Research on presenting life cycle assessment results concisely to a non-technical audience

Keywords: Life Cycle Analysis, LCA communication, LCA Executive/Management Summary

Bachelor Thesis - Bachelor Integration Project

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1.2 Abstract

Life cycle assessments (LCA) have become increasingly applied, in a progressive trend to map environmental impact of processes. However, issues in communication of LCA results are experienced as a result of divergent methodological approaches, making interpretation of results complex for a non-technical LCA audience (Gradin, 2020) (Sala and Andreasson, 2018). Difficulties in presenting such results in a concise manner are experienced by Ecoras, an environmental sustainability consultancy company and stakeholder of the project. Therefore, a combination of literature research and reviews on LCA documents is done in this paper, in order to evaluate the content, structure and visualisation of LCA summaries. What was found in the research, is that the main issue in misunderstanding LCA results is not the presentation of the final impact. Rather, it is not being able to understand why the results are as they are. To tackle this problem, the recipients should be taken through the process of the LCA, being provided with sufficiently enough context. In summaries this is often attempted, but the logic is not always followed. Therefore, this paper suggests presenting the relevant LCA methodological background in a structure, similar to that of the execution of the LCA in its respective phases, while making proper use of the system boundary diagram and result visualisation.

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1.3 Glossary of abbreviations

AESI	Absolute Environmental Sustainability Indicators
ALCA	Attributional Life Cycle Analysis
BTX	Buolene, Toluene, Xylene
CE	Circular Economies
CLCA	Consequential Life Cycle Analysis
CR	Chemical Recycling
DGU	Deep Green Utility
DNM	Data Needs Matrix
EF	Environmental Footprint
FU	Functional Unit
ILCD	The International Reference Life Cycle Data System
iLUC	Indirect Land Use Change
ISO	The International Organization for Standardization
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCA	Life Cycle Assessment/Analysis
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene Plastic
MPW	Mixed Plastic Waste
CRP	Chemical Recycling Plant
POME	Palm Oil Mill Effluent
PTO	Power Take-Off
SMGP	Single Market for Green Products

1.4 Introduction

In an era where environmental footprints are becoming more frequently addressed, life cycle assessments, or life cycle analyses, applications are becoming increