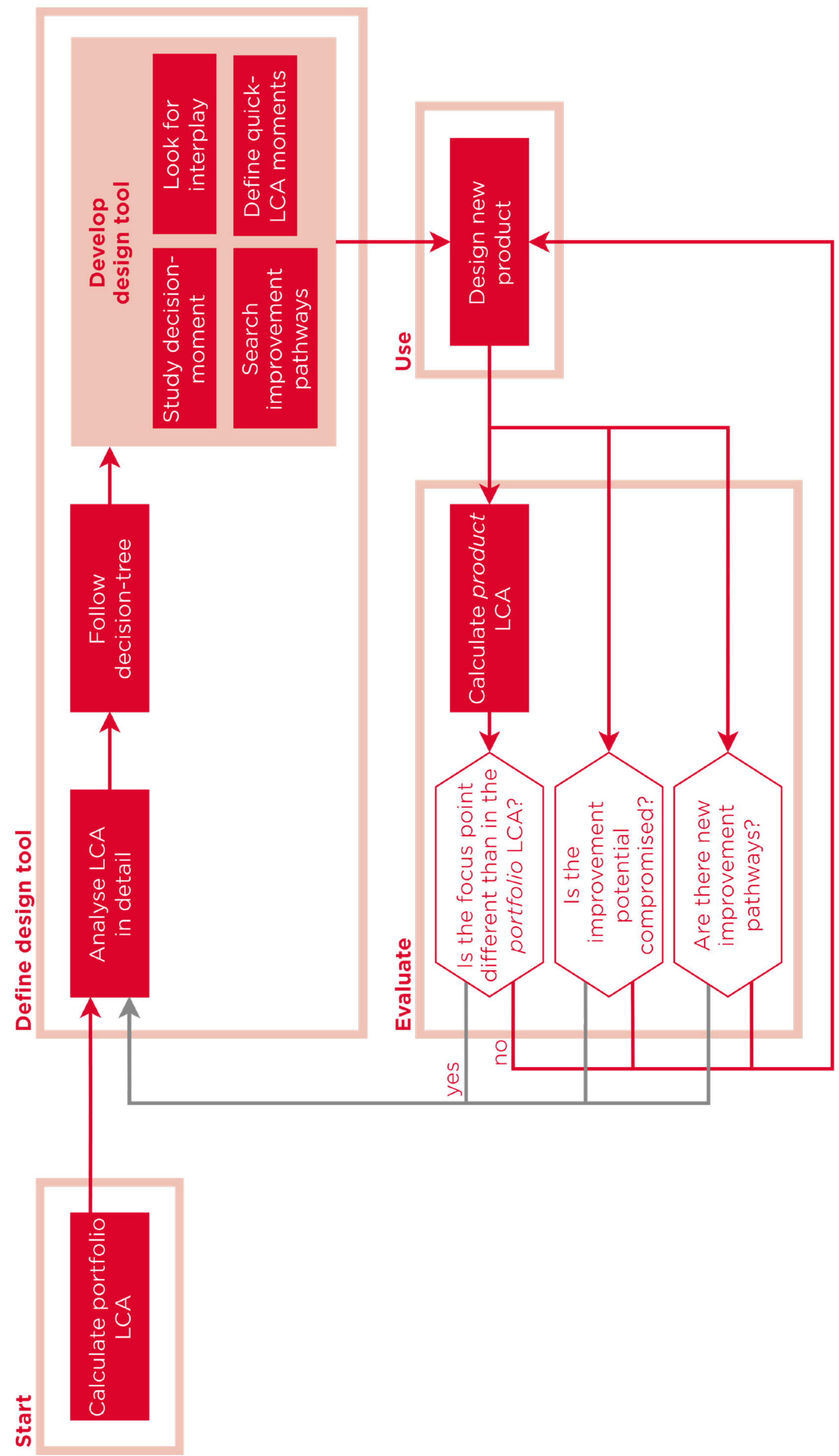


Figure 4.1. *Schematic representation of steps of developing a design tool according to the framework.*

decision tree, to developing the design tool. The design tool can then be used, resulting in new product designs being introduced to the company's portfolio. After the introduction of every new product, an evaluation takes place. It is evaluated if the majority of the environmental impact of the new product is in the same module as in previous analyses of the LCAs of the portfolio. Next, the improvement potential is analysed, and it is explored if the improvement pathways are still up-to-date.

Below, a more detailed explanation is given of the steps of development, use and evaluation of the design tool:

1. Calculate LCA-results:
    a. Determine normalisation and weighting factors: Determine what environmental indicators are relevant for the company, and how important they are compared to each other. A normalisation and weighting method can be selected based on *Box II*, or the procedure can be followed that was used to determine the normalisation and weighting factor for Aalberts IPS (*Box V*). These normalisation and weighting factors will not only be used for the quick-LCAs to develop the design tool, but also for the LCAs that take place during the product development process.
    b. Perform LCA: Complete an LCA for the entire product portfolio, or at least the product range(s) for which the design tool is made.* The LCA should be performed according to the EN 15804 norm. When calculating the results after introducing improvements to the products, make sure to only update the affected data, it is not necessary to perform a full LCA again.
    c. Calculate the weighted LCA results: Divide the outcome of the LCA of each environmental indicator by the normalisation factor, and multiply by the weighting factor. The results from all environmental indicators can then be added together into an indicator graph.
2. Analyse LCA results in detail: Determine where the most substantial impact of the analysed products is located. Also evaluate the differences between the impacts of the modules; whether there is one module that constitutes the vast majority of the impact, or if more modules contribute substantially. Next, zoom in to the module with the largest impact, to get a better idea of what impact category causes the impact.
3. Follow decision tree: Go through the questions in the decision tree (as found in *Section 4.1.2*), using the analysed LCA results. It might be necessary to revisit the detailed LCA analysis step to answer the follow-up question of the decision tree. Based on the variable with the highest impact, a suggestion for relevant design tools and recommendations for the specific situation follows.

    If the outcome of the decision tree consists solely of recommendations, the next steps do not need to be followed. In that case, the recommendations should be proposed to the relevant stakeholders within or outside of the company. After adding new products to the portfolio, it should be evaluated if a design tool could be useful for the changed situation.
4. Define design tool: In this step, the suggestions for design tools and recommendations based on the decision tree are tailored to the needs of the company. Make sure to involve the users of the design tool in its development.
    a. Study product development process: The product development process should be studied to find out how the decision that is relevant for the design tool is made. This is done following the same steps as were used in *Section 3.2.2* for the development of the AIPS design tool, answering the following questions:
        i. What structure does the product development process within the company follow? This will be used as a backbone for the design tool.
        ii. In what steps and levels of detail is the final decision made? And how are they spread over the steps of the product development process?

        If the impact is caused by a process that can in no way be influenced by the company, the company can try to broaden their influence by addressing supply chain partners. If that yields no results, the decision-tree can be followed again to select the variable that has the second-highest impact.
    b. Search improvement pathways: In what ways can the environmental impact of the relevant variable be reduced? Useful resources are academic literature, government reporting, as well as industry conventions and best practices.
    c. Look for interplay: Changes to mitigate the impact of one variable can increase the impact in another part of the product's lifecycle. Be aware of those changes affecting other modules that have a significant impact. Then describe ways to account for such interplay of decisions. This can be done by providing criteria for which the quick-LCAs are not useful, or by including the aspect into the quick-LCA. The decision tree already accounts for a selection of expected instances of interplay. However, the interplay in the studied situation might differ from the expected scenarios.

**If the product range for which the design tool is developed is not in any way similar to the products in the current portfolio, external LCAs or EPDs can be used. These can be found in EPD repositories, such as The International EPD System (n.d.), or in academic literature. A similar approach was used for the cases studies, see Section 4.1.3.*

   d. Define quick-LCA moments: Define for what steps in making the decision for the chosen variable a quick-LCA can be useful. Also specify what steps need to be taken to perform the LCA: what data should be gathered, how the quick-LCA should be performed and how the results should be interpreted.
   e. Develop design tool: For each step of the decision for the selected variable, describe how the environmental impact of the product can be reduced. Also incorporate the recommendations and quick-LCA moments into the design tool. For the latter, describe how the data should be gathered and the results should be interpreted.
5. Use: For the use of the design tool, it is important that all parties involved in the decision-making process are educated on how to use it, including the LCA expert. The product developers should know what steps they should perform and what aspects of the product should be considered. The LCA expert must be informed of what quick-LCAs are required, and what data is required for this. They will also interpret the results, not only to find what option or variable contributes most to the environmental impact, but also how reliable the outcomes of the quick-LCA study are.
6. Evaluate: After the introduction of a new product to the company's portfolio, it should be evaluated if the design tool is still aligned with the changing situation. Below, three possible reasons are listed that could require an update to the design tool. If these, or any other reason, prove the design tool to be out-of-date, the aforementioned steps will be repeated in order to develop an updated version. Instead of starting from scratch, it will be determined if the findings that were used to develop the previous design tool are still adequate or if they are in need of an update. In some cases this can mean a simple addition of a consideration to the design tool, in others the changes could be more structural.
   a. LCA-results: Perform an LCA study of the newly developed product. The data that is used for the quick-LCAs can be used as a starting point for this analysis. Compare the results to the LCA of the full portfolio. If the module with the highest impact is not consistent between the new product and the portfolio, it should be considered if the design tool requires an update. When a trend is noticed or expected that new products have the same shifted focus point, a design tool should be developed for the new focus point.
   b. Improvement potential: It should be evaluated if the improvement potential justifies the module or variable that is used as the focus of the design tool, evaluating the balance between invested resources and expected environmental benefits. If the investments no longer outweigh the outcomes, a new design tool should be developed.
   c. Improvement pathways: When advancing research presents improvement pathways that were not considered in the initial development of the design tool, these should be added to the design tool to remain at a competitive advantage. These progressing improvement pathways can be found by attending industry conventions, sharing best practices and keeping up with academic literature.

4.1.2. Decision tree

In order to develop a design tool, the decision tree as presented in *Figure 4.2* is followed as part of the framework. The decision tree poses questions that the user should be able to answer based on the LCA analysis, or in some cases some additional review within the company or of literature. This leads to a suggestion of recommendations and design tools that are applicable to the company's situation. Where design tools provide extensive guidance on procedures during the product development process, recommendations cover a narrower scope or are to be performed outside the product development process. It must be noted that the outcomes of the decision tree are intended as an inspiration of what a design tool could look like, and that further tailoring according to the step-by-step guide (*Section 4.1.1*) is essential. Further reasoning for the steps of the decision tree as well as how the decision tree was developed, can be found in *Section 4.3*.

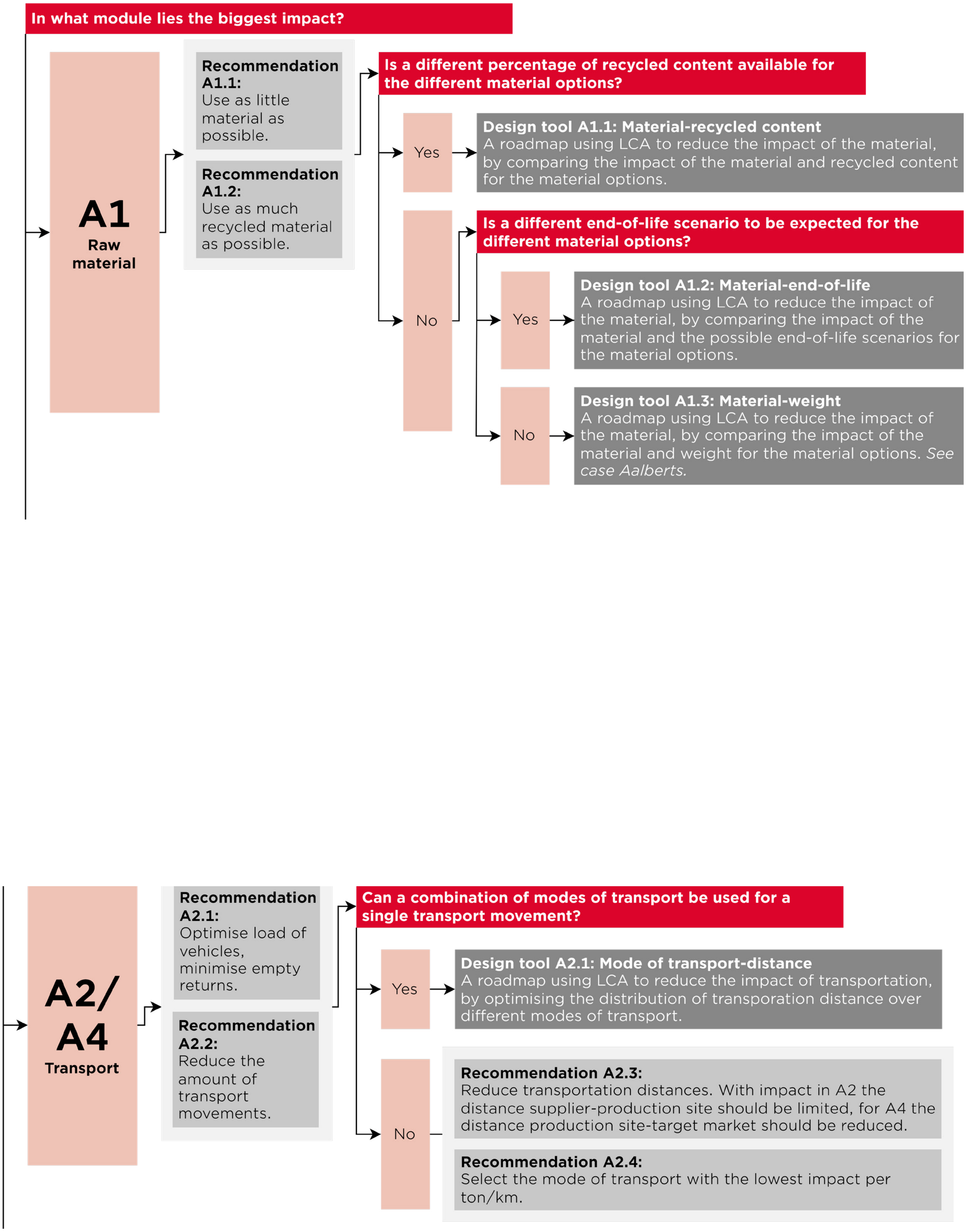
The questions in the decision tree follow the structure of the EN 15804, regarding the scope of the modules and what variables are declared within each module. It can be observed that not all modules that are part of the norm are presented within the decision tree.

Firstly, the modules of A2 (transport to gate) and A4 (transport gate to site) are combined. As both modules concern transportation steps, they are very similar. Only for the recommendation of reducing the transportation distances (Recommendation 2.3), a slightly different approach is required. This difference is explained in the decision tree.

Due to the similar nature of modules B2-5, these have also been combined in the decision tree. These modules cover the environmental impact of maintenance (B2), repair (B3), replacement (B4) and refurbishment (B5), and are all being influenced by the amount of energy and materials consumed, combined with maintenance frequency.

Lastly, modules C (end-of-life) and D (recovery) are left out entirely. The impact within both modules is largely determined by the material decision that is specified within module A1. Therefore, the consideration of recovery scenarios is added to module A1 in the decision tree.

Figure 4.2.
Decision-tree as part of the framework



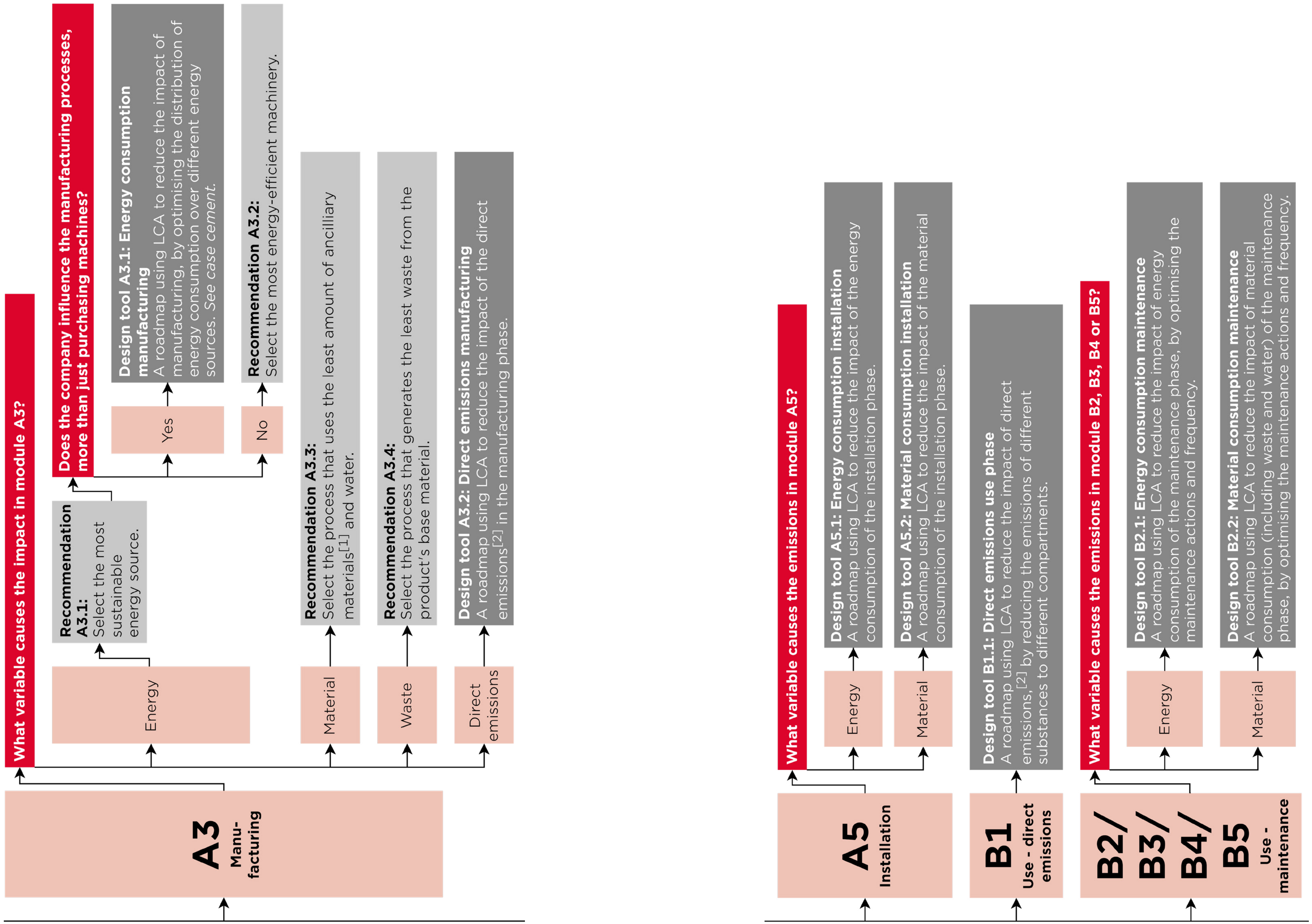


Figure 4.2. *(continued)*
Decision-tree as part of the framework

Figure 4.2. *(continued)*
Decision-tree as part of the framework

4.2. Case studies

Two case studies were conducted to demonstrate how the framework can be used to develop a design tool within a company's context. These cases were selected to represent scenarios different from the case of Aalberts IPS, with different materials and an impact in different life cycle phases. The cases of cement and LED were found to meet these criteria. In this section, a short summary of the findings of both case studies is presented. A full description of performing the steps of the framework can be found in *Appendix G*.

It is important to note that the results of the case studies may differ from what a company would achieve by following the framework themselves. Firstly, Environmental Product Declarations were used to set the scope of the cases, providing an insight into what happens between the company gates, and what is outside of the influence of the company. Given the lack of insight from the EPDs regarding the structure of the product development process and the decision-making process, assumptions were made based on the experience within Aalberts IPS. Another limitation of the current procedure is that EPDs only present in what module the impact lies, without providing any additional insights. LCAs from academic literature were used to understand what caused an impact in a module, and further details. Besides, it was decided to use the generic weighting set for Product Environmental Footprints developed by the European Union (EPLCA, 2018), as no insights were found on what impact categories the company would value most.

What must also be noticed is that the case studies were not performed by the intended user. The proposed audience is a sustainability manager of the company itself, and not the developer of the framework. Besides, the sustainability manager will have a much broader knowledge within the industry in question, where no previous knowledge was available for the current case studies. This difference in skill and knowledge means that the outcomes presented here might differ from outcomes if the steps were performed by the intended users.

For these reasons, the level of detail and the usefulness in the suggested design tools is lower than if it were developed within a company. However, they are still useful to get an understanding of what a design tool could look like in a situation other than the case study at Aalberts IPS. In *Section 4.4*, the cases are used for an evaluation of the framework.

4.2.1. Cement

The first case that was studied, is that of cement production at Aalborg Portland A/S. The cement is produced by grinding limestone and clay, which are then combined and then heated in a kiln. Next, the calcination

Figure 4.3.
Design tool for cement case

Cement

	0/1. Idea/Business case	2. Concept	3. Development
Production process	• Choose sustainable energy source [Energy sources + efficiency]	• Select equipment	• Increase thermal efficiency • Increase capacity of kiln
Product composition		• Set rough cement composition [Cement composition]	• Specify exact clinker content
External synergies	• Look for symbiosis possibilities	• Work out symbiosis	

LCAs

Energy sources + efficiency

- Gather data
    - Define energy sources
    - Define efficiency
- Perform LCA
- Analyse results
    - How do benefits alternative fuels weigh up to loss in efficiency, and other trade-offs?

Cement composition

- Gather data
    - Specify clinker types
    - Specify composition
- Perform LCA
- Analyse results
    - What clinker composition has the lowest impact?
    - What clinker type has the highest relative impact?

LED

	0/1. Idea/Business case	2. Concept	3. Development
LSE	• Research technological improvements LED lights and drivers	• Select efficient LED & driver	• Design electronic circuit
LAE	• Define lighted area • Define optimal intensity & spectrum range	• Design intensity control system	
Lifespan		• Define lifespan [Lifespan-energy consumption]	

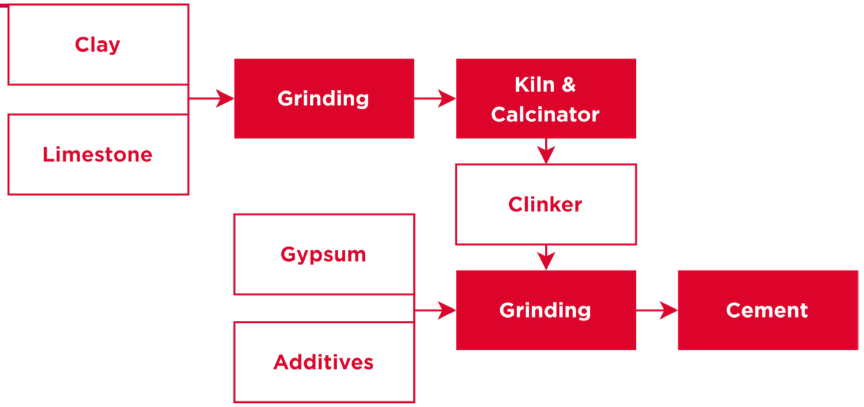
LCAs

Lifespan-energy consumption

- Gather data
    - Define efficiency of original and replacement product
    - Define impact of production steps (modules A1-A5)
- Perform LCA
- Analyse results
    - Is it better to replace the product early?

Figure 4.4.
Design tool for LED case

Figure 4.5. *Flowchart of cement production. Adapted from Sjunnesson (2005)*



process begins which takes place in a second kiln, where carbon dioxide is released from the limestone to produce clinker. This clinker is then ground together with gypsum and other additives to form cement. These steps are visualised in *Figure 4.3*. The cement is one of the main ingredients for concrete production, but this is out of scope for the current case study.

The EPD by Aalborg Portland A/S (2023) shows that the majority of the impact lies within the manufacturing phase (A3), which is mostly caused by the ecotoxicity (60%) and climate change (29%) impact categories. Studies by Feiz et al. (2015), García-Gusano et al. (2014) and Sjunnesson (2005) indicate that most of the climate change impact is caused by the direct emissions from the calcination step (~60%), and the combustion of fuel during the same process (~30%). The impacts in the ecotoxicity category are inconclusive, as Ige et al. (2022) attributes a majority of these impacts to the raw materials phase, contradicting the EPD where a majority of the ecotoxicity is caused in the manufacturing process.

For the design tool, the impacts from the climate change impact category were used, as no conclusive explanation could be found for the impacts in the ecotoxicity category. Besides, the climate change category is very relevant to consider due to the large share of the global climate change effects that can be attributed to the concrete industry (IEA, 2018). If custom weighting factors would have been made for the cement scenario, it is likely that the climate change effects would become more relevant than the eco-toxicity effects.

This means that the focus of the design tool was determined by the module that has the largest impact on the climate change impact category. As discussed previously, the majority of the impact is caused by the direct emissions of the calcination step, followed by its energy consumption. However, as no feasible improvements can be made to reduce the direct emissions from the calcination step (Feiz, 2016; Schneider, 2015), the focus has been chosen to be the energy consumption of the calcination step.

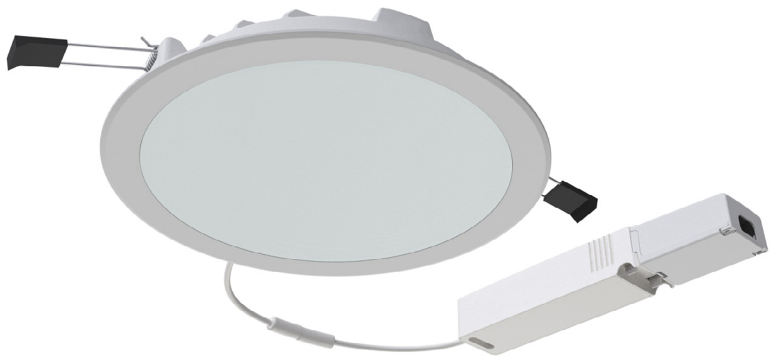


Figure 4.6. *Planar LED Downlight by Trilux GmbH & Co (TRILUX GmbH & Co, 2023)*

Using this focus point as input for the decision tree yielded a recommendation regarding energy type, as well as a design tool to reduce the energy consumption.

Figure 4.4 shows the design tool that was developed for the case of cement, highlighting the three improvement pathways that were found in Feiz (2016), IEA (2018) and Schneider (2015): production process, product composition and external synergies. The production process is defined in three steps, choosing a sustainable energy source using LCA, selecting equipment and then defining the production process in detail. The product composition is defined by roughly outlining the desired clinker composition using LCA, and then specifying it in more detail in the next step. The external synergies are defined by a general search for possibilities and then working those out in more detail with the involved stakeholders in the next step of the product development process. The steps to perform both LCAs, from data gathering to analysing the results, are discussed on the right side of the figure.

4.2.2. LED luminaire

Next, the case of the planar LED downlight by TRILUX GmbH & Co was studied, as shown in *Figure 4.6*. Within the scope of the company, the materials are sourced for the electronic and structural components, as well as the packaging. In the production facility, the circuit board is assembled, as well as the entire lamp. During the use phase, electricity is used to fulfil its function of providing light. In between, transportation steps take place, and at the end of the useful life, the metal, plastics and electronic parts are recycled.

The EPD (TRILUX GmbH & Co, 2023) presents the environmental impact of the LED luminaire, showing an overwhelming majority of impact in the operation energy use (B6) module. This module has the largest impact across all modules, with on average 96% of the total product's impact. This corresponds with the results of other studies (Casamayor et al., 2017;

Principi & Fioretti, 2014; Wang et al., 2020), clarifying that the operational energy use is caused by the electricity consumption.

The above analysis was able to answer the first question in the decision tree. The second question regarding the (relative) performance of the lamp required additional research. It was found that a LED's lumen efficiency is known to degrade over its lifespan (Lumileds, 2016), and its relative efficiency degrades as efficiencies in new LED technologies are still increasing (Pattison et al., 2022).

Answering both questions in the decision tree, a design tool was developed that inquires the optimal balance between lifespan and energy consumption during the use phase.

The design tool for the LED case is shown in *Figure 4.5*. Again, three improvement pathways are shown, namely Light Source Efficiency (LSE), Light Application Efficiency (LAE) and lifespan (Pattison et al., 2022; Richter et al., 2019). Each are worked out in the different phases of the product development process. For LSE, first the available LED and driver technologies are researched, then an appropriate technology is selected, which is then combined into an electronic circuit. The LAE is defined by first stating the desired lighted area and intensity, after which the control system is developed. The lifespan is defined with help of an LCA in the conceptual phase. The steps to perform this LCA are described in the right part of the figure.

4.3. Developing the framework

In this section it is described how the framework that is presented in *Section 4.1* was developed. First, the steps that were taken to develop the design tool at Aalberts IPS are evaluated (*Section 4.3.1*) and it is considered how situations might differ from the one previously analysed and what that would mean for the outline of a design tool (*Section 4.3.2*). This yielded an overview of different scenarios that are considered within the scope, and what design tools or recommendations would be suitable (Appendix H). Next, a decision tree was developed to allow for easy understanding of what would be suitable for the situation at a company (*Section 4.3.3*). Then the step-by-step guide was developed, presenting how to tailor the design tool and recommendations that follow from the decision tree to the company's situation (*Section 4.3.4*).

4.3.1. Steps for developing design tool Aalberts IPS

The steps that were taken to develop the design tool for Aalberts IPS were used as a starting point for developing the framework. The procedure of developing the design tool offered insight into what the general process would look like for other situations. Additionally, knowing what aspects were studied for the situation at Aalberts IPS provided an indication of how these inputs might change for different scenarios. Below, a short overview is presented of the development of the design tool, based on what is presented in *Section 3.2*. For each step it was evaluated how this influenced the outcome and what is most relevant to consider in scenarios other than Aalberts IPS.

The first step that was taken to develop the design tool at Aalberts IPS was to consider the LCA data and expertise within the company. This was done to get familiar with the company and the context of the problem they are facing. The findings of this step are used to define the boundaries of the scope that is considered within the research, meaning that these aspects should be considered before using the framework. Therefore, this step will be excluded from the process of developing a design tool for a specific company.

Next, the product development process at AIPS was evaluated, considering the general phases of the product development process, as well as how each decision is made. This allowed the design tool to be developed in synergy with the current product development process, making it easier to implement. It could be concluded that the insights about the product development process mostly changed the structure of the design tool. This must therefore be considered in the later stages, after defining the topic of the design tool.

Lastly, the results from the LCAs that were performed for EPD reporting were studied in detail. From this, it could be concluded what causes the total environmental impact of the product, and therefore, where efforts for product improvements are most likely to result in a more sustainable product.

4.3.2. Determining possible scenarios for design tools

As differences in LCA results would require substantially different design tools, and because of the lacking knowledge with regard to sustainability within companies, an evaluation was performed on what design tools would need to look like for the different outcomes. The structure of the EN 15804 standard as defined by CEN (2019) has been used to systematically evaluate the different outcomes.* For each module (or lifecycle phase) and variable that needs to be declared within the modules, it was evaluated what a scenario would look like to have the largest impact there. The EPD repository (The International EPD System, n.d.) has been scanned for inspiration for the different scenarios. Two of the EPDs that were found, were worked out into the case studies that are discussed in *Section 4.2*.

The analysis yielded an extensive overview of scenarios that are covered within the scope of the framework, which is presented in *Appendix H*.

** A more detailed explanation of the EN 15804 standard can be found in Section 2.3. An overview of the modules is provided in Figure 2.2 on page 27.*

For each module and variable it is described what a possible design tool would look like for that situation. It was found that for some situations, the variable would only be relevant to consider in relation to other variables due to interplay. Additionally, it was found that not for all cases a design tool similar to the one presented for Aalberts IPS would be useful. In cases where the variable is defined outside the control of the company, no design tool would be useful, where for cases where the variable is defined outside of or in merely one step of the product development process, a recommendation would suffice.

4.3.3. Developing the decision tree

The overview of possible design tools and recommendations based on where the impact of the products lies, is already a great resource. However, it is not yet intuitive for companies to know what design tool will be suitable for their situation. To address this issue, a decision tree was developed. By responding to the questions, companies will be guided towards the most suitable design tool or recommendation for their unique circumstances. The decision tree is shown in *Figure 4.2 on page 60*.

The questions in the decision tree largely follow the structure of modules and variables that are used earlier, but in some cases another question was required. To address this, other indicators were evaluated that define if a design tool would be suitable for the situation. Based on both attributes, the questions in the decision tree were formulated.

It must be noted that the process of developing the decision tree is substantiated to a limited extent. A thorough examination of the limitations and validity of the decision tree is presented in *Section 5.2.3*.

4.3.4. Describing the step-by-step process

Based on the decision tree alone, companies would not be able to develop a suitable design tool. Analysis steps need to be performed before the decision tree can be followed, to formulate answers to the questions posed. Additionally, further analysis and synthesis steps are required to turn the proposed design tool resulting from the decision tree into one that is fully tailored to the company's situation. The steps that are formulated are described in the step-by-step guide that can be found in *Section 4.1.1*.

These steps are largely based on the steps that were taken to develop the design tool for Aalberts IPS. First the LCA is analysed, of which the results are used to answer the questions in the decision tree. Having found a suggested design tool or recommendation, the product development process is evaluated and improvement potentials are explored in other sources. It was then also described what needs to be considered during the use of the design tool, and how it can be evaluated whether the design tool continues to fit the changing situation as time passes.

4.4. Evaluation

The evaluation of the framework for design tool development entails an analysis of its practical implementation within different industrial contexts. This is done by examining the process of developing the design tools for the cases of Aalberts IPS, cement and LED. This evaluation aims to provide a nuanced understanding of the framework's versatility and effectiveness. The design tools for the cases of cement and LED have been previously addressed in *Section 4.2*, exemplifying how the framework can be used and what outcomes it can yield. The design tool for Aalberts IPS is presented in *Chapter 3*, which inspired the structure of the framework. The steps of the framework are applied to the Aalberts IPS case to examine if the design tool could be improved after the more general insights from the development of the framework. An extensive description of following the steps presented in the framework for all three cases can be found in *Appendix G*.

It is important to acknowledge the potential influence of confirmation bias within the scope of this evaluation, resulting from the use of the three cases in the development of the framework. Therefore, the findings of this evaluation should be treated with caution. More extensive testing is required to provide comprehensive conclusions. It is also important to note that the evaluation performed in the current section is of a more theoretical nature than the evaluation that was performed on the Aalberts IPS design tool as discussed in *Section 3.3*. Nonetheless, this evaluation provides valuable insights into the use and comprehensiveness of the framework.

Comparison outcomes of framework

In all three cases, the framework enabled the development of a valuable design tool. The steps described in the framework are easy to follow to develop a useful design tool. All three design tools provide the product development team an accessible guide to incorporate the environmental impact of the products during the product development process.

For the case study of Aalberts IPS, a different approach was used than for the study of the cases of cement and LED. The situation at Aalberts IPS was studied with access to internal documents and data, as well as the expertise on the technology that is developed. This was not the case for the cases of cement and LED, leaving only publicly available information from EPD repositories and academic literature to be used. None of the design tools were developed by the intended audience of sustainability officers. This has resulted in differences in the outcome of the design tools, and suggests that the design tools presented in the report could be different from in-practice results.

Most notably, the level of detail of the steps in the decision-making process differ between the cases of cement and LED compared to the case of Aalberts IPS. Where for the design tool for Aalberts IPS, the material decision could be split up into the decisions for the main body and the subparts on the detail levels of alloy family and specific alloy, no such distinction could be made for the cases of cement and LED.

Dismissal outcome of decision tree
It was found for two of the three cases it was possible to dismiss the outcome of the decision tree. For the case of cement, the design tool was developed for the energy consumption of the manufacturing stage instead of the direct emissions of the same phase because no feasible technology was available to reduce the impact of the latter. Similarly, the design tool for Aalberts IPS was developed according to the material-weight design tool suggested in the decision tree, despite expecting different percentages of recycled content and recycling scenarios (see *Figure 3.1 and 3.2 on pages 32 and 34, respectively*).

Even though sound reasoning could be provided to dismiss the outcome of the decision tree in both cases, this requires a reflection on the significance of using the decision tree. If the outcomes of the decision tree could be consistently regarded as 'too difficult' to incorporate into the design process, only a fraction of the environmental impact reduction can be achieved. Besides, it could be argued that the selected design tool from the decision tree could be a mere projection of the practitioner's preset intention.

However, despite the possibility to dismiss decision tree outcomes, the decision tree provides meaningful contributions to tailoring a design tool for a company's situation. Even when eventually another design tool is selected from the decision tree, the practitioner is forced to consider the original decision tree outcome and how it could benefit the company's product design. Whenever the ambition within the organisation changes, the design tool can then be updated to be in line with the earlier decision tree outcome. This way, the use of the framework remains accessible for a wide range of companies, which can result in a greater overall reduction of environmental impact compared to an inaccessible method that can provide greater individual improvements.

Decision tree and improvement pathways
The improvement pathways that are integrated into the design tools for the cement and LED case cover a broader scope than was suggested in the outcomes from the decision tree. Therefore, it could be argued that the step 'search improvement pathways' is more useful than the decision tree.

However, as stated previously, the case studies for the cement and LED case were performed in a structurally different way than would be the case in practice. For the cement and LED case, a very thorough literature

review was performed that presented the improvement pathways. For the Aalberts IPS case, the initial development of the design tool was done based on pre-existing expertise within the company. When following the steps of the framework for the latter case, the step 'search improvement pathways' yielded limited additional insights. As the case of Aalberts is more likely to be representable for the use of the framework in practice, the outcomes of the decision tree will continue to prove useful. In conclusion, the thorough improvement pathways that were found for the cases of cement and LED make these design tools more valuable, but do not mean the decision tree is less valuable.

5 Concluding

This chapter concludes the thesis. It does so by first comparing the outcomes of the thesis to the current literature, and how it complements the available studies in *Section 5.1*. Next, a critical reflection is performed of the quality and limitations of the outcomes, as discussed in *Section 5.2*. *Section 5.3* considers whether the scope as defined in *Section 1.4* remains true for the design tool and framework as presented in the previous chapters. Throughout *Sections 5.2* and *5.3*, recommendations are proposed based on the points of reflection. Additionally, in *Section 5.4* some general recommendations are described. The conclusion of the research is presented in *Section 5.5*.

5.1. Reflection

This section discusses how the results from this thesis cover the gap in literature that is presented in the problem definition (*Section 1.1*). It provides an insight into how the current work fits within the available research and how it complements these studies. Additionally, it is discussed how the outcome answers the research question posed in *Section 1.3*.

Literature indicates that the greatest environmental improvements can be achieved when the environmental impact of the product is considered in the early product development phases (Bhander et al., 2003; Hetherington et al., 2013; Vinodh & Rathod, 2010). This corresponds to the conclusion in *Table 3.2 on page 44* that the decisions in later stages of the product development process are of such a high level of detail that changes to the environmental impact of the product would be negligible. The design tool for Aalberts IPS therefore focusses on the earliest phases, from ideation to development. A focus on the earlier phases of the product development process is less pronounced in the framework. In the step-by-step guide, the structure of the product development process is evaluated as well as where in the product development process the relevant decisions are made. This will be used to inform for what phases the design tool will be used. It is likely that this will result in the same focus on the earlier design phases, as also exemplified in the cases of cement and LED.

Additionally, literature suggests that retrospective LCAs, assessing the impact of products that are already in use, can be used in the earliest phases when the product design has not been defined yet (Millet et al., 2007; Roberts et al., 2020). In the design tool and framework, the use of the retrospective LCA is placed before the earliest design phases. The retrospective LCA from EPD reporting is used in the development of the design tool, which takes place before the product development starts. Incorporating the analysis of the retrospective LCA into the design tool that can be used for multiple products, reduces the overall workload. The evaluation of the retrospective LCA allows for capitalising the opportunity that the LCA data from EPD reporting provides.

Furthermore, it was found in literature that simplified prospective LCAs can be used during the concept development phases to evaluate the environmental impact of options under consideration. This is incorporated into the design tool for Aalberts IPS and the framework by means of the quick-LCAs. In multiple stages during the product development process, the options under consideration can be compared by means of a simplified LCA. The quick-LCAs suggested for the Aalberts IPS design tool are very similar to the case study presented in Roberts et al. (2022), solely focussing on the environmental impact of materials, neglecting any possible differences in other lifecycle phases. For the quick-LCAs the LCA expertise acquired from EPD reporting can be used for sustainable product development.

The knowledge barrier that was found to hinder the adoption of sustainable product development in businesses, is addressed by the design tool and framework. The design tool developed for Aalberts IPS greatly complements the product developers' knowledge on product development, and bridges their gap in knowledge on sustainability matters by providing concise guidance on how to incorporate the environmental concerns into the product design. The structured nature, following the current product development process at Aalberts IPS, facilitates easy adoption. The framework is intended for the sustainability managers, which have a greater understanding of the topic of sustainability but struggle to implement changes into the product development process. The step-by-step guide provides a comprehensive overview of what aspects of the company context need to be considered and how this can be translated into a valuable design tool. The decision tree serves as inspiration to define what the design tool could look like in their situation.

All in all, the outcomes of the current thesis are in line with the available literature and complement it by providing practical guidance within companies. Its value lies in gapping the knowledge barrier that companies face in implementing sustainable product development by the structured nature of the design tool and framework.

5.2. Limitations

In this section, a critical review is performed of the quality and limitations of the outcomes of the research. It is evaluated how the assumptions that were made influence the results of the research, and in what ways the outcomes might be compromised. Firstly, some comments are made about the research in general (*Section 5.2.1*), then the design tool (*Section 5.2.2*) and framework (*Section 5.2.3*) are reflected on separately.

5.2.1. General

First, an overarching reflection of the limitations is performed, regarding the uncertainty within Life Cycle Assessments.

Uncertainty in LCA

For all LCA studies, uncertainty is important to consider. In each step of performing a Life Cycle Assessment, choices are made that affect the overall reliability of the outcomes. It is affected by the type of the data that is used and the tests that are performed to gather the data, but also generalisations and imperfections that are made in the modelling process (Heijungs & Huijbregts, 2004).

Additional care must be taken with evaluating the outcomes of prospective LCAs. Their conclusions are inevitably less reliable than the conclusions from retrospective LCAs due to their forecasting nature (Herrmann et al., 2014). This is addressed by a critical review of the results from the prospective quick-LCAs by the LCA expert that performs the study. Whenever the uncertainty is too high or the results are too close, the results are deemed unusable.

The simplified nature of the quick-LCA presents another uncertainty. The quick-LCA only focuses on one aspect of the product's lifecycle, introducing the possibility that the parts of the product that are left out of consideration would change its conclusion. However, the focus point is chosen based on LCAs of the full portfolio, ensuring a confidence that the quick-LCA results reflect reality. Additionally, in the Aalberts IPS design tool, differences in the manufacturing process and recycling rates are indirectly covered by the steps 'consider processes' and 'consider recycling'.

5.2.2. Design tool

In this section the validity of the design tool that was developed for Aalberts Integrated Piping Systems and its limitations are discussed. *Section 3.3* describes the evaluation step that has been performed and the improvements to the design tool that have been made based on this. From the evaluation step it could be concluded that the design tool provides a clear insight into the environmental impact of the products, and could be easily understood in congruence with the current product development process.

However, some limitations of the validity of the design tool remain. These will be discussed below, starting with the uncertainty that is represented within the values that are chosen for cut-off criteria, next the inclusion of recycling scenarios is discussed and lastly the comprehensiveness of the Ecochain software and EcoInvent database.

Subjective values

In three instances in the design tool, a factor defines how to proceed. This is the case for the difference of a factor two between estimated energy consumption of material options for the step 'consider processes', the difference in recycling percentages of over 50 percentage points in the step 'consider recycling', and lastly for moving from the subpart alloy family step to the definition of the specific alloy where the impact of the subpart needs to be above 5% of the total impact. Where an effort is made to substantiate the assumptions – as is discussed in *Section 3.2.4* – further testing is required to evaluate the validity of these values.

> Recommendation: Critically evaluate the validity of the cut-off values for the steps 'consider processes', 'consider recycling' and 'moving from subpart alloy family to specific alloy' before using the tool. These tests should provide insight in the variance in the aspects that are left out of consideration, e.g. the environmental impacts of the options for manufacturing processes that are defined by the material choice. This insight in the variance can then be used to evaluate if the selected values account for the variance.

Recycling in LCA calculations

The recyclability of different material options is currently incorporated into the design tool in the step 'consider recycling', which only covers situations where a big difference in recyclability exists between options. Incorporating the recyclability of the material options in the LCA analysis could provide more detailed insights about the differences between material impact and recyclability. Where uncertainty is inherently present in the definition of the end-of-life phase, due to its forecasting nature and the lack of influence of the company in traditional end-of-life scenarios, the accumulation of the uncertainties in the current case deems the results from an analysis too far from reality.

This uncertainty is caused firstly by the lack of consensus over recycling percentages of metals. The data that can be found is of varying quality and differs per region (Graedel et al., 2011), and only represents the recycling percentages on element (e.g. iron, zinc) level instead of representing differences between alloys (e.g. carbon steel, brass).

Additionally, there is a limited availability of disposal and recovery scenarios in Ecochain. Not for every material option that is specified in the material extraction phase, a corresponding end-of-life scenario can be found. This means that the differences in impact between the material types are not accurately represented.

It is explored if the recovery potential could be calculated outside of the LCA software, by presenting the material impacts compensated for the recycling percentage. That way, only the portion of the material impact that is not recycled is attributed to the current product. However, as the environmental impacts of disposal and recovery processes are not covered, the conclusions from the calculations have a high possibility of being incorrect. In order to still account for large differences in recyclability, the step 'consider recycling' was added.

> Recommendation: In cases with more insight into the recycling percentages, and which are represented in the Ecochain software, it is valuable to consider adding the end-of-life scenarios in the material quick-LCAs.

EcoInvent database
Ecochain is used for the LCAs within Aalberts IPS, which makes use of the EcoInvent database. Where this software program and its selected databases are well-suited for performing LCA to evaluate the general impacts after completion of the product, they are less fit for the purposes that are described in the design tool.

Firstly, the quick-LCAs for specific alloys require a level of detail that is not well accounted for in the databases. In typical use of the software, the database entry representing the alloy closest to the one in question is selected. For the alloy LCAs however, the alloy is built up from the individual elements. This yields less reliable results, firstly because the environmental effects of the alloying process are not accounted for. Secondly, the database does not contain accurate references for all the separate alloying elements. This should be considered while assessing the validity of the results from the quick-LCA study.

Secondly, as discussed previously, the end-of-life scenarios for the desired materials are not adequately covered in the EcoInvent database used in Ecochain. This leads to the recovery rate not being covered in the quick-LCAs, but also distorts the products' results in the portfolio LCA.

> Recommendation: As the databases presented in Ecochain are constantly updated and expanded, it should be regularly reviewed if the missing database entries have been added. Additionally, it is recommended to inquire the possibilities of accessing a broader database with the Ecochain support.

5.2.3. Framework

A reflection of the limitations of the framework is described below. It is discussed what the selection of modules for the decision tree means for the validity of the framework, as well as the outcome of merely recommendations. Lastly, a critical reflection is performed of the procedures of the development of the decision tree. Additional remarks on the validity of the framework can be found in *Section 4.4*, where an evaluation is performed based on case-studies.

Selection of modules for the decision tree
For some modules it is more likely that the highest environmental impact lies within that module than for others. After a quick scan through the Environmental Product Declaration repository (The International EPD System, n.d.), it was found that for most EPDs the module with the highest impact was the material extraction phase, followed by the manufacturing phase. Cases where the impact lies mostly in another module were hardly found. Upon further consideration, it is also regarded that for some modules it is unlikely that the highest impact lies there. For instance for the transportation or installation steps, which typically only make up a small part of the supply chain. Besides, products with a relatively high impact in the transportation step are likely to also have large transportation costs, which often results in companies moving the production closer to the user.

These modules are not excluded from the decision tree, despite the unlikeliness that the largest impact is represented there. Only modules C and D are excluded – as is explained in *Section 4.1.2* – because of the interdependency of the decisions made in A1, C and D. All other modules are included because there could always be a case where these modules have the highest environmental impact, however implausible. Besides, there are instances where a design tool is developed for a variable that does not have the highest impact. In that case, it becomes more likely that the transport and installation modules are considered.

Only recommendations from decision tree
For some scenarios, the only outcomes of the decision tree are recommendations. In that case, no design tool is developed, but instead it is suggested to propose the recommendations to the relevant stakeholders, within or outside of the company. Lacking the structure of the design tool, the outcome of using the recommendations is expected to be less effective. However, the recommendations still provide a possible solution to reduce the impact in a certain module and variable. It provides

valuable insight for companies that struggle to start reducing their products' environmental footprint.

Development of decision tree

The development of the decision tree relies on case-studies and thought experiments, as is discussed in *Section 4.3*. A non-comprehensive set of case-studies is considered, for Aalberts IPS, cement and LED. The remaining scenarios that are covered in the decision tree are based on thought experiments, considering what a scenario would look like if the majority of the environmental impact would be in a certain lifecycle phase. The reliance on case-studies inflicts a bias, and the thought experiments result in an uncertainty as the scenarios are fictional. This reduces the validity of the decision tree.

An example of the bias inflicted by the case-studies is the judgement about the energy source, as can be found in the table in *Appendix H*. It is stated that this decision is not complex and happens outside of the product development process. However, this is based on the situation at Aalberts IPS, where the option for energy source are grey or green electricity. In that case, switching the energy source solely implies finding an energy electricity and signing a contract. For other cases, such as a switch from a coal-powered to an electricity-powered kiln, the process is more complex. Here it also entails changes to the machinery and infrastructure.

This bias and uncertainty, combined with other concerns regarding the value of the decision tree as expressed in *Section 4.4* and the current section implies the need of a critical reflection. As the decision tree serves the purpose of inspiring sustainability managers and providing an insight of what a design tool could look like in their company context, it is of limited concern that the procedures are not thoroughly substantiated. The further steps described in *Section 4.1.1* provide enough guidance to the company to adapt the proposed design tool to their company needs. As found from performing the case-studies of cement and LED, the step 'search improvement pathways' could in that case compromise for the flawed judgement incorporated into the decision tree (see *Section 4.4*). The decision tree therefore still provides valuable insights as it can be used to inspire sustainability managers, but the following steps in the step-by-step guide remain crucial to tailor the design tool to the company context.

Aside from informing the decision tree, the case-studies and thought experiments informed the step-by-step guide. It is necessary to evaluate the validity of this guide based on the statements made regarding the decision tree. Firstly, it can be stated that the structure of the process for developing a framework is substantiated in literature, which is discussed in detail in *Section 5.1*. The instances where LCA data and expertise can be used during the product development are based on the suggestions by Millet et al. (2007) and Roberts et al. (2020). Additionally, the case-studies and thought experiments only informed the step-by-step guide by means of providing a general insight into the possible range of scenarios it needs to cover. Where the individual scenarios might be different if a more comprehensive range of cases is considered, the range of scenarios is expected to remain unchanged. These reasons provide a confidence that the step-by-step guide is still a valuable and useful tool for implementation of sustainable product development.

> Recommendation: Further substantiate the decision tree by performing a more detailed analysis of the scenarios within scope. For each life cycle phase, multiple case-studies must be performed to cover the full range of companies within the construction products industry. Such further analysis would allow for an extended use of the decision tree aside the current purpose of inspiring sustainability managers.

5.3. Boundaries

In the scope it is defined what companies can use the outcomes of the research, and what companies are outside the thesis' boundaries. The current section will examine whether the scope as defined in *Section 1.4* remains true and discusses for what situations outside the defined scope the outcomes could be of use as well.

The framework is made specifically to help companies that have performed LCA for EPD reporting according to the EN 15804 standard. As the structure of the decision tree follows the structure of the standard, it is unclear whether the results of LCAs performed following Product Category Rules other than EN 15804 can be used.

> Recommendation: Evaluate the validity of the framework for companies that are performing LCAs without using the EN 15804 standard. The differences between Product Category Rules (PCR) for performing an EPD should be studied, in order to conclude if the suggested framework applies for companies that use another PCR.

The next requirement for using the framework is the presence of LCA expertise within the company. For the development and use of the design tool, an LCA of precedent data is required, as well as performing LCAs during the use of the design tool. Where the first instance could easily be outsourced, this is more difficult for the quick-LCAs during product development. Where it is possible to outsource all the quick-LCAs, this is likely to result in high costs. Another possibility is to educate someone to specifically perform the steps of the quick-LCA without a general understanding of the theory of LCA. The steps for performing a quick-LCA are relatively simple, but not knowing the theory increases the risk of mistakes and misinterpretation. Therefore, it can be concluded that the requirement of in-house LCA expertise remains true for companies using this study.

In the step-by-step guide it is stated that if the to-be-developed product is in no way similar to the products in the current portfolio of the company, external LCAs can be used to provide insight into the expected environmental impacts. Using external LCAs extends the scope of the thesis to companies that do have internal knowledge on LCA but have not yet performed LCAs for EPD, for example start-ups.

Lastly, it is defined that the research is specifically aimed at new product introductions, as opposed to redesigns or small product improvements. For redesigns or product improvements, there is a clear reference point for the environmental impact of the product. This indicates a clear benefit from the LCAs performed for EPD reporting. However, the product development process for a redesign or improvement is different than for NPI. Not every decision is considered for the redesign or improvement, which could mean that the variable with the highest environmental impact is left out of consideration. The outcomes of the research can still be used for those situations, depending on what will be considered during the redesign.

> Recommendation: It should be further evaluated to what extent the design tool is useful for cases where a product is redesigned or small improvements are made. Further examination is required of how the product development process differs from new product introductions to redesigns and product improvements.

5.4. Recommendations

Apart from the recommendations that are already discussed throughout the reflection and limitation sections (*5.1* and *5.2* respectively), some general recommendations can be made. These are presented below.

Verify outcome of using the design tool
Where the usability of the design tool has been evaluated by asking involved stakeholders for improvements, its actual use has not been studied. This could point out different improvements that could be made to the design tool. Besides, it would be interesting to consider whether using the design tool will actually result in more sustainable product design. A study could be performed where a product is designed using the traditional methods, of which the outcomes will be compared to using the design tool.

Verify framework for other cases
An evaluation of the framework is performed based on the cases of cement, LED and the case at Aalberts IPS, as is presented in *Section 4.4*. In *Section 5.2.3* the limitations of the procedure of developing the decision tree are discussed, from which the recommendation to study more cases follows. These additional studies will not only increase the validity and usefulness of the decision tree, but also provide additional insight into the value of the framework. Besides, it will ensure that the framework is suitable for the full range of companies that are included in the scope.

Additionally, the verification step discussed in Section 4.4 is not performed by the intended audience. The difference in knowledge on LCA and sustainability between the author and sustainability managers within firms likely influenced the outcomes of using the framework. Therefore, further testing is required to determine if the sustainability managers fully understand how to use the framework, and are able to develop a valuable design tool.

5.5. Conclusion

Companies are increasingly recognising their role in mitigating climate change effects and are performing Life Cycle Analysis (LCA) for Environmental Product Declarations (EPD) to get an insight in the environmental impact of their products. Where this data and expertise provides great opportunity for companies to reduce their environmental impact, they face challenges to incorporate it into their product development process.

The first step of the research was a review of the current practices of Life Cycle Assessment and sustainable product development. It could be concluded that the greatest improvements of a products' environmental impact can be achieved when LCAs of available products and a simplified LCA are used in the earlier stages of the product development process. The LCA of the portfolio of Aalberts IPS revealed a large impact of the material decision on the environmental impact, thus defining the focus of the proposed solution. These findings, combined with the analysis of the product development process within Aalberts IPS and the sustainability targets were then used to develop a design tool.

This design tool for Aalberts IPS suggests how the environmental aspect can be considered for every step of the definition of the material decision. Recommendations are presented alongside instances where simplified LCAs can be used. Where the recommendations cover a broad scope, the LCAs allow for specific comparison of options. Together they provide structured and comprehensive guidance for incorporating the environmental dimension of products during their development. The recommendations and LCAs are presented following the structure of the product development process that is currently used, facilitating easy adoption of the design tool because of its familiarity.

The steps that were taken to develop the design tool for Aalberts IPS served as a starting point for the development of a framework that allows companies in the broader context of the construction products industry to develop a design tool for the purposes of sustainable product development. Expanding on the case of Aalberts IPS, it was evaluated what differences in context are covered in the scope of the construction products industry, and what a design tool would need to look like to establish practical value in a variety of contexts.

Within the framework, a comprehensive outline of steps is presented that need to be performed in order to develop a design tool fit for a company's situation. It covers the analysis of the context after which the decision tree can be followed for a suggestion of what the design tool will focus on. Next, steps are proposed to fully define the design tool.

The framework allows companies to seize the opportunity that performing Life Cycle Analysis for Environmental Product Declaration reporting provides. The structured nature of the framework reduces the likelihood of overlooking important components and ensures easy operation. The knowledge and theory that are used to develop the framework allows users without extensive knowledge on the topic of sustainable development or Life Cycle Assessment to develop a structured design tool.

While this thesis represents significant contribution towards sustainable product development, opportunities for further research remain. To establish its real-world impact, extended testing and evaluation are recommended. It is important to assess whether using the design tool indeed results in the development of more environmentally sustainable products and whether the framework effectively guides sustainability managers in the creation of suitable design tools. Through such practical investigations, the full potential of this thesis's contributions can be realized.

All in all, the current thesis allows companies to use the opportunity that performing LCAs for EPD reporting provide for sustainable product development. The design tool and framework provide a structured and accessible approach to integrate LCA data and expertise into the product development process. Its adaptability for businesses with varying levels of sustainable development expertise ensures a wide spectrum of potential adopters. As numerous companies embrace the practices proposed in the current thesis, the cumulative positive effect on reducing environmental impact holds the promise of a significant societal transformation towards sustainability.

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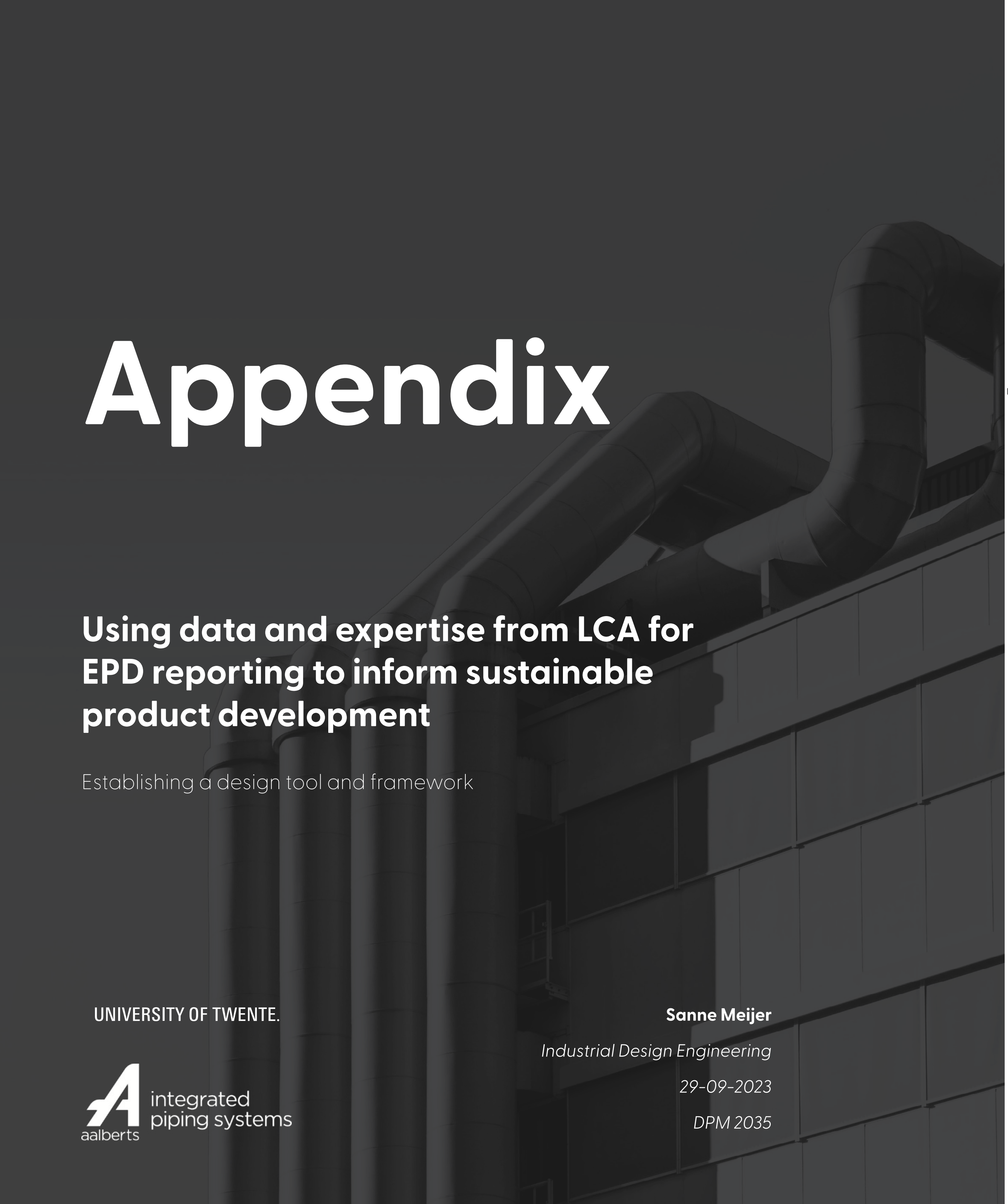


Appendix

Using data and expertise from LCA for EPD reporting to inform sustainable product development

Establishing a design tool and framework

UNIVERSITY OF TWENTE.

integrated piping systems
aalberts

Sanne Meijer

Industrial Design Engineering

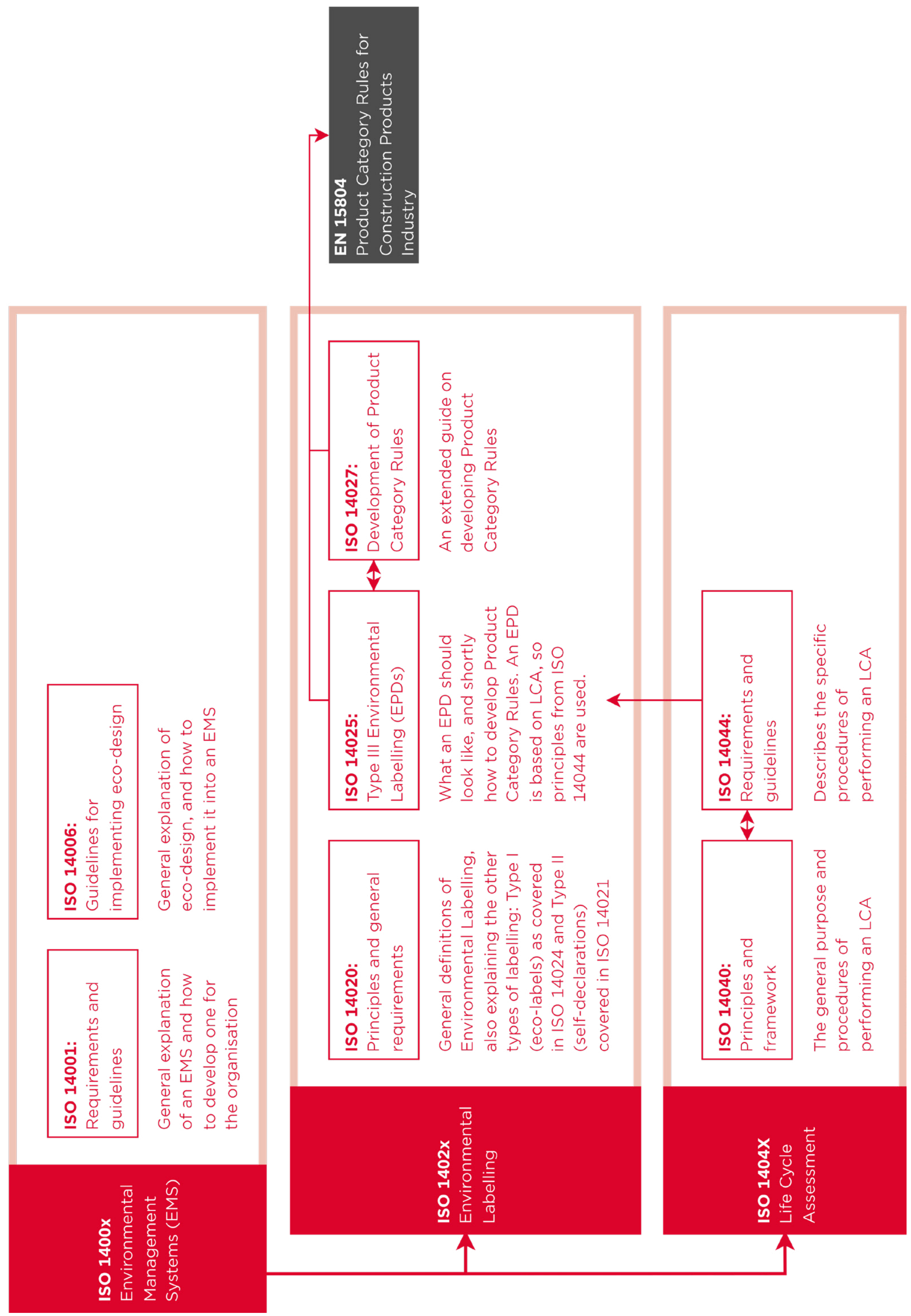
29-09-2023

DPM 2035

Table of contents

A ISO standards

An overview of the standards in the ISO 14000 series that are used in this thesis, and how they relate to each other. The EN 15804 that is used in this thesis is also included in the overview.



B Guide for design tool

Introduction
This design tool aims to help incorporate the environmental impact of a product for new product introductions (NPI). It follows the growing trend to incorporate sustainability into the core business. Not only are regulations pressing more and more to environmentally friendly policies, the market demand changes alongside it. Aalberts has formulated sustainability goals and is working on sustainable improvements throughout the company; from moving to green energy to mapping the impact of the products. A next step would be to reduce the environmental impact of the products that are being produced.

The current design tool is based on the results from the first life-cycle analyses (LCAs) that have been performed at Aalberts IPS. Those indicated that the vast majority of the impact of the product (>90%) lies in the materials purchasing. The processes happening at the AIPS facility, or the transportation steps have limited impact. Therefore, the design tool focusses on choosing the most sustainable material. The weight of the products should be reduced for the same reason. The design tool is shaped in line with the current product development process for NPI, pointing out relevant decisions for environmental improvements.

Overview of design tool
The design tool is written for people involved in the product development process and describes the steps that they should take in order to incorporate the environmental aspect into the decision-making. It consists of two sides, the front shows an overview of the steps related to the general product development process, the back explains the proposed steps in more detail. Per decision topic, two steps are performed by the product development team. First the materials in consideration are specified, so that the LCA-expert can model a comparison. The next step is to interpret these results. The tasks of the LCA expert should be performed within one week, so the product development team can continue with the development of the product. Below, a quick overview is given of the two sides of the design tool. In the next section, steps that require some more explanation are presented.

Front
On the front side, the steps of the product development at Aalberts IPS are shown, with a time range where the different decision topics take place. It can be seen that all decisions should be solidified at the end of the third, development phase. However, the main body alloy family and specific alloy is preferably considered in the earlier phases. Only after the ideation phase, the sub-part alloy family and specific alloy consideration starts.

The centre of the design tool presents the steps that should be taken by the product development team. From data gathering to analysing the results, for each of the decision topics. The start- and end conditions are given, representing what is necessary to start using the design tool, and what the results are after using it.

The steps of the sub-parts alloy family and specific alloy comparison should be repeated for every sub-part under consideration. That way only one variable is changed at the time, reducing complexity in the comparison.

Back
The same steps that are mentioned on the front are also shown on the back, but with added detail. It also provides an example of how the gathered data in the first step should be presented to the LCA-expert, and what the results could look like.

The data should be presented to the LCA-expert so that it is clear what the material types and weights are that will be compared. For the alloy comparison that means that they should be split up into the elements that make up the alloy. These should add up to the same total weight for the options (unless a significant difference in performance is expected).

The results should be interpreted by comparing the values between the different options and components. The main focus should be on the differences in values between the options, the total values are less relevant. The values are expressed in ‘AIPS indicator’, which is explained below.

Elaboration
Specify materials (+coatings)
In the same step where the material options are defined, the coatings must be specified. The material of the coating, as well as the chemicals used during application of the coating are often much more harmful to the environment than the main body material. As some materials require a coating, and others do not, the comparison of impact of material options is only representative when the coatings are considered.

Specify weights
It is possible that for different material options, different weights are to be expected. For instance, if a material is stronger and thus a thinner layer

will suffice. It can also be influenced by the design or density. If such a difference is expected, this should be taken into account in the comparison.

Consider supplier options
Many suppliers are currently working on more sustainable alternatives to the classic materials. Therefore, it is relevant to consider these alternatives, next to the general material types. As you rely on the way that suppliers present their information, these differences cannot be implemented further into the quick-LCA's, but can be kept in mind throughout the next steps.

Consider processes
Different materials can require different processing. If a difference of a factor two or larger is expected between options, the results of the quick-LCA's for the material determination become unreliable and should be dismissed.

Consider recycling
If there is a big difference between the recyclability of materials, the results from the material quick-LCA should not be used. They might falsely favour a material with a low material impact that cannot be recycled over an option that is well recyclable but has a higher initial impact. Therefore, if the difference in recycling percentage between two material options is >50%, the results of the LCA should be dismissed.

Moving from sub-part alloy family to sub-part specific alloy
If the impact of the material options for the 'sub-part alloy family' step is significantly lower than the impact of the main body, it is not useful to evaluate the impact of the specific alloys in the next step. It can then be assumed that the differences between the alloy types will not have a significant contribution to the total impact. In other words, it is only relevant to evaluate the impact of the sub-part specific alloy if the impact of the sub-part alloy family options are >5% of the total impact.

AIPS indicator
The scores in the graphs are presented in the AIPS indicator. This is calculated using multiple environmental indicators, each contributing according to their relevance within Aalberts IPS. The relevance was determined by asking people from several departments within Aalberts which indicators must be considered, and how important each indicator is. This resulted in a weighted score for each of the environmental indicators. An overview of the indicators and their weighting scores is shown in the table below. A short explanation of the environmental indicators is presented on Ecochain's website (Ecochain, 2023).

Environmental Indicator	Weight
Climate change – kg CO2-eq	**1,00**
Ozone depletion – kg CFC11 eq	0,03
Acidification – mol H+ eq	0,07
Eutrophication, freshwater – kg P eq	0,02
Eutrophication, marine – kg N eq	0,08
Eutrophication, terrestrial – mol N eq	0,04
Photochemical ozone formation – kg NMVOC eq	0,06
Resource use, minerals and metals – kg Sb eq	**0,74**
Resource use, fossils – MJ	**0,21**
Water use – m3 depriv.	**0,21**
Particulate matter – disease inc.	0,02
Ionising radiation – kBq U-235 eq	0,01
Ecotoxicity, freshwater – CTUe	**0,29**
Human toxicity, cancer – CTUh	**0,33**
Human toxicity, non-cancer – CTUh	**0,47**
Land use – Pt	0,11

The design tool is developed as part of graduating the Masters degree of Industrial Design Engineering at the University of Twente. A more detailed explanation of the use of the design tool, as well as more reasoning behind the choices made, can be found in the full report from the graduation assignment.

C Weighting factors

As described in Box V, the weighting factors to determine the AIPS indicator are defined in two steps. First available weighting sets in literature are evaluated, then interviews are performed. Table 1 shows the weighting sets from literature, scaled to 1,00 for the global warming potential environmental indicator. The total score is calculated as the average of the three weighting sets.

Second, interviews are performed across different relevant departments within Aalberts IPS. The weighting factors that were established in these interviews are shown in Table 2, as well as the combined weighting score. The first results (I) are from my own assessment, based on the KPI's within Aalberts and my knowledge of sustainability of LCA. The second results (II) are from product management, who have a good idea of the customers' demand with regards to sustainability. Interview III was performed with the global sustainability officer, knowing what the IPS part of the Aalberts network aims for with regards to sustainability. The last interview (IV) was performed with the corporate sustainability coordinator, who knows the overall strategy of sustainable development within the Aalberts group.

Environmental Indicator	**EC-PEFC[i]**	**ECV[ii]**	**Stepwise[iii]**	**Total**
Global warming potential – kg CO2-eq	1,00	1,00	1,00	**1,00**
Ozone depletion – kg CFC11 eq	0,30	0,00	0,02	**0,11**
Acidification – mol H+ eq	0,10	0,41	0,02	**0,18**
Eutrophication, freshwater – kg P eq	0,09	0,04	0,01	**0,05**
Eutrophication, marine – kg N eq	0,43	0,66	0,01	**0,36**
Eutrophication, terrestrial – mol N eq	0,24	0,29	0,00	**0,18**
Photochemical ozone formation – kg NMVOC eq	0,23	0,24	0,06	**0,18**
Resource use, minerals and metals – kg Sb eq	0,29	0,00	0,00	**0,10**
Resource use, fossils – MJ	0,18	0,00	0,00	**0,06**
Water use – m3 depriv.	0,13	0,00	0,00	**0,04**
Particulate matter – disease inc.	0,14	0,10	0,00	**0,08**
Ionising radiation – kBq U-235 eq	0,09	0,00	0,01	**0,03**
Ecotoxicity, freshwater – CTUe	0,38	0,04	0,01	**0,14**
Human toxicity, cancer – CTUh	0,40	0,04	0,07	**0,17**
Human toxicity, non-cancer – CTUh	0,36	0,11	0,07	**0,18**
Land use – Pt	0,40	0,00	0,43	**0,27**

Table 1: Weighting factors from literature. Sources i: EPLCA (2018); ii: Sustainability Impact Metrics (2023); iii: Weidema (2009).

Environmental Indicator	Literature	I	II	III	IV	Total
Global warming potential – kg CO2-eq	1,00	1,00	1,00	1,00	1,00	**1,00**
Ozone depletion – kg CFC11 eq	0,11	0,01	0,01	0,01	0,01	**0,03**
Acidification – mol H+ eq	0,18	0,07	0,01	0,07	0,01	**0,07**
Eutrophication, freshwater – kg P eq	0,05	0,01	0,01	0,01	0,01	**0,02**
Eutrophication, marine – kg N eq	0,36	0,01	0,01	0,01	0,01	**0,08**
Eutrophication, terrestrial – mol N eq	0,18	0,01	0,01	0,01	0,01	**0,04**
Photochemical ozone formation – kg NMVOC eq	0,18	0,01	0,01	0,08	0,01	**0,06**
Resource use, minerals and metals – kg Sb eq	0,10	0,90	0,90	0,90	0,90	**0,74**
Resource use, fossils – MJ	0,06	0,10	0,80	0,10	0,01	**0,21**
Water use – m3 depriv.	0,04	0,09	0,01	0,80	0,10	**0,21**
Particulate matter – disease inc.	0,08	0,01	0,01	0,01	0,01	**0,02**
Ionising radiation – kBq U-235 eq	0,03	0,01	0,01	0,01	0,01	**0,01**
Ecotoxicity, freshwater – CTUe	0,14	0,60	0,01	0,70	0,01	**0,29**
Human toxicity, cancer – CTUh	0,17	0,70	0,10	0,60	0,09	**0,33**
Human toxicity, non-cancer – CTUh	0,18	0,80	0,70	0,60	0,09	**0,47**
Land use – Pt	0,27	0,08	0,09	0,09	0,01	0,11

Figure 2: Weighting factors from literature and interviews, combined into the final weighting factor for the AIPS indicator. Interviewees: I: author, II: product manager, III, global sustainability officer, IV: corporate sustainability officer.

D LCA expert

This appendix will provide additional information on the steps that need to be performed by the LCA expert during the use of the design tool. Section D.1 explains the steps that are presented in Section 3.1.2 in more detail, where Section D.2 explains the calculations within the Excel sheet that is used, and how one could develop a similar Excel template.

The quick-LCA of the example case for the step 'main body specific alloy' as presented on the back of the design tool (Figure 3.1 and 3.2 on pages 32 and 34), is used to explain the steps for the LCA expert. This is the case for a comparison of options for types of stainless steel.

D.1. Performing a quick-LCA

In this section, a more detailed explanation will be provided of the steps that the LCA expert needs to perform during the product development process, of which a brief explanation is provided in Section 3.1.2. The steps are based on using the software Ecochain Helix and Excel for further calculations. The explanations are intended for someone who is already familiar with the Ecochain software for the purpose of performing an LCA for EPD reporting.

1. Entering data

This step is no different from entering data for the LCA for EPD reporting, except the scope is limited to just the raw materials supply module (A1). The input data is presented in a table by the product development and should specify what materials must be compared and what weights of each of the material is used for the different design options.

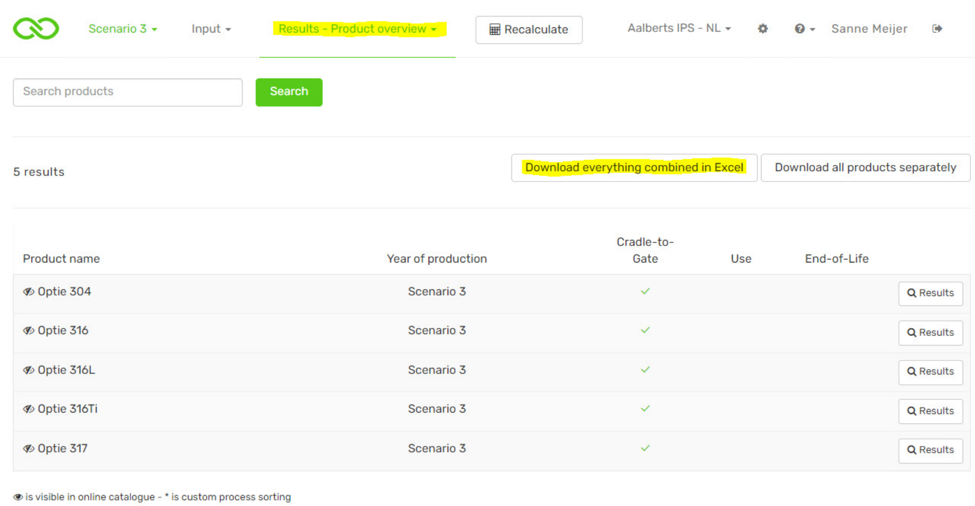
2. Processing data

The majority of the calculations are performed by the Ecochain software, but this does not allow for normalisation and weighting steps. These are therefore performed in Excel. In order to move the calculations from Ecochain to Excel, they are exported as follows:

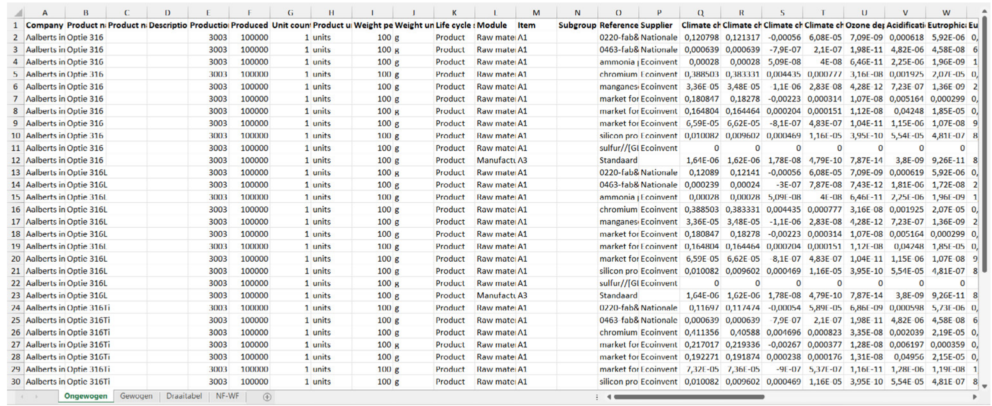
i. Go to Results > Product overview

ii. Then select 'Download everything combined in Excel'

The exported data will look something like this:



Note: The screenshots are made in a Dutch version of Excel but in the text the English names are mentioned. As the layout of Excel is unchanged by the language that is selected, the buttons that are shown can be found on the same places as indicated in the screenshots.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	
1	Company	Product n	Product n	Descriptio	Productio	Produced	Unit count	Product u	Weight pe	Weight un	Life cycle	Module	Item	Subgroup	Reference	Supplier	Climate ch	Climate ch	Climate ch	Climate ch	Ozone dep	Acidificati	Eutrophic	Eu
2	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		0220-fab&	Nationale	0,120798	0,121317	-0,00056	6,08E-05	7,09E-09	0,000618	5,92E-06	0,
3	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		0463-fab&	Nationale	0,000639	0,000639	-7,9E-07	2,1E-07	1,98E-11	4,82E-06	4,58E-08	6
4	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		ammonia		Ecoinvent	0,00028	0,00028	5,09E-08	4E-08	6,46E-11	2,25E-06	1,96E-09	1
5	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		chromium	Ecoinvent	0,388503	0,383331	0,004435	0,000777	3,16E-08	0,001925	2,07E-05	0,
6	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		manganes	Ecoinvent	3,36E-05	3,48E-05	-1,1E-06	2,83E-08	4,28E-12	7,23E-07	1,36E-09	2
7	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	0,180847	0,18278	-0,00223	0,000314	1,07E-08	0,005164	0,000299	0,
8	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	0,164804	0,164464	0,000204	0,000151	1,12E-08	0,04248	1,85E-05	0,
9	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	6,59E-05	6,62E-05	-8,1E-07	4,83E-07	1,04E-11	1,15E-06	1,07E-08	9
10	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		silicon pro	Ecoinvent	0,010082	0,009602	0,000469	1,16E-05	3,95E-10	5,54E-05	4,81E-07	8
11	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Raw mate	A1		sulfur//[Gl	Ecoinvent	0	0	0	0	0	0	0	
12	Aalberts in	Optie 316			3003	100000	1	units	100	g	Product	Manufactu	A3		Standaard		1,64E-06	1,62E-06	1,78E-08	4,79E-10	7,87E-14	3,8E-09	9,26E-11	8
13	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		0220-fab&	Nationale	0,12089	0,12141	-0,00056	6,08E-05	7,09E-09	0,000619	5,92E-06	0,
14	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		0463-fab&	Nationale	0,000239	0,00024	-3E-07	7,87E-08	7,43E-12	1,81E-06	1,72E-08	2
15	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		ammonia		Ecoinvent	0,00028	0,00028	5,09E-08	4E-08	6,46E-11	2,25E-06	1,96E-09	1
16	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		chromium	Ecoinvent	0,388503	0,383331	0,004435	0,000777	3,16E-08	0,001925	2,07E-05	0,
17	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		manganes	Ecoinvent	3,36E-05	3,48E-05	-1,1E-06	2,83E-08	4,28E-12	7,23E-07	1,36E-09	2
18	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	0,180847	0,18278	-0,00223	0,000314	1,07E-08	0,005164	0,000299	0,
19	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	0,164804	0,164464	0,000204	0,000151	1,12E-08	0,04248	1,85E-05	0,
20	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	6,59E-05	6,62E-05	-8,1E-07	4,83E-07	1,04E-11	1,15E-06	1,07E-08	9
21	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		silicon pro	Ecoinvent	0,010082	0,009602	0,000469	1,16E-05	3,95E-10	5,54E-05	4,81E-07	8
22	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Raw mate	A1		sulfur//[Gl	Ecoinvent	0	0	0	0	0	0	0	
23	Aalberts in	Optie 316L			3003	100000	1	units	100	g	Product	Manufactu	A3		Standaard		1,64E-06	1,62E-06	1,78E-08	4,79E-10	7,87E-14	3,8E-09	9,26E-11	8
24	Aalberts in	Optie 316Ti			3003	100000	1	units	100	g	Product	Raw mate	A1		0220-fab&	Nationale	0,11697	0,117474	-0,00054	5,89E-05	6,86E-09	0,000598	5,73E-06	0,
25	Aalberts in	Optie 316Ti			3003	100000	1	units	100	g	Product	Raw mate	A1		0463-fab&	Nationale	0,000639	0,000639	-7,9E-07	2,1E-07	1,98E-11	4,82E-06	4,58E-08	6
26	Aalberts in	Optie 316Ti			3003	100000	1	units	100	g	Product	Raw mate	A1		chromium	Ecoinvent	0,411356	0,40588	0,004696	0,000823	3,35E-08	0,002039	2,19E-05	0,
27	Aalberts in	Optie 316Ti			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	0,217017	0,219336	-0,00267	0,000377	1,28E-08	0,006197	0,000359	0,
28	Aalberts in	Optie 316Ti			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	0,192271	0,191874	0,000238	0,000176	1,31E-08	0,04956	2,15E-05	0,
29	Aalberts in	Optie 316Ti			3003	100000	1	units	100	g	Product	Raw mate	A1		market for	Ecoinvent	7,32E-05	7,36E-05	-9E-07	5,37E-07	1,16E-11	1,28E-06	1,19E-08	1
30	Aalberts in	Optie 316Ti			3003	100000	1	units	100	g	Product	Raw mate	A1		silicon pro	Ecoinvent	0,010082	0,009602	0,000469	1,16E-05	3,95E-10	5,54E-05	4,81E-07	8

Each row represents one of the materials for each of the products, where the 'Reference' tab specifies which material it is (e.g. row 5 is for the material 'chromium'). For every material, the full list of environmental indicators are calculated, extending further than what is captured in this screenshot.

iii. Place the exported data in the Template Quick-LCA's.xlsx in the tab 'original data'

The Excel file is accessible within Aalberts IPS, Section D.1 explains the calculations that are programmed in the file so anyone without access could make their own.

iv. Fill out the normalisation and weighting factors in the tab 'Norm-

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1		Climate ch	Climate ch	Climate ch	Climate ch	Ozone dep	Acidificatio	Eutrophica	Eutrophica	Eutrophica	Photocher	Resource u	Resource u	Water use	Particulate	Ionising ra	Ecotoxicity	Human to	Human to	Land use -
2	Normalisation factor	1,21E-01	0,00E+00	0,00E+00	0,00E+00	4,58E-09	2,10E-03	2,37E-07	1,61E-04	8,71E-03	1,27E-04	2,71E-04	1,63E+00	8,99E-03	2,08E-08	3,69E-03	1,10E+00	1,29E-10	1,92E-08	1,81E+00
3	Weighting factor	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

weight'

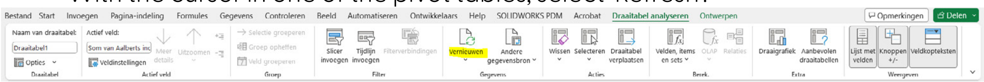
The norm and weighting factors are set according the AIPS weighted indicator. If another norm or weighting set is to be used, these should be added here. The Excel file will automatically calculate the normalised and weighted scores and display them in the 'Weighted data' tab.

3. Presenting results

To present the results, the tab 'Pivot tables' is used.

i. Refresh pivot tables

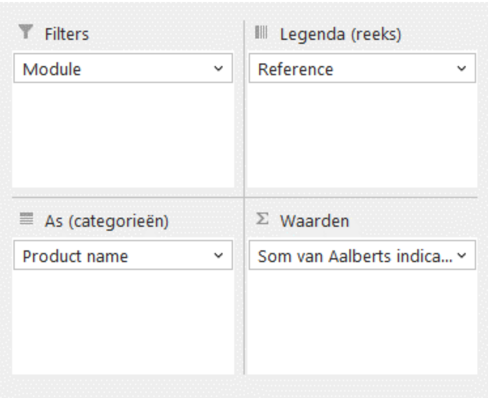
With the cursor in one of the pivot tables, select 'Refresh':



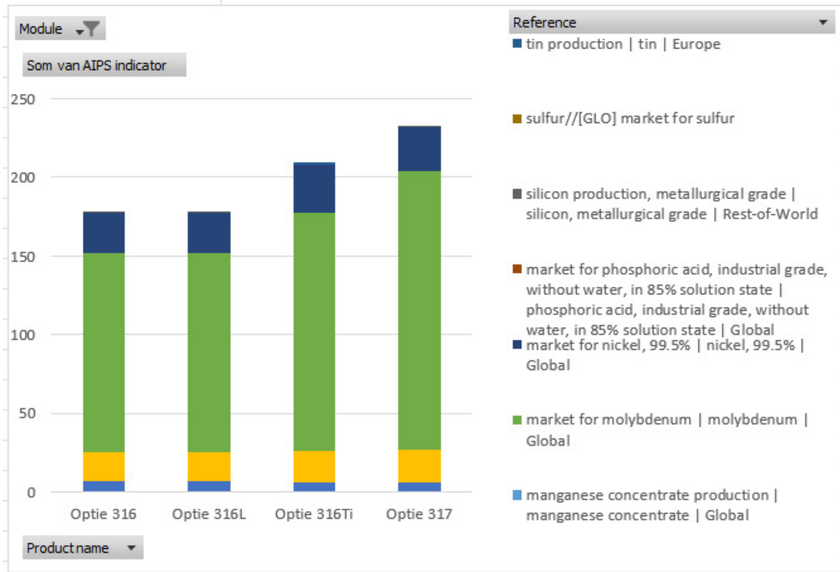
ii. Set up the first pivot table

For the filter 'Module', the 'Raw materials supply' must be selected.

The graph should display for every product how the different materials contribute to the total environmental impact (expressed in AIPS indicator). These results will be presented to the product development team. The



names of the materials are still the names of the database reference, which might be a bit confusing if presented to the product development team. Therefore, an optional step is to copy the pivot table, rename the materials and present it in a regular graph.



4. Assess validity

The validity of the results should be assessed, as to prevent the product development team to use unreliable data for their decisions. Therefore, if the uncertainty is too high, or the outcomes are too close together, the results should not be used. To assess the validity, the database entry is most relevant. For some materials, mostly on the specific alloy detail level, no representative database entry is available. Therefore, when evaluating the results, it is important to consider the uncertainty that this adds to the comparison.

This step also accounts for the cases where large differences between manufacturing processes and recycling percentages are expected. The product developers must make sure to indicate such expectations to the LCA expert. Figure 2 helps understand in what scenario the results can and cannot be used. The left bar displays the scenario when the difference between the environmental impact of the options is expected to become smaller if the manufacturing processes or recycling percentages are taken into account. In that case, the results should not be used. This scenario is true for situations where the manufacturing processes are expected to have a larger impact for the option where the quick-LCA presents a lower impact, and for situations where the recycling percentages are lower for the option with the lowest environmental impact from the quick-LCA. The bar on the right displays the scenario for which the difference between the environmental impact of the options is expected to become larger if the manufacturing processes or recycling percentages are taken into account. In that case, the results can still be used.

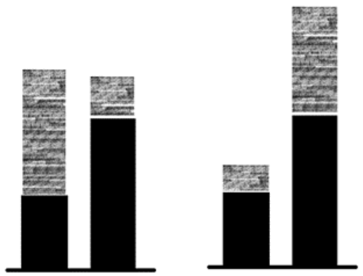


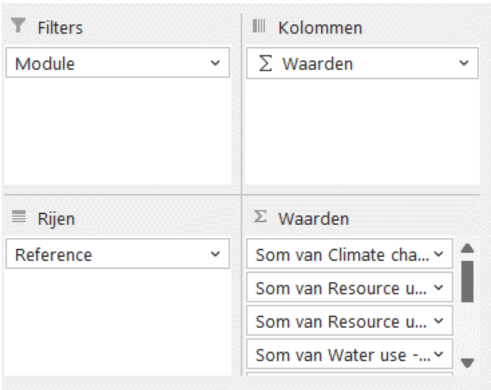
Figure 2: Visualisation of cases in which the results from the LCA should be disregarded .

5. Evaluate the results

In order to get a better idea of where the impact comes from, an additional graph can be presented. This provides insight into which impact categories contribute to the impact of the material, and suggest what improvements can be made.

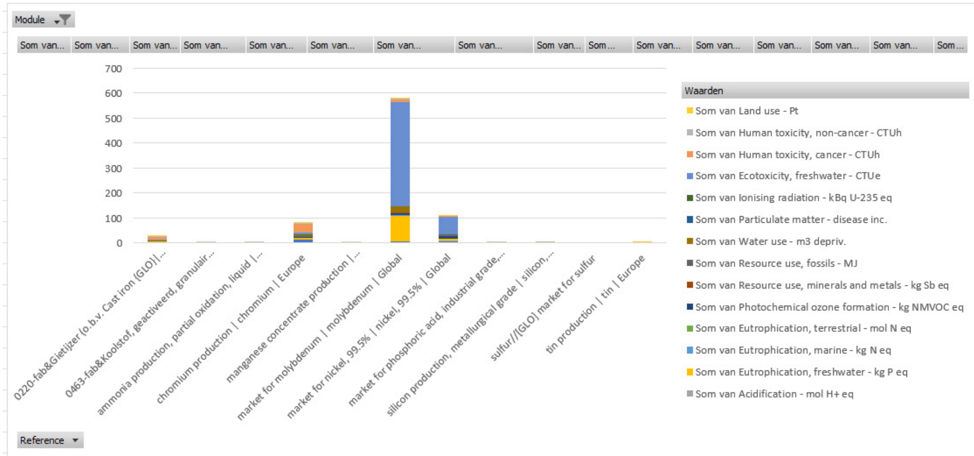
i. Set up the second pivot table

Again, the filter 'Module' should have the 'Raw materials supply' selected.



For the values, all environmental indicators for which a normalisation and weighting factor is defined, must be selected.

The graph should present for every material how the impact is built up based on the different environmental impact categories.

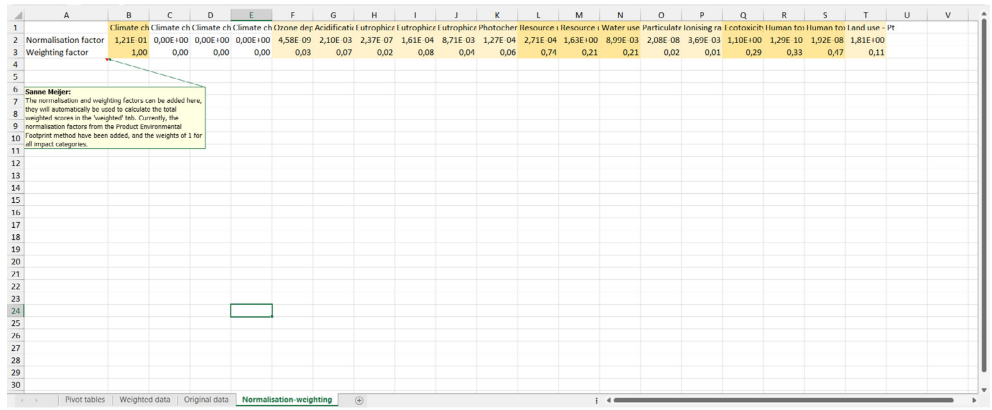


ii. Analyse the second pivot table.

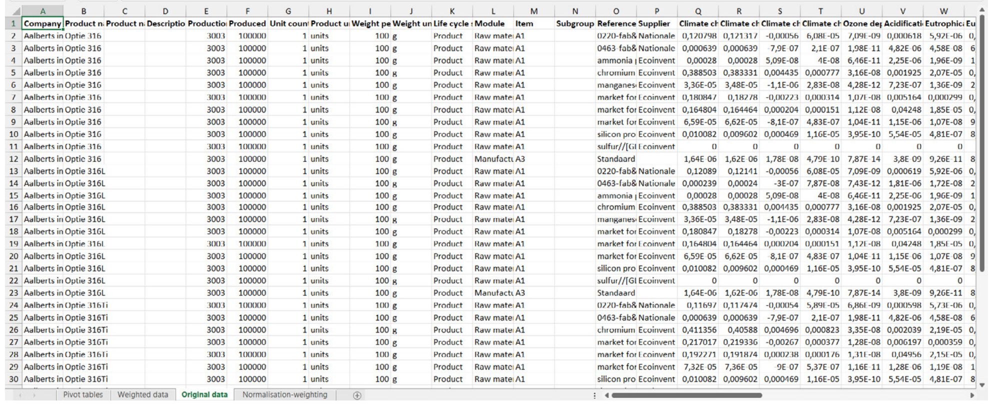
This pivot table provides an insight into what environmental indicators cause the impacts for the materials. Additional study is required to determine what mechanisms cause the environmental impact. In Section 3.1.2 of the report, the example of the mechanisms of copper ecotoxicity is described.

D.2. Excel sheet for quick-LCA

This section describes the calculations taking place within the Excel file that is used for the detailed examination of the results from the quick-LCA's as performed in EcoChain. The document Template Quick-LCA's.xlsx is available for Aalberts IPS employees. This section will discuss in detail how anyone without access to the template document could build their own Excel file for detailed LCA study.

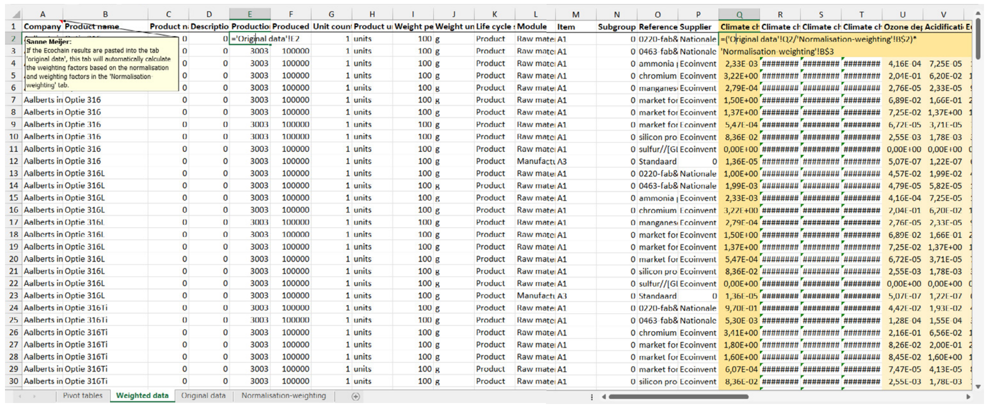


On the last tab, the normalisation and weighting factors can be added. In the template document, the Aalberts IPS normalisation and weighting factors are added, but these can be adapted to another normalisation and weighting set. Whenever another Impact Assessment Method is selected, this will likely mean that other impact categories are represented. These will need to be updated in that case, along with the values for the normalisation and weighting factors.

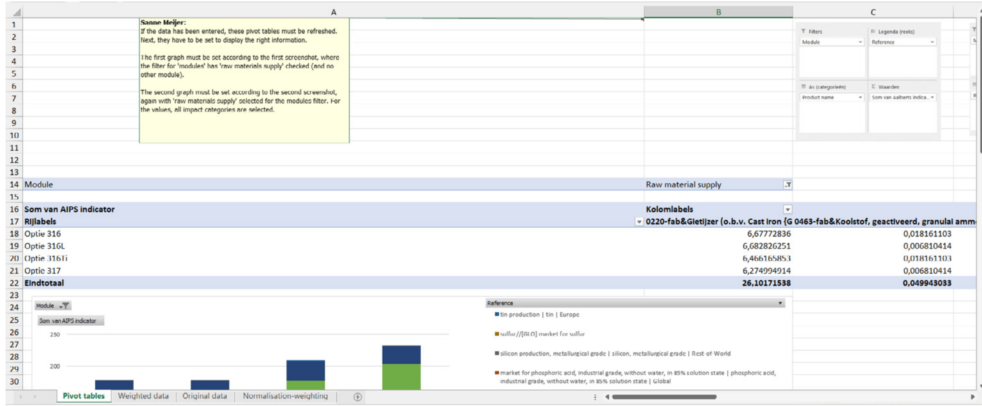


The original data, as exported from EcoChain, can be pasted in the document in this tab. Make sure to select the field A1 to paste the data.

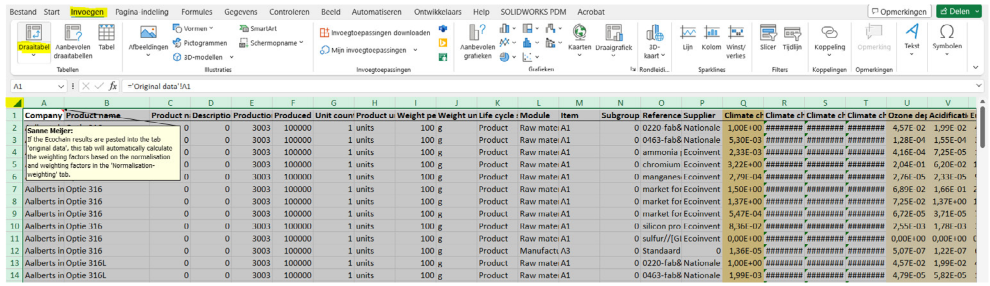
Note: The current screenshot of the template document contains the data from the example case for options of stainless steel, where the file for Aalberts IPS employees contains no data.



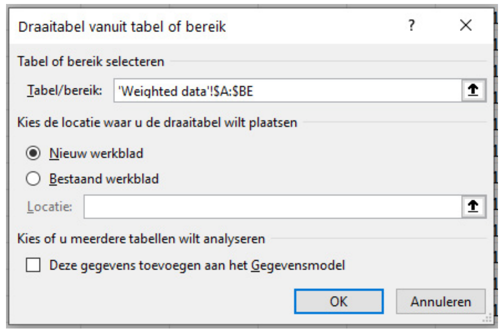
The calculations are made in the tab 'weighted data'. The general information is transferred to the tab by simply making the fields equal to the fields in the 'original data' tab (see formula in E2). The environmental impacts are calculated according to the characterised outcomes in the 'original data' tab, divided by the normalisation factor and multiplied by the weighting factor (see formula in Q2).



In the first sheet, the pivot tables are presented. These are made based on the tab 'weighted data', by selecting the complete tab, and then selecting Insert > Pivot table.



This pivot table can then be placed in a new tab that is then named 'pivot table'. This needs to be done twice, where the second pivot table must be placed in an existing tab, namely the one that was just created.



After the data has been entered into the tab 'original data', the pivot tables must be adjusted to present the desired information. The steps to do so are described in Section D.1.

E

Experience of performing CLA at Aalberts IPS

As part of getting to know the matter of LCAs within the company, an LCA was performed of a product range that had not yet been evaluated within Aalberts IPS. This was done for the SmartPress range. The goal of performing the LCA was to get an insight of what performing an LCA is like within a company, and what challenges arise. Apart from the LCA for SmartPress that was performed from the beginning, the LCAs of the entire portfolio were analysed in order to determine the focus point of the design tool, and the quick-LCAs were performed to exemplify the use of the design tool.

The differences between performing the LCA for Aalberts and the theory on LCA, as well as previous experience of performing an LCA for scenarios approaching reality, are discussed. This is done following the general structure of performing an LCA, from goal definition to inventory analysis and impact assessment, and finally interpretation is (ISO, 2006).

Previous experience
My current experience with performing LCAs has been within theoretical projects within courses at the University of Twente. This meant that there was no access to company specific data or the production site. All the data that was used as input for the LCA analyses was therefore based on assumptions and literature review.

The LCAs of previous experience were performed in the GaBi Educational software. This is provides an extensive range of possibilities for customisation. The lifecycle of the product is modelled by specifying the inputs and outputs of every step of its production, use and disposal. Instead of filling in the details yourself, it can also be selected from a wide range of databases that are available. Apart from the products specifics, the characterisation, normalisation step can also be adapted, either by selecting an already available method, or customising one.

For the LCAs in previous experience, the goal was to compare two or more options on the same functionality. That meant that it was crucial to specify a functional unit that specified the amount of the same function in order to compare the products.

Additionally, the LCAs that were performed were mostly retrospective, so of products that were finished and in the market for a while. However, during a design project, a comparison has been made of design options. Where these options were quite clearly defined, it was noticed that the level of detail that is required to perform an LCA of the full lifecycle of a product is much higher than the level of detail that is present in the concepts during the design process.

Goal definition
The structure of the goal definition for the LCA within Aalberts is largely defined by EN 15804 norm that is followed. The goal of the LCA performed at Aalberts is to inform their customers of the environmental footprint of their products by presenting them in an EPD.

The comparison between products is outside the scope of the EPD reporting, where this has been a central goal of the LCA's that I have previously performed. This also results in differences in the functional unit. Where in my previous experience, it was crucial to carefully specify the function and amount that are used in the comparison in the functional unit, this was not done for the LCAs within Aalberts IPS. Because the comparison takes place outside of the scope of the LCA analysis, its function might differ. As described in Section 2.3, if a product's function cannot be unambiguously be determined, a 'declared unit' may be specified. That is the case for the Aalberts IPS products, where the declared unit is specified as one piece of the product.

Inventory analysis
The inventory analysis centres around data gathering. In previous projects I have only worked with fictional scenarios, meaning that all data that was used was sourced from literature and heavily based on estimations. For the LCA at Aalberts, real company data was used. It appeared that some data was easy to access, where other data was much more difficult to gather. The material types and weights (A1) could be found in the technical drawings of the products, the transportation distances up to the gate (A2) could be calculated based on the locations of the suppliers. The energy source during the manufacturing step (A3) was also known within the company.

The data collection was more difficult for the energy consumption during manufacturing (A3). The only way to get an insight of the energy that was consumed to produce one product, was to measure the energy consumption during a single order. Due to the time constraints within the graduation assignment, and the extensive scope of the SmartPress product range, tests were performed to a selection of product compositions. From here, extrapolations were made to estimate the energy consumption of all other compositions.

There were, however, also variables for which no real company data was available. This was the case for the recycling scenarios, including the recycling percentage as well as transportation distances. These were outside the influence of the company and could therefore only be estimated. This was done in a similar way as in previous projects, by referencing literature.

Another difference that was noticed in the inventory phase of the LCA, was that instead of modelling a single product, an entire product line was evaluated. The software of Ecochain Helix was very suitable for this task, as new products could be easily added and their characteristics specified. In the software GaBi that I have previously used, this task would be much more tedious. Here, all the steps of the production process would need to be individually specified for each configuration in order to see the differences in the results.

Impact assessment

The impact assessment step is performed in less detail within Aalberts IPS than it is in my previous experience. For EPD reporting, the desired outcome is in characterised results, without considering the normalisation and weighting step. Where I understand that the characterised results are more science-based than the values after a normalisation and most notably a weighting step, I do believe that having a standardised norm and weighting set for the EN 15804 standard would help users interpret the significance of their outcomes.

As the normalisation and weighting steps are not commonly used, the software Ecochain does not provide the possibility to add these to the comparison. For the EN 15804, the results are solely expressed in the characterised impact categories. For another impact assessment method, the Eco-Cost Indicator by the Stichting National Environmental Database (2020) does provide an indicator value, stacking the values from the impact categories. However, it does not allow for customised normalisation and weighting factors.

Fortunately, the results from the LCA as calculated in the software, are easily exported to Excel. Here the additional calculations for the normalisation and weighting step can be added. This also allowed the further study of the results in more detail, separating the results into customised graphs. More about this can be found in Appendix D.

Interpretation

The interpretation step is performed in less detail for the EN 15804 standard than in my previous experience. The assumptions and decisions within the goal definition and inventory stage must be explained, and an assessment must be made of their validity. This must then be presented in the background report. However, no further study is required of the results, they are simply presented along the format that is provided by EN 15804.

In my previous experience, it was a key part of performing the LCA study to determine if the results are within expectations and what causes the large impacts. This stems from the difference in goal, where the goal within my previous experience was to compare products and provide insights in how to improve the environmental sustainability of a product, as stated previously, the comparison happens outside of the scope of the EPDs. Therefore, the deeper analysis of the results is likely to also happen outside of the LCA study. What must be noted is that for the scope of the thesis, the further study of the results is required. This is in line with the purpose of the thesis to use the LCA data and expertise to inform sustainable improvements to the products' design.

F Evaluation of design tool at Aalberts IPS

The design tool for Aalberts IPS has been evaluated by presenting it to stakeholders within the company that are involved in the product development process. The stakeholders that were interviewed were from the following departments, each with their own role in the product development process:

- Product development, involved in the design of the products;
- Manufacturing engineering, involved in the choice of machinery and the definition of manufacturing processes;
- Product management, informing the product development process from the view-point of the customer and market trends;
- Purchasing, providing insight into the material and supplier options;
- Supply chain, mostly focussing on the day-to-day tasks of ensuring supplies are on time and orders are manufactured in time. They do not have a significant contribution in the product development process, hence the outcomes from the interview were not as useful;
- Marketing, involved in presenting the final products to the market, also less involved in the product development process.

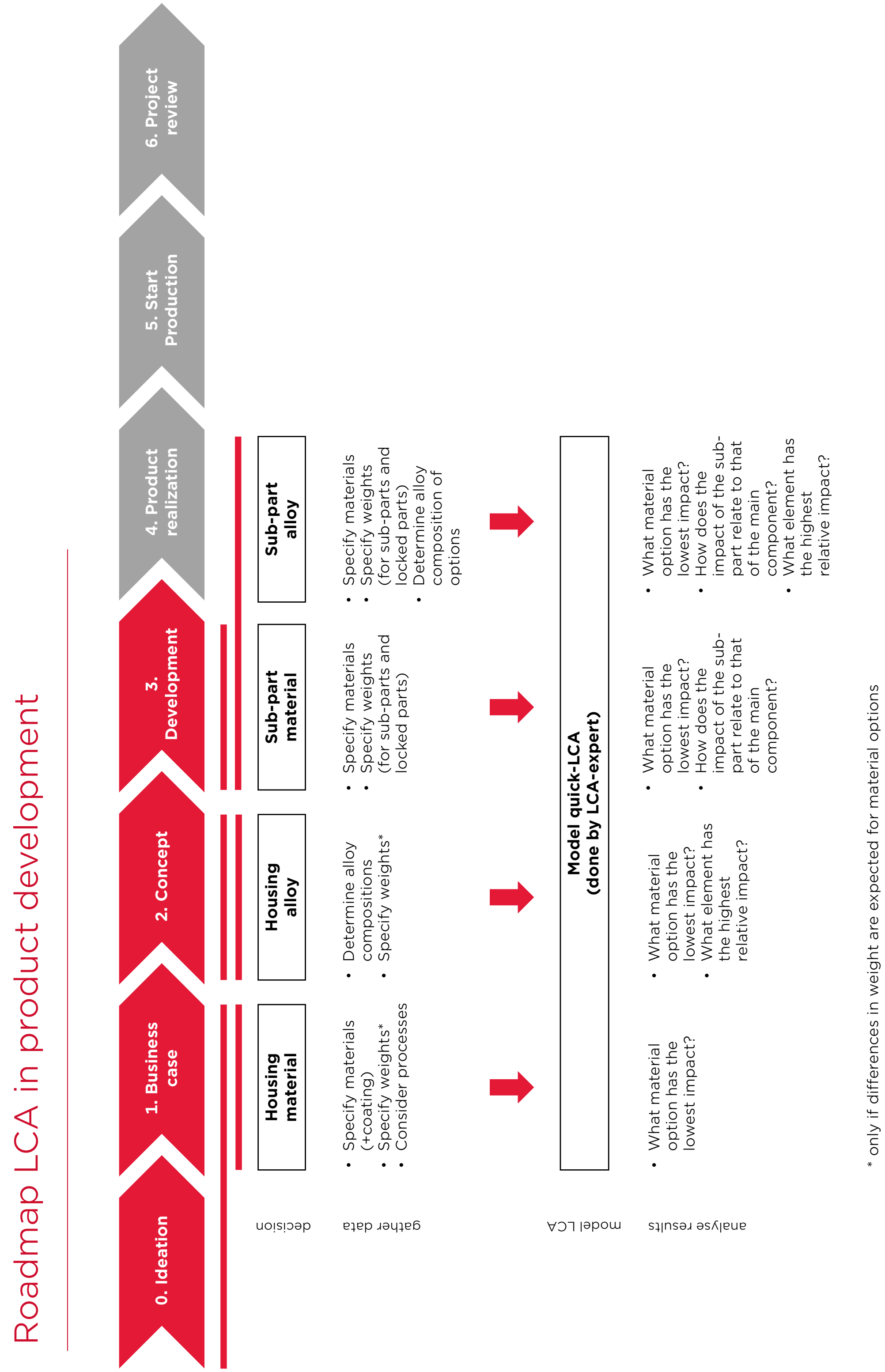
In this part of the Appendix, the version of the design tool that was presented is shown, before the improvements were made (Section F.1). Additionally, the questions that were asked during the interviews are presented (Section F.2).

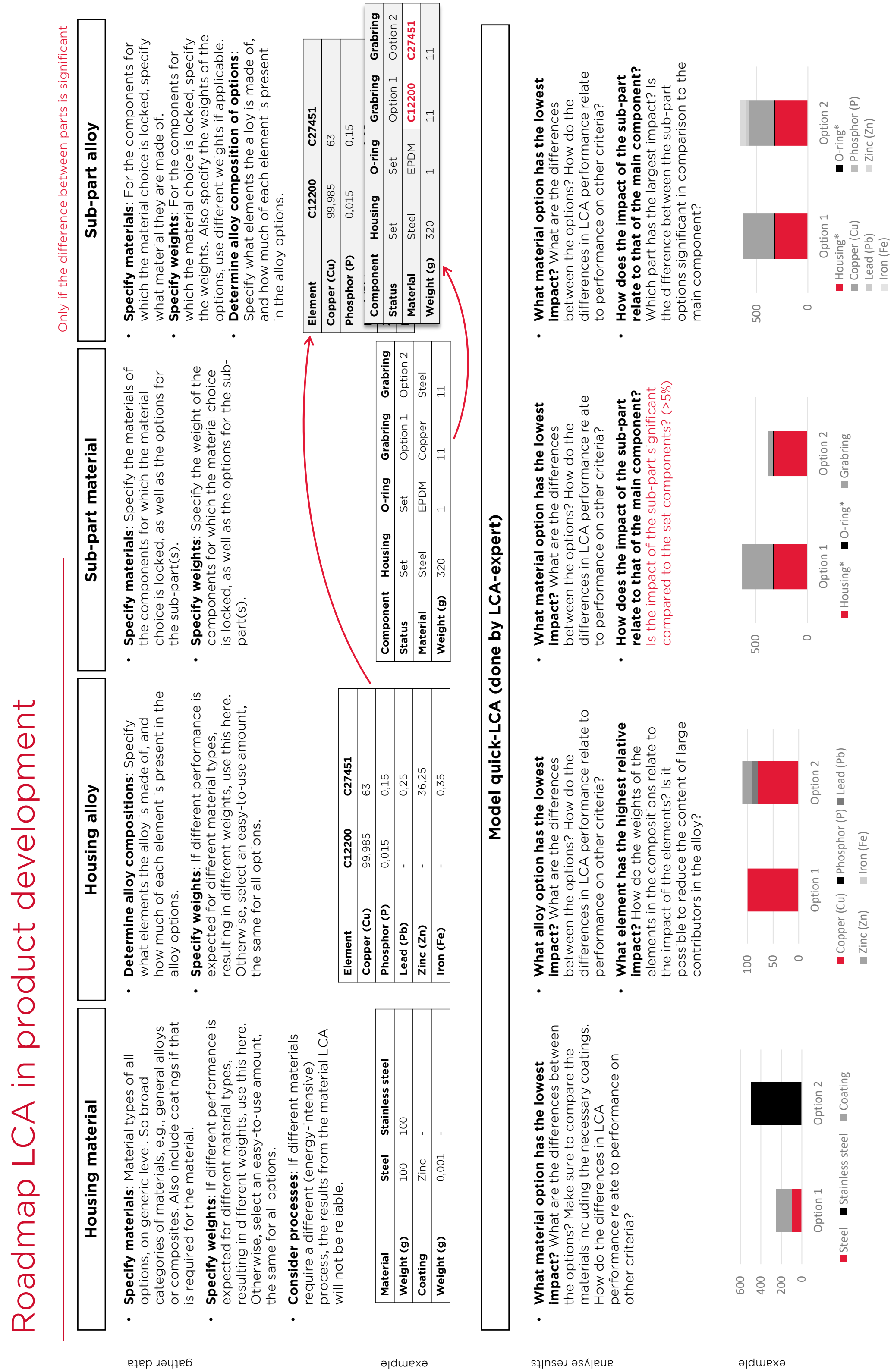
F.1. First version of design tool Aalberts IPS

The first version of the design tool for Aalberts IPS is presented in the figures.

Figure 3: Design tool initial version, before verification: front (displayed on the right)

Figure 4: Design tool initial version, before verification: back (displayed on the next page)





Note: Apart from the changes that were implemented based on the feedback during the evaluation step (described in Section 3.3), some smaller changes in were made. Firstly, the term 'roadmap' was changed to 'design tool', as this more fittingly described the contents. Next, the names of the steps of the decision-making process were altered. The term 'housing' was replaced for 'main body', as that is the term that is used in practice. The steps 'material' and 'alloy' consideration are renamed to 'alloy family' and 'specific alloy' respectively, because that aligns better with what could be found in literature, e.g. UNEP (2011). Lastly, the unit 'AIPS indicator' was added to the axis of the example graphs, and the tables for 'subpart alloy' were separated to avoid confusion with the arrows.

F.2. Interview questions design tool evaluation

Note: The interviews were performed in Dutch, the questions below are thus a translation. Additionally, as stated in the research methodology as presented in Section 1.5, the interviews were performed in a semi-structured fashion. This meant that apart from the questions that are listed below, input from the interviewees was gathered.

Introduction

The goal of the design tool is to incorporate the environmental impact of the products in the product development process. The structure of the design tool is made to match the current product development process, and it indicates for every step of the process how to incorporate the environmental impact of the product. The design tool focusses on the material decision, as LCAs pointed out that this causes the largest portion of the product's environmental impact. For each step of the decision-making process of the material, it is described what is expected of the decision-makers and what tasks are performed by the LCA expert.

Questions

- General
  - Do you understand how to use the design tool, and what your role is in its use?
  - Are all the terms that are used clear?
  - Do the results from the quick-LCAs present you will all the information that you need in order to make the decision?
  - Is anything missing? E.g. data, explanation or decision-making steps. How would you like to see this added to the design tool?
- Timeline
  - Do you recognise the schematic of the product development process? Do you understand how to use it?
  - Are all the steps of the decision-making process assigned to the right stages of the product development process?
  - For each of the decision topics, when should the decisions be made at the latest? In what stage of the product development process is that?
- Relation other criteria
  - For each of the decision-moments, what criteria are relevant

(other than the environmental impact that is considered in the design tool)?
  - How important are those criteria, related to the environmental impact?
  - Do you think that the environmental impact could already influence the decision-making currently?
    - If so, in what cases?
    - If not, what do you think should happen before this would be the case?
- Specific questions
  - Are there instances where the weight of the product is different for different alloy family or specific alloy options? In other words, is the step 'consider weights' of added value?
  - Are there instances where different options for alloy families require a different coating? In other words, is the step 'specify coating' of added value?
  - Is it necessary to explain the unit of the environmental impact and how this is calculated?

G Case studies

Three case studies – of cement, a LED luminaire and Aalberts IPS – are used to evaluate the validity of the framework. For each case, all the steps of the framework are performed, which is described in detail below. The conclusions from the cement and LED case are presented in Section 4.2, where the initial development of the design tool for Aalberts IPS – which served as the basis for developing the framework – is discussed in Chapter 3.

It must be noted that the case-studies for cement and LED are performed differently than the typical use of the framework, as they were not performed within the company. Therefore, assumptions were made of the scope and nature of the product development process based on the EPD reports. Additionally, the EPD reports did not provide the required level of detail for the framework. Therefore, additional insights were sourced from academic literature. The lack of access to the business also meant that no custom weighting factors could be developed. Therefore, the Product Environmental Footprint (PEF) weighting set was used (EPLCA, 2018).

The cases of cement and LED are based on EPDs found in the EPD repository (The International EPD System, n.d.) and also used to exemplify the use and possible outcomes of the framework in Section 4.2. The third case discusses the situation at Aalberts IPS, for which the design tool is developed as discussed in Chapter 3.

G.1. Cement

The first case that is studied, is that of cement production at Aalborg Portland A/S. The cement is produced by grinding limestone and clay, which are then combined and then heated in a kiln. Next, the calcination process begins which takes place in a second kiln, where CO2 is released from the limestone to produce clinker. This clinker is then ground together with gypsum and other additives to form cement. Cement is one of the main ingredients for concrete production, but this is out of scope for the case. The EPD by Aalborg Portland A/S (2023) presents the environmental impact of the cement, and will be used to develop a design tool.

1. Calculate LCA-results

In this step, the LCA results should be calculated. For this the results presented in the EPD are used. It should be noted that in the EPD, only the modules A1-A5 have been declared. As the cement is an intermediate product, little can be said about the use, maintenance and disposal phase.

The results are presented in the figures below. Figure 3 shows the result per environmental indicator for each module, all scaled to add up to 100%. Figure 4 shows the weighted indicator score, where the impact of each environmental indicator is added together for each module.

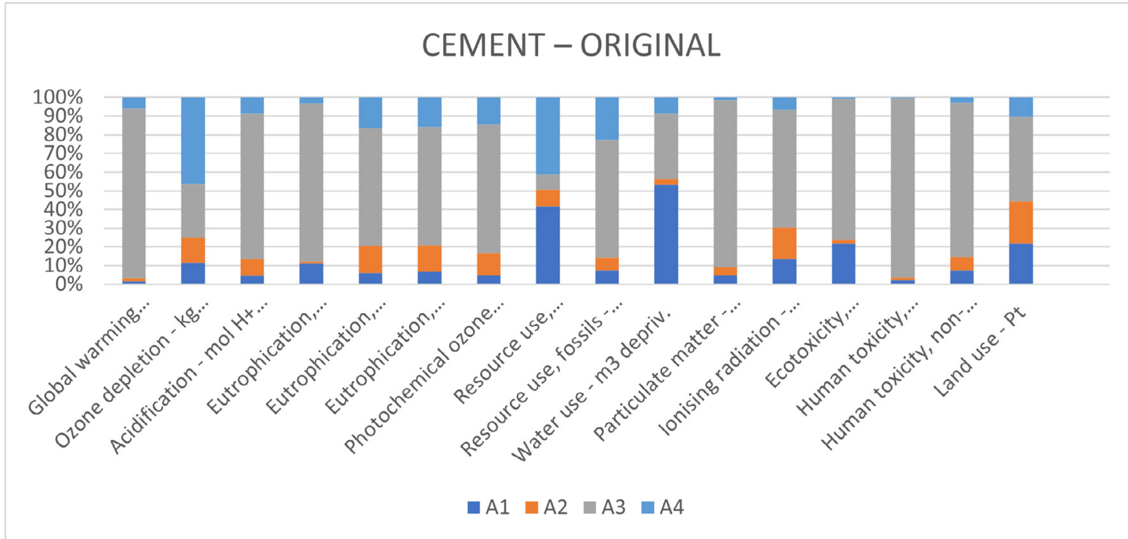


Figure 5: Characterised EPD results for cement. Data from Aalborg Portland A/S (2023)

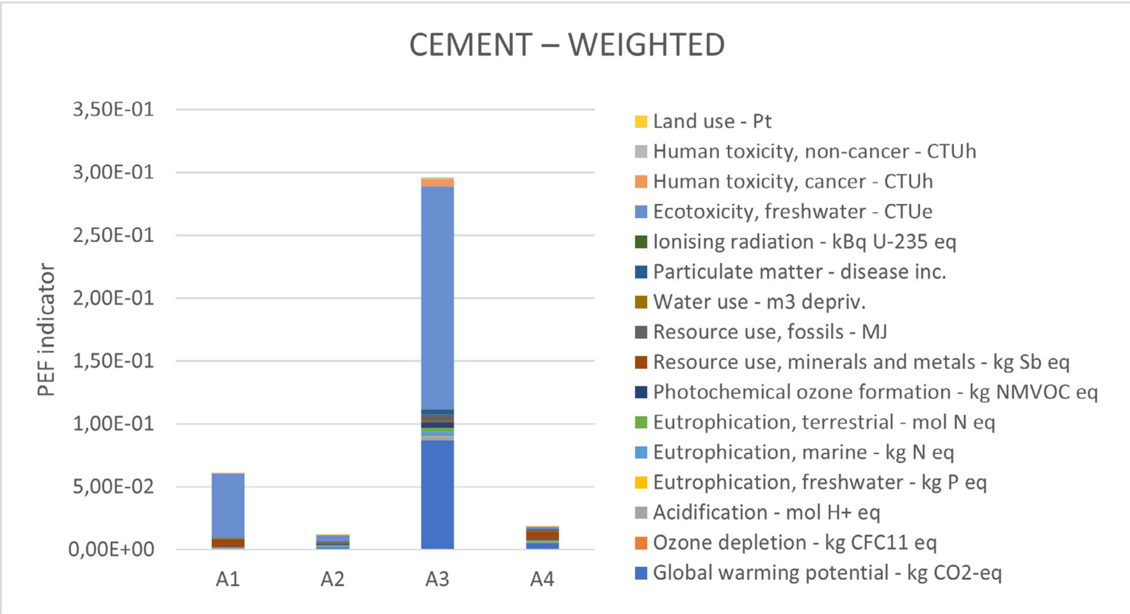


Figure 6: Weighted EPD results for EPD cement, cumulative impact per module displayed in PEF indicator

2. Analyse LCA-results

In this step, the results from the LCA are analysed. The goal is to identify in what module the biggest impact can be found, and to get an idea of what causes that large impact. From Figure 4 it can be clearly seen that the largest environmental impact lies in the manufacturing stage. This is true for all indicators except for resource use (minerals and metals) and water use, for which the impact lies in the materials phase (A1). On average, module A3 causes 76% of the impact. This large impact in the manufacturing stage is mostly caused by two environmental indicators: ecotoxicity (60%) and climate change (29%).

Additional LCAs about cement were studied to find what causes the impacts found in the EPD. Studies conducted by Sjunnesson (2005), Feiz et al. (2015) and García-Gusano et al. (2014) indicated consistent conclusions regarding the impacts for the climate change indicator. The studies found that approximately 85% of the impact occurred during the use phase, aligning closely with the EPD results where the manufacturing stage accounted for 91% of the impact of climate change. A large portion of these emissions can be attributed to the calcination process. Of the climate change impacts, around 60% is due to the direct emissions of CO2 during the calcination step, and another 30% is attributed to the fossil fuels used for heating the kiln (Feiz et al., 2015; García-Gusano et al., 2014; Sjunnesson, 2005). The factors driving the impact for ecotoxicity remained unclear. Ige et al. (2022) attributed approximately 80% of the impact to raw materials, contradicting the EPD results where 75% of ecotoxicity impact

lies in module A3.

For the purpose of this thesis, the climate change environmental indicator will be used. While the impact for ecotoxicity is higher, indicating more potential for improvement, the causes of this impact could not be sufficiently explained. However, the climate change category is very relevant to consider due to the large share of the global climate change effects that can be attributed to the concrete industry (IEA, 2018). If custom weighting factors would have been made for the cement scenario, it is likely that the climate change effects would become more relevant than the eco-toxicity effects.

Within the climate change environmental indicator, the combustion of fossil fuel during the calcination step will be selected for further examination. This again diverges from what is stated in the framework, as the largest impact can be found in the direct emissions from the calcination steps. However, previous studies (Feiz, 2016; Schneider, 2015) have indicated that no feasible improvements can be made to reduce emissions during this specific step.

3. Follow decision tree

Next, the steps from the decision tree are followed to find what recommendations and design tools fit the situation. Below, the questions and answers used in the decision tree are presented.

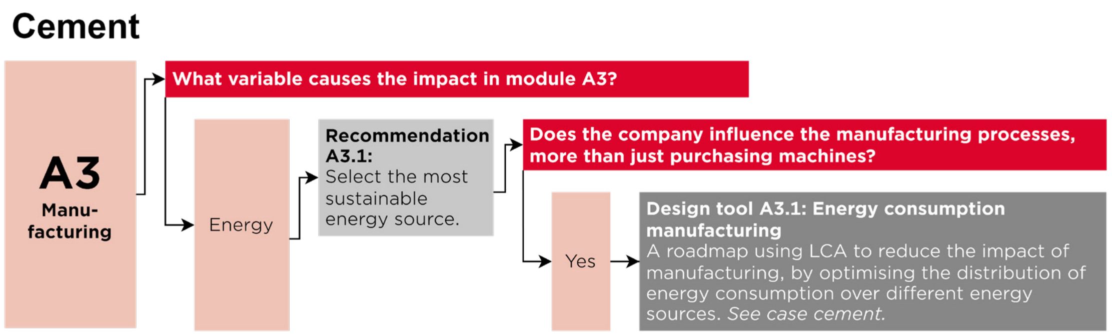


Figure 7: Steps from decision tree for cement case, based on EPD and LCA

This results in a recommendation regarding the energy source and a design tool about reducing the energy consumption.

4. Develop design tool

In this step, the conclusions from the decision tree will be used to develop a design tool for the specific situation for the cement production case. This will be done in the following steps:

a. Study decision-moment

The EPD is used as a scenario for what the company can influence in their product development and what not. In this case, it is assumed that the company can select the raw materials going into the production, it has control over the processes taking place at the production facility and the transportation steps to the gate, and from gate to site. However, they have no influence over the concrete production and use that takes place after the cement is shipped from their facility.

Additionally, the EPD on which the case is based provides no insight into the specific steps that are performed during the product development process at Aalborg Portland A/S. However, based on previous experience, as well as the experience from developing the design tool for Aalberts IPS, some assumptions could be made.

Within Aalberts IPS, the decisions affecting the energy consumption during the manufacturing stage are made in three steps. First, the general machine type is selected, e.g. hydraulic versus electric machines. In the case of cement production, this could concern a general decision what type of kiln will be used, accommodating to what type of fuel. Next, at Aalberts the specific machine is chosen, while keeping the efficiency and other determining properties in mind. A similar step likely occurs at Aalbort Portlant A/S too. In the last step, the specific process is developed. Here there is room for improvement, increasing the efficiency or reducing the emissions slightly.

b. Search improvement pathways

The following improvement pathways were found based on Feiz (2016), IEA (2018) and Schneider (2015):

- Production processes
  - Alternative fuels
  - Efficiency
- Product composition
  - Low-carbon cements
  - Clinker-to-cement ratio
- External synergies
  - Industrial symbiosis
  - Carbon capture and storage

The production processes can be improved by selecting alternative fuels, corresponding with the recommendation to select the most sustainable energy source. This alternative fuel can be in the form of waste materials, or renewable energy sources such as biomass. Next to that, the efficiency of the kiln can be considered (Schneider, 2015). However, as energy efficiency has already been subject to optimisation for financial reasons, this pathway is estimated to have the least potential to reduce the environmental impact of cement production (IEA, 2018).

The product composition can also help reduce the impact of the cement. Where they appear to focus on reducing the impact of raw materials, they

mainly reduce the energy consumption during the manufacturing stage. As the calcination of clinker contributes most to the impact in A3, using alternative materials that do not require calcination, is able to significantly reduce the impact in the manufacturing stage (Feiz et al., 2015).

Lastly, external synergies can reduce the environmental impact of cement production. Firstly, industrial symbiosis considers whether wastes from one facility can be used in another (Yazan & Fraccascia, 2019). In the case of cement production, waste such as tyres can be useful as alternative fuel, or metal casting slags can be used as alternative to clinker to reduce the clinker-to-cement ratio. Next, external synergies can be in the shape of carbon capture and storage. As the production of cement inherently emits CO2, it can be sought to reduce the environmental impacts of these emissions by storing these emissions.

It must be noted that some of the improvement pathways that were found, are also effective at reducing the impact of the direct emissions during the calcination step. For instance, reducing the amount of clinker means that less calcination needs to take place and thus less direct emissions of CO2 take place. Besides, the carbon capture can mitigate the detrimental effects of the inherent emissions during the calcination step.

c. Look for interplay

For this step, it is evaluated whether an improvement pathway can result in increased environmental impact elsewhere, whether that be within the manufacturing phase, or another module entirely. These insights will be included in the final development of the design tool.

Firstly, the two pathways to reduce the impact of the production process itself conflict. Alternative fuels tend to have a lower calorific value and a higher moisture content. This results in a lower efficiency of burning the fuel in the kiln. Besides, some alternative fuels contain substances that are not present in typical fuels, but are harmful for the environment.

Next, reducing the clinker-to-cement ratio by using more furnace slag, can increase the electricity consumption during the manufacturing stage. As furnace slag is a much harder material, it takes more energy to grind. In other words, the electricity consumption during the milling step is higher for the furnace slag than it is for clinker. This can be evaluated with a quick-LCA, getting an idea of how the numbers resulting from a change relate to each other.

Lastly, the clinker-to-cement ratio can also affect the durability of the concrete (Schneider, 2015). If a cement fails quicker and thus has a shortened lifespan, the impacts of the manufacturing phase are more pronounced when a specified amount of time is compared.

d. Define quick-LCA moments

As previously stated, the use of alternative fuels can result in a reduced efficiency and the emission of harmful substances. Therefore, it is important to understand how the benefits of the alternative fuels weigh up to the disadvantages. When different fuel options are considered, a quick-LCA can be performed to assess the environmental impacts and select the most beneficial option.

In order to perform the LCA, the energy sources and efficiencies must be specified. For this, research needs to be performed into the availability and chemical characteristics of the fuel types. It must also be investigated whether kilns used for traditional fuels can be used for alternative fuels, and what the specifications of those kilns are. The LCA is then performed selecting the energy sources from the database, and specifying the amount of each fuel, based on the efficiencies. The results from the LCA assess how the benefits of selecting an alternative fuel weigh up to the losses due to lower efficiencies, or trade-offs in other environmental impact categories.

Another situation where a quick-LCA can prove useful, is for defining the clinker content of the cement. With an LCA, the differences in raw material extraction and manufacturing impact can be compared for clinker and the alternative materials. That way, an optimal composition can be found. This would also be useful to assess the adverse effects of the reduction of the clinker content as stated in the previous section.

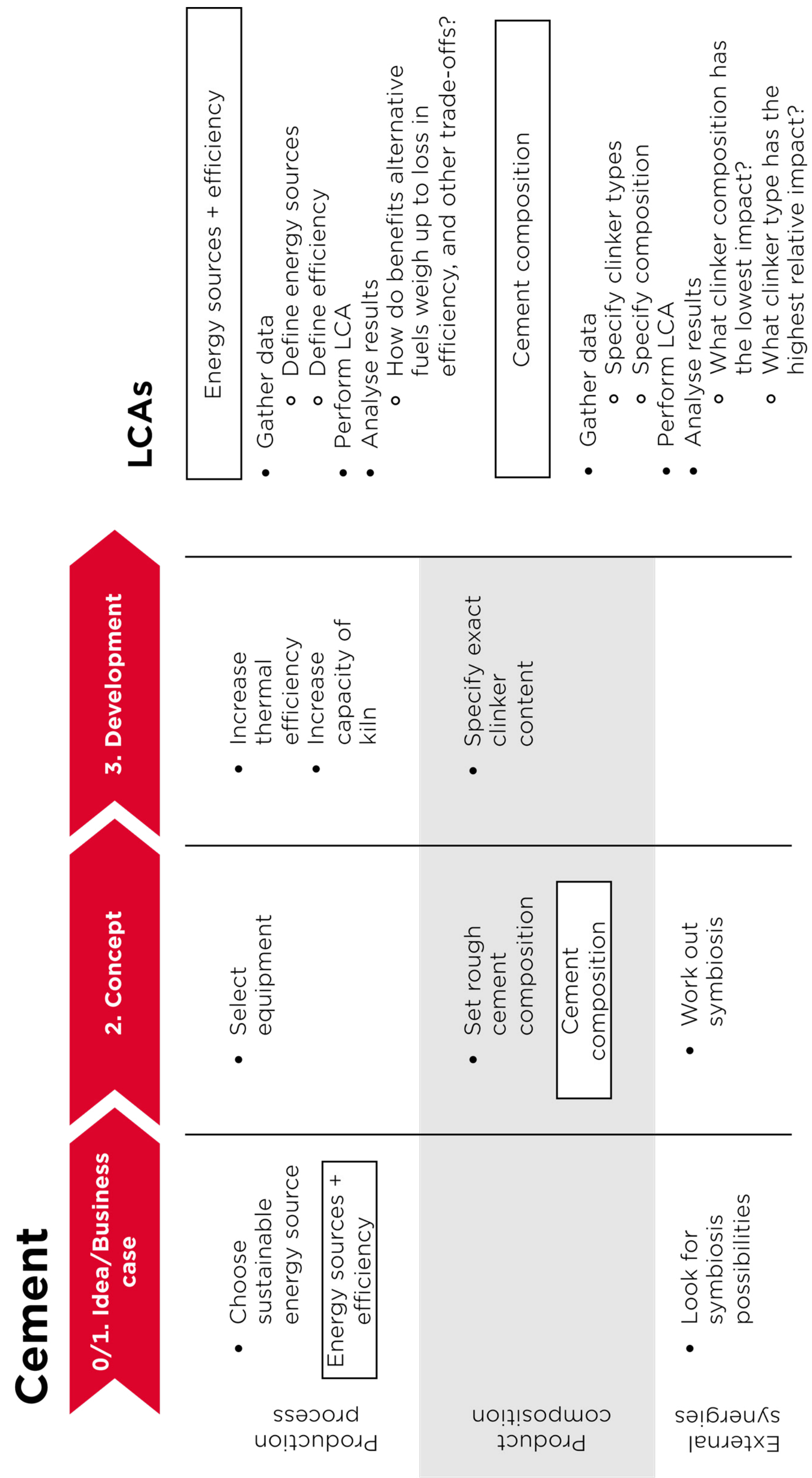
The LCA for determining the clinker composition is similar to the LCAs specified for the Aalberts IPS design tool. First, the clinker types need to be specified, as well as the cement composition, specifying the weights of each of the clinker types. The LCA should then be analysed by evaluating what cement composition is the most beneficial, and how the relative impact of each clinker option compares.

In the interplay, the relation between clinker type and electricity consumption during the milling step, and the durability of the cement is mentioned. This interplay can be considered, however it must be ensured that this does not overly complicate the analysis.

e. Combine into design tool

The above findings are combined into a design tool suiting the cement case, presented in Figure 6. It must be noted that the level of detail in this design tool is much lower than a design tool that will be used in practice, due to the limitations previously addressed. However, it provides a good insight of what a design tool could look like for the cement case. The top of the design tool shows the steps during the product development process, the bottom shows in more detail the steps that need to be taken to perform the LCAs.

Figure 8: Suggested design tool for cement case (displayed on the right)



The design tool shows how the three improvement pathways are defined in consequential steps during the product development process. The production process is defined by first choosing a sustainable energy source in the idea phase, using LCA to guide the decision. Next, the specific equipment is selected based on the choice for the energy source, and finally the processes are defined in more detail, aiming to increase the thermal efficiency. The product composition is determined by first setting rough clinker composition in the conceptual phase. Here LCA can be used to evaluate the differences in impact across environmental indicators for the clinker alternatives. External synergies are also investigated, first by evaluating possible relations in the idea phase, working them out in the concept phase.

As is the case with the Aalberts IPS design tool, the focus lies in the product development steps up to the development phase. After that, no useful analysis and development steps could be found.

5. Use
The design tool will be used, where all people that are involved in the decision-making process are educated on how the design tool must be used.

6. Evaluate
After using the design tool for a while, it can become necessary to re-evaluate and improve the design tool based on the changing situation. This section shortly discusses the three ways in which the design tool can become obsolete, and how likely it is to happen for the design tool suggested for the cement case.

It is expected that the LCA results will change based on the improvements suggested in the design tool, which could result in a shift in which module the largest impact lies. Changing out the share of clinker in the cement can change the impact of the raw materials extraction phase, alongside the desired change in impact in the manufacturing stage. This could mean that the materials phase ends up as the largest contributor to the total score. The design tool should then be completely replaced by a design tool focussing on the materials module.

The improvement potential is less likely to deem the design tool outdated. Where the main focus on improvement of the production processes now lies on using (renewable) waste materials as fuels, the discussion about using renewable electricity is only just starting. In other sectors, with admittedly lower demands for the system, renewable electricity sources have already been implemented to a much larger degree. However, also in other high-demand sectors, changes are made to switch to renewable energy sources. Exemplary are the efforts by ArcelorMittal to develop kilns running in 100% renewable electricity (ArcelorMittal, 2022). It can be concluded that the improvement potential for the proposed improvement

pathways will continue to be relevant.

Lastly, the design tool can require an update based on changing improvement pathways. Increasing focus on sustainability and regulation will continue to push companies and researchers to find new improvement pathways. These should continuously be evaluated and where relevant, added to the design tool.

G.2. LED luminaire

The second case-study is performed for a Planar LED Downward light, produced by TRILUX GmbH & Co. The production process is fairly straightforward. Materials are sourced for the electronic and structural components, as well as the packaging. Within the production facility, the circuit board is assembled, as well as the entire lamp. During the use phase, energy is used to fulfil its function of providing light. In between, transportation steps take place, and at the end of the useful life, the product is disposed of. The EPD by TRILUX GmbH & Co (2023) presents the environmental impact of the LED, and will be used to develop a design tool.

1. Calculate LCA-results
The results as presented in the EPD will be the starting point for analysing the environmental impacts. Similar to the cement case, more LCAs from literature will be used to get an idea of what causes the emissions. The EPD covers the modules according to ‘cradle to grave’. All modules, from raw material extraction up to disposal and recovery are covered. However, the impacts from modules A1-A3 are presented in a combined score. The declared unit is one downward light. Not all of the environmental indicators for which a weighting factor was available were declared, no values were available for the impact categories of particulate matter, ionising radiation, ecotoxicity, human toxicity (cancer and non-cancer) and land use.

The results from the EPD are presented in the figures below. Figure 7 shows the characterised results per environmental indicator for each module, all scaled to add up to 100%. Figure 8 shows the weighted indicator score, where the impact of each environmental indicator is added together for each module.

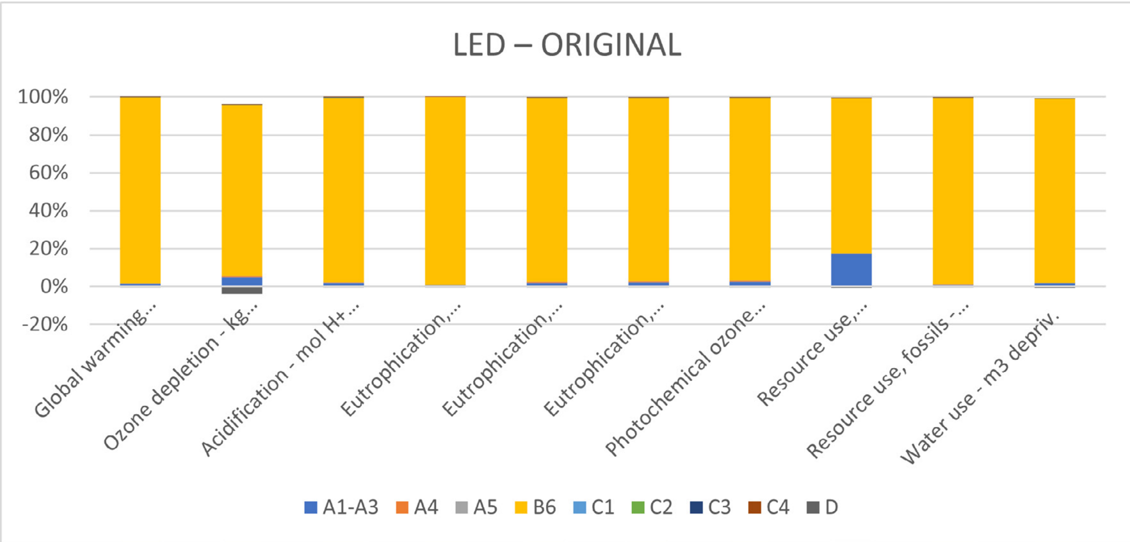


Figure 9: Characterised EPD results for LED luminaire. Data from TRILUX GmbH & Co (2023)

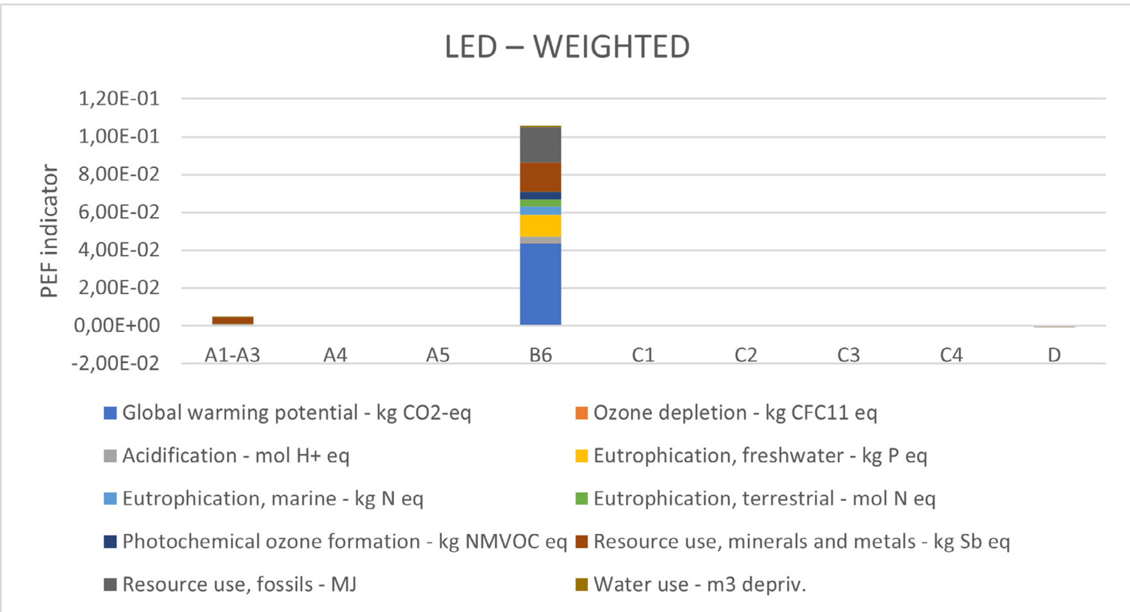


Figure 10: Weighted EPD results for EPD LED luminaire, cumulative impact per module displayed in PEF indicator

2. Analyse LCA-results

From the EPD results, it can be seen that an overwhelming majority of the impact is caused in the B6 module, the operational energy use. This is true for all of the environmental indicators, with an average of 96%, and a lowest value of 83% for resource use, minerals and metals. Here 17% of the impact is caused by the combined modules of A1-A3. From Figure 8 it can be seen that most of the impact caused by the B6 module, is caused by the climate change category (40%), followed by the use of fossil fuels (17%) and minerals (16,8%). The second most impactful phase is the combined score of A1-A3 with 4%, mostly caused by the minerals and metals consumption and climate change.

These findings correspond with findings in supplementary sources (Casamayor et al., 2017; Principi & Fioretti, 2014; Wang et al., 2020), and these studies showed that the impact in the operational energy use phase are caused by the electricity usage.

3. Follow decision tree

Knowing where the impacts lie within the product's lifecycle, the decision tree can be followed. The steps that were followed to find what design tool and/or recommendation are suitable are as follows:

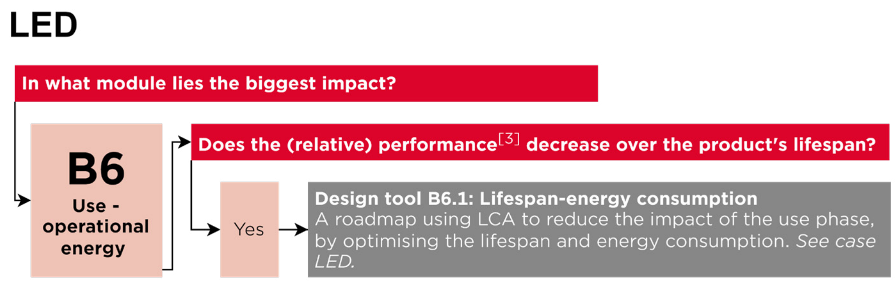


Figure 11: Steps from decision tree for LED case, based on EPD and LCA

The second question could not be answered by the analysis of EPD and LCA data, hence literature was studied. If this analysis were performed within a company, it is likely that this information would already be present within the company.

It was found that the lumen efficiency of LED lights is known to degrade over its lifespan (Lumileds, 2016). Its relative performance also decreases, as the efficiencies of newer LED technology are still increasing, even though this increase is slowing down (Pattison et al., 2022). Knowing that the (relative) performance decreases over the product's lifespan, means that overall energy savings might be achieved by reducing the lifespan of the LED luminaire.

In the end, the decision tree yields a design tool that serves to find the optimal balance between lifespan and energy consumption during the use phase.

4. Develop design tool

Having pointed out what type of design tool could be useful for the LED light, further analysis should be performed of the product development process. As stated before, for the cases that were studied, there was no access to real company data. Therefore, literature was studied.

a. Study decision-moment

It is assumed that the product development process at TRILUX involves the design of the LED package, selecting LED and driver technology as developed in other companies. Other aspects of the LED package, such as the structural components of the luminaire are fully designed by the company. In the EPD it is specified that their facility mostly concerns assembly, so it is assumed that they outsource the production of the structural components. This means that they have limited control over the raw materials and production of the electronic components, and the production of the structural components. They do have control over the raw materials going into the structural components and the production processes at the assembly site.

Regarding the steps that are taken during the product development process, the experience from within Aalberts proved unhelpful, as the products considered at Aalberts IPS have no environmental impact during their use phase. However, the general idea of defining characteristics in multiple steps does still apply. Evaluating the improvement pathways will provide a better insight on what decisions are taken. This will then be taken into account and used to form the design tool.

b. Search improvement pathways

In a report by Pattison et al. (2022), the following improvement pathways were found.

- Light source efficiency
  - Thermal efficiency
  - Driver efficiency
  - Optical efficiency
- Light application efficiency (LAE)
  - Optical delivery efficiency
  - Intensity effectiveness
  - Spectral efficiency

Light source efficiency (LSE) measures how effectively the LED can generate a certain amount of light. Several factors impact light source efficiency, including thermal efficiency, where the generation of heat reduces the overall efficiency of the light source. To maintain optimal efficiency, cooling mechanisms are necessary to regulate the temperature. Another factor is driver efficiency, which involves the conversion of high-voltage AC to low-voltage DC for LED usage, resulting in energy loss during the process. Lastly, optical efficiency plays a role, as lenses, reflectors, and other methods used to transform a single LED into a functional lamp can reduce the total amount of emitted light. As it is assumed that the company does not develop LED technology in-house, these improvement pathways

should only be considered in selecting the best technology to use in the LED package.

Light application efficiency (LAE) focuses on the efficiency of the light source to fulfil its function of making the right things visible. Optical delivery efficiency measures the proportion of emitted light that actually reaches the intended illuminated area, aiming to minimize light scattering. Intensity effectiveness refers to emitting only the necessary amount of light, adjusting the intensity in response to the available daylight conditions. Spectral efficiency is another aspect of LAE, which involves emitting only the wavelengths of light that are useful for the given task while avoiding the emission of invisible or less useful wavelengths. As this pillar has become of interest only recently, there is still a lot of improvements that can be made here (Pattison et al., 2022)

The design tool not only aims to improve the energy efficiency, but also intends to find the optimal lifespan based on reducing efficiency over its lifespan, and increasing efficiency of newer technologies. In most LED lights, the lumen efficiency has reduced to 70% after a lifespan of 50.000 hours (Lumileds, 2016). For the relative efficiency, compared to newer technologies, the forecast by Yamada et al. (2019) was used. As can be seen in Figure 10, these efficiencies will continue to increase in the coming years, but slower than in the years before.

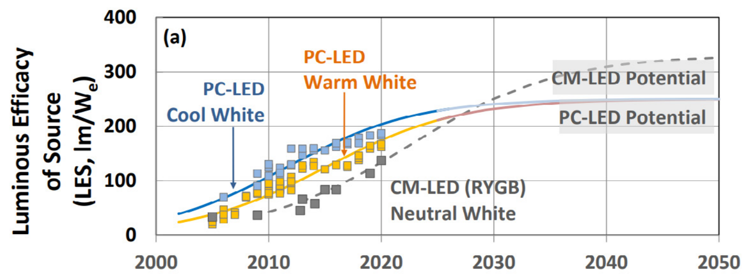
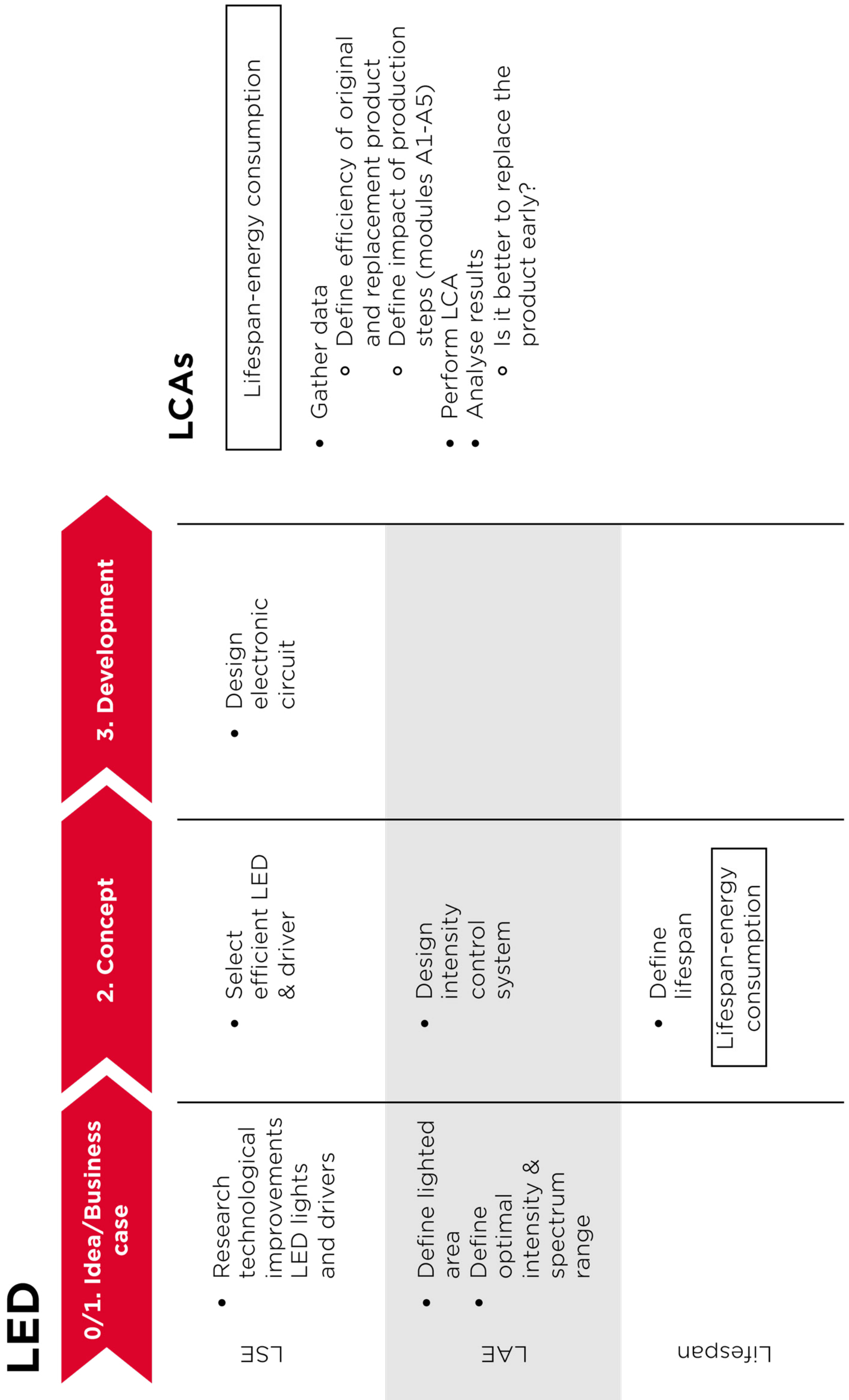


Figure 12: LED Luminaire efficiency trends for large downlight application (source: Pattison et al. (2022)).

c. Look for interplay

Within the scope of reducing the energy consumption during the use phase, two variables conflict. Increasing the application efficiency means the light will need to be directed to where the light is necessary. This involves more lenses and reflectors and other optical systems, reducing the optical efficiency of the light source.

Besides, the design tool following from the decision tree inherently points at another conflict: that of reduced efficiency versus impact of production. A longer lifespan means less total impact on the manufacturing steps, as only one product will be used. However, this comes with an increased energy consumption as the product is less energy efficient than the



replacement product.

d. Define quick-LCA moments

For the design tool found in the decision tree, it is specified that an LCA can be useful during the product development process. This LCA will help evaluate whether the extension of the lifespan is preferrable or not. The LCA that will be performed is similar to the study described in Richter et al. (2019), comparing different replacement scenarios. For example, one scenario without replacement for a specified lifespan, and one replacing the product halfway. The data that is required for the LCA is firstly the efficiency of the original product, and a forecast of increased efficiency for the replacement product based on Pattison et al. (2022) (see Figure 10). Besides, a general estimation of the impact of the production and installation steps is needed (modules A1-A5). This will be based on the LCA of the portfolio. The scenarios are then modelled, filling in the overall energy consumption based on the efficiency, as well as the total impact of production, based on the number of replacements. The results will then present which scenario is more beneficial, which can be evaluated based on the different environmental indicators and the overall indicator score.

It must be noted that this type of LCA only accounts for the decreasing relative efficiency, looking at the difference between the original product and the new, improved technology. It does not account for the reduced lumen efficiency over the lifespan of the product. In this case, it is deemed too complex to quantify the recline in efficiency over the lifespan, complicating the performance of the LCA. However, if the company is interested in investigating the effects of this decreased efficiency, it could be included. To do so, more research is required into the decline of efficiency of the product in study, as well as calculations of the total energy consumption based on different lifespans according to the decline of lumen efficiency that is found.

e. Combine into design tool

The design tool is developed based on what was found in the steps described above, and presented in Figure 11. Again, this design tool is of a lower level of detail than it would be in practice but provides is a useful illustration of what a design tool could look like nonetheless. It follows the same structure as the suggested design tool for the cement case, where the top suggests steps to take during the product development phases, and the bottom specifies how the LCA should be performed in more detail.

Figure 13: Suggested design tool for LED case (displayed on the left)

The relevant decisions, as highlighted in the improvement pathways, are assigned to the lifecycle phases in which they occur. The choice of LED and driver technology happens in two steps, first researching the technological advancements, so that in the next step, the most efficient technology can be selected. To increase the light application efficiency, the requirements are set in the idea phase, specifying where the light is wanted, and what intensity and spectral range is most suited for the task. This is then used in the concept phase to work out an intensity control system. The chosen light technology and intensity control system will be combined into the final electronic circuit design. The LCA takes place in the concept phase, considering the different options for LED and driver technology, with their cumulative efficiency.

5. Use
Having developed the design tool, it is put into practice. It is made sure that all people that are involved in the steps mentioned in the design tool know how to use the design tool.

6. Evaluate
While the design tool is being used, it is constantly evaluated if the it continues to fit the situation. The step-by-step guide describes three ways in which the design tool can become obsolete, in this section it is shortly considered how likely it is that the design tool needs to be updated based on those.

Firstly, the results from the LCA of the portfolio can change. As the impact within the B6 phase currently accounts for 96% of the total impact, across all environmental impact categories, it is unlikely that the impact will shift to another module. Therefore, based on the LCA results, the design tool is estimated to be useful for an extended period of time.

The improvement potential is more likely to deem the design tool outdated. As can be seen in Figure 10, the trend of increasing efficiency slows down. Therefore, replacing the product with a new product becomes less likely to be beneficial. This means that based on the relative efficiency, the decision tree would yield another result. Where the lumen efficiency is left out of scope for the purpose of this demonstration, this is likely to stay relevant. Changes to the design tool are likely to be in the form of adding a recommendation, or removing a step.

Next, the design tool can require an update based on improvement pathways. As the light application efficiency was only recently added as a focus for reducing the energy consumption in LED technology, it is likely that new technologies and insights arise from that research topic. Besides, another focus can be discovered, next to LSE and LAE. For this, small adjustments to the design tool will suffice as well.

G.3. Aalberts IPS

As stated previously, the case-study for Aalberts IPS has been performed in a different way than the cases of cement and LED. The situation at Aalberts IPS has already been studied in order to develop a design tool, which is used to develop the framework. In other words, before the steps of the framework were formulated, the design tool for Aalberts IPS was

already defined. The following evaluation steps are performed to find out if the steps of the framework would lead to a different resulting design tool than the steps that were used in the first place. It also provides additional insight as in contrast to the other cases, this case was performed within the company. That means that it more closely resembles the use of the framework in practice.

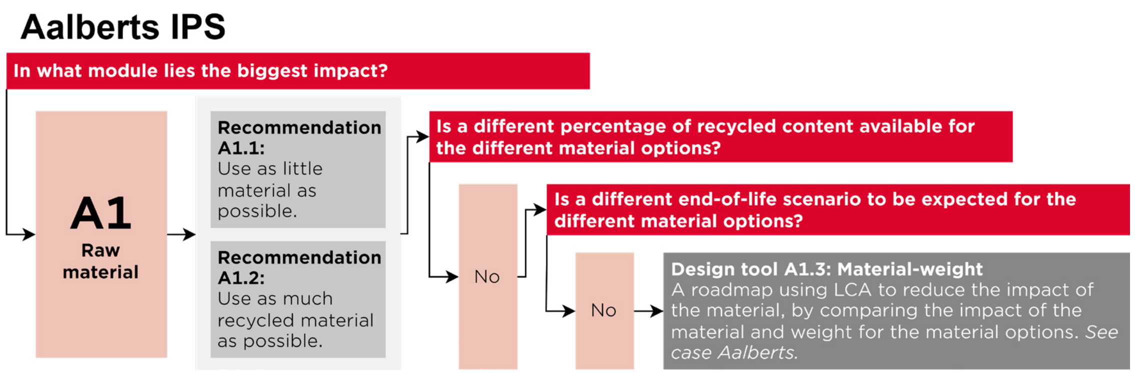
The steps below are described in a concise way, as it is mostly already discussed in Section 3.2 of the report. Only the differences between the process described there and the findings from following the framework are discussed.

1. Calculate LCA-results
The results of the LCA of the product portfolio of Aalberts IPS is presented in Section 3.2.3, showing graphs of the total impact of the products expressed per lifecycle phase (Figure 7), the relative impact of materials per ton (Figure 8) and a comparison of the contribution of subparts to the total mass of the product compared to the environmental impact (Figure 9).

2. Analyse LCA-results
The conclusions that are drawn from the LCA of Aalberts' portfolio are also discussed in Section 3.2.3. A short summary of the conclusions is as follows:

- The vast majority of the impact is in the raw material supply phase (A1), on average across the different products this phase accounts for 90% of the total impact.
- The environmental impact of the material differs greatly for different alloy families. Brass has a much larger environmental impact per unit of mass than for instance stainless steel. Of the products compared, carbon steel has the lowest relative impact.
- Subparts that comprise only a fraction of the weight of the product can have a large impact on the total environmental impact of a product.

3. Follow decision tree
Based on the analysis of the LCA results, the decision tree could be followed:



For the follow-up questions, further analysis was required. It was found that the percentage of recycled content is expected to vary between options. However, suppliers of the material currently provide limited insight into the recycled content that is used. Therefore, the second question was answered with 'no'. This lead to another question, about whether different end-of-life scenarios are to be expected. This is indeed the case, but the uncertainty of the end-of-life scenarios would greatly compromise the outcomes of the analyses. More about this is discussed in Section 5.1.2. This lead to the design tool A1.3 'material-weight' to be most suitable.

4. Develop design tool
The recommendation and design tool are further defined in the next steps.

a. Study decision-moment
The decision for the material of the product is taken in the following steps (as is also discussed in Section 3.2.4):

- Main body – alloy family
- Main body – specific alloy
- Subpart – alloy family
- Subpart – specific alloy

With each step, the level of detail increases, from general alloy family to the specific alloy of the largest part of the product (the main body). The same steps are followed for the smaller parts.

b. Search improvement pathways
The improvement pathways that have been implemented into the design tool for Aalberts IPS before the framework was developed are the following:

The material choice focusses on using materials that are less environmentally straining. This improvement pathway is based on the conclusion from the portfolio LCA, showing great differences in environmental impact per mass of a product for different materials.

The next improvement pathway is to reduce the amount of alloying elements that have a great environmental impact whenever the specific alloy is custom-made for the situation. As the material decision is defined in two levels of detail, an analysis was performed of the differences between potential options in the step of defining the specific alloy. It was found that different alloying elements also show great differences in relative environmental impact. If these differences are known, a specific alloy can be defined to contain less of the environmentally straining alloying elements.

Following the steps from the framework, an additional study was performed of possible improvement pathways. According to Raabe et al. (2019), the sustainability of metal products can be improved by designing for longer lifespan, designing for reuse, designing for including recycled content in the products, and lastly choosing alloys from a limited spectrum for easy recycling.

Most of these improvement pathways have already been considered in the initial development of the Aalberts IPS design tool, but not added due to the following reasons. The lifespan of AIPS' products is highly dependent on the lifespan of buildings, therefore a focus on increasing the lifespan is considered to be of limited effect. Most of the fittings that are produced within AIPS are currently irreversibly pressed to connect to the pipelines. It would be valuable to consider reusable alternative designs. However, it has not been included in the initial design tool because of the higher complexity of the design considerations. Next, as already mentioned, the suppliers currently do not provide sufficient insight into the recycled content of their materials. This makes designing for recycled content impossible.

The last improvement pathway would be interesting in the context of the current design tool. An overview of alloys that are considered recyclable could be used to assess the recyclability of the alloying options in consideration.

c. Look for interplay
The current design tool accounts for two types of interplay. Firstly, when a different material requires different manufacturing processes, this is accounted for in the step 'consider processes'. Second, the difference in recycling percentage between material options is considered in the step 'consider recycling'. Where Table 2 in Section 3.2.2 presents more instances of interplay, the low impact in these lifecycle phases makes them negligible.

d. Define quick-LCA moments
The decision tree suggests the use of quick-LCA for the assessment of the influence of material and weight on the environmental impact of the product. In the design tool for Aalberts IPS, this is implemented on all levels of the decision-making process of the material. Firstly, to compare the alloy family options for the main body, then the specific alloy for the same part. Next, the alloy family is chosen for the subparts, followed by an analysis of the specific alloy of the subparts.

e. Combine into design tool
The findings from following the steps of the framework would not require a structurally different design tool than the one that is presented in Section 3.1 of the report. The only change that could be suggested would be to introduce some recommendations based on the improvement pathways that were found in Raabe et al. (2019).

What could be noted from the design tool for Aalberts IPS, is that the design tools that were initially found but dismissed due to the complexity of performing further analyses, were used as recommendations instead. Where the intention of design tool A.1.1 and A.1.2 is to include the respective recycled content and end-of-life scenarios into the quick-LCA calculations. This was considered too complex and the uncertainty too high to provide useful insights. However, the recycled content is indirectly taken into account in the step 'consider supplier options', and the end-of-life 'scenarios is similarly accounted for in the step 'consider recycling'

5. Use

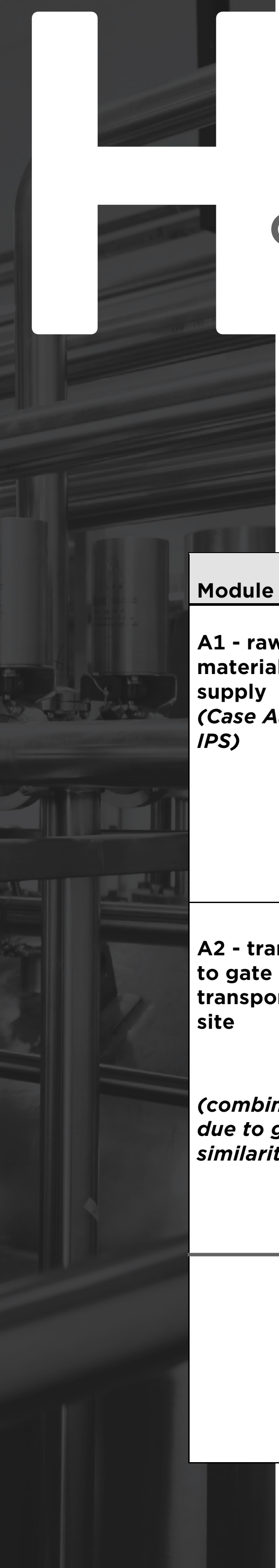
The evaluation steps described in Section 3.3 suggest easy application of the design tool.

6. Evaluate

Given the current LCA results it is considered unlikely that the results for new products will have the largest portion of the environmental impact in another module. Even materials with a low material impact, such as carbon steel, have a large majority of the impacts in the raw material extraction phase. Therefore it is expected that despite using the design tool to develop more sustainable products, the focus on the materials module will remain.

The focus on the material decision is also likely to remain relevant based on the improvement potential. In the current product development process, no attention is paid to the environmental impact of material options. Therefore, it is expected that much improvements can be made on this topic still.

Lastly, it is possible that new improvement pathways will emerge. However, these are expected to require only limited changes to the design tool. Instead of re-evaluating every step of the framework, steps could simply be added to the current design tool to consider other improvement pathways.



Overview of possible scenarios for design tool

Module	Variable	Within PDP	Complexity	Within influence	Value LCA	Type	Explanation possible design tool
A1 - raw material supply *(Case Aalberts IPS)*	material type	Yes	High	Yes	+	Design tool (A1.3)	Use quick-LCAs to determine the most sustainable material option (Case Aalberts IPS)
	weight	Yes	Medium	Yes	Low	Recommendation (A1.1)	General recommendation to reduce weight, not useful to develop into its own design tool
	recycled input	Yes	High	Yes	Low	Design tool (A1.1)	Here a quick-LCA can be used that compares the initial environmental impact of the material types with the recycled content of the options. That way a fair comparison can be made of the material options.
A2 - transport to gate + A4 - transport to site	distance	Not quite	Low	Not quite	Low	Recommendation (A2.3)	A recommendation would be useful for the supply chain department (outside the product development process) to lower the transportation distances. For A4 this would be a bit different, the target market should be closer to the production site
(combined due to great similarity)	mode of transport	Not quite	Medium	Not quite	Medium	Recommendation (A2.4)/design tool (A2.1)	There are a lot of modes of transport, so it might be helpful to evaluate the environmental impact of the options. If they are always selected from the same list, one calculation suffices (instead of calculating it repeatedly in a desgin tool)
	weight	Yes	Medium	Yes	Low	-	Not too relevant on its own, as the product design and the transportation steps are defined in such different parts of the development process. However, it would be interesting to see how the weight affects both the material impact and transport category, so a design tool of that interplay might be relevant.
	load efficiency	Not quite	Medium	Not quite	Low	Recommendation (A2.1)	There is a logical relation between load efficiency and environmental impact, an LCA wouldn't be very helpful here. Also not so complex that a design tool is required. Might be interesting to look at the interplay between all factors of transport

Module	Variable	Within PDP	Complexity	Within influence	Value LCA	Type	Explanation possible design tool
A3 - manufacturing *(Case cement)*	energy source	No	Low	Yes	Medium	Recommendation (A3.1)	This decision is not so complex that you need a design tool for it, this is usually just a matter of finding an alternative and implementing it.*
	energy consumption	Yes	Medium	Yes	Low	Recommendation (A3.2)/design tool (A3.1)	Depends on whether the machine is simply chosen or if the processes are also tailored to the company. For only choosing a machine, a recommendation would suffice, but if the processes are also defined then this adds complexity, making a design tool more useful.
	material, waste	Yes	Low	Yes	Medium	Recommendation (A3.3, A3.4)	Considering this could be really relevant, as the choice for a type of processing defines the amounts of ancillary materials and wastes generated. It will also be defined in multiple steps.
	direct emissions	Not quite	High	Not quite	High	Design tool (A3.2)	It really depends on the situation if the company can influence the emissions, sometimes they're inherent to the process steps (e.g. CO2 emissions for calcination). If the company does have an influence it is complex and therefore requires a design tool.
A5 - installation	material (type and amount)	Not quite	High	Yes	High	Design tool (A5.2)	If most of the impact is in this variable, the decision requires more attention that it is traditionally given. A design tool is a good way to provide structure to that.
	energy (type and amount)	No	N/A	No	Low	Design tool (A5.1)	If most of the impact is in this variable, the decision requires more attention that it is traditionally given. A design tool is a good way to provide structure to that.
B1 - emissions during use	direct emissions	Not quite	High	Not quite	High	Design tool (B1.1)	Similar to the direct emissions in the manufacturing phase, the use of a design tool depends on whether the company can influence the emissions or if they are inherent to the process. Again, if the company can influence it, it is a complex decision, requiring a design tool

**This judgement is based on the situation at Aalberts IPS, where the options for the energy source are grey or green energy. In that case it is indeed a matter of finding a supplier for the alternative energy and signing a contract. However, in other instances a switch to another energy source can be more complex. For a switch from a coal-powered kiln to an electricity-powered kiln a complex set of changes is required to the machinery and infrastructure. More about this flawed judgement is discussed in Section 5.2.3.*

Module	Variable	Within PDP	Complexity	Within influence	Value LCA	Type	Explanation possible design tool
B2 - maintenance B3 - repair B4 - replacement B5 - refurbishment	frequency	Yes	High	Yes	Low	Design tool (B2.1, B2.2)	The maintenance frequency is interesting and complex to consider, as more maintenance could increase the lifespan, but the maintenance actions do have their own environmental impact. A thorough study could be done to evaluate the most beneficial option. However, it should be evaluated if this level of detail is desired for a quick-LCA during the product development process
	material (type and amount)	Yes	High	Yes	High	Design tool (B2.2)	Inquiring the impact of different material options is relevant, as is the trade-off between more material (and thus higher impact) and longer lifespan
	waste	Yes	High	Yes	High	Design tool (B2.2)	Relevant to consider alongside the use of material for the maintenance steps
	water consumption	Yes	High	Yes	Low	Design tool (B2.2)	Again, the trade-off between impact of a maintenance action versus the benefits in increased lifespan
	energy (type and amount)	yes	High	Yes	Low	Design tool (B2.1)	Again, the trade-off between impact of a maintenance action versus the benefits in increased lifespan
B6 - operational energy use *(Case LED)*	energy source	No	Low	No	Low	-	Typically, the producing company has no influence over the energy source that the users use for their product.
	energy consumption	Yes	High	Yes	Low	Design tool (B6.1, B6.2)	This is a complex improvement, where the structure of a design tool can be helpful
	lifespan	Yes	High	Yes	Low	Recommendation (B6.1)/design tool (B6.1, B2.1, B2.2)	Lifespan is relevant not only within the B6 module, but also all of the maintenance modules. Within the operational energy use it is also interesting if the (relative) energy efficiency of the product decreases over time. In that case, it might be better for the environment to replace the product than to use it for longer periods of time.
B7 - operational water use	amount	Yes	High	Yes	Low	Design tool (B7.1)	The water consumption during the usephase is defined in multiple steps of the decision-making process, thus a design tool is useful
C1 - de-construction, demolition	energy source	No	N/A	No	Low	-	So far out of the influence of the company that design tool nor recommendation are useful

Module	Variable	Within PDP	Complexity	Within influence	Value LCA	Type	Explanation possible design tool
	energy consumption	No	N/A	No	Low	-	So far out of the influence of the company that design tool nor recommendation are useful
C2 - transport to waste processing	distance	No	Low	No	Low	-	So far out of the influence of the company that design tool nor recommendation are useful
	mode of transport	No	N/A	No	Low	-	So far out of the influence of the company that design tool nor recommendation are useful
	weight, load efficiency	No	N/A	No	Low	-	So far out of the influence of the company that design tool nor recommendation are useful
C3 - waste processing for reuse, recovery or recycling	energy source	No	N/A	No	Low	-	So far out of the influence of the company that design tool nor recommendation are useful
	energy consumption	No	N/A	No	Low	-	So far out of the influence of the company that design tool nor recommendation are useful
C4 - disposal	weight of waste	Yes	N/A	Yes	High	Design tool (A1.2)	End-of-life scenarios are interesting to consider alongside material impact
D - reuse, recovery and/or recycling potentials	weight per eol treatment	Yes	N/A	Yes	Low	Design tool (A1.2)	Intesting to consider alongside the material impact, in order to compare the initial material impact of a product with the recycling percentages (and other recovery scenarios).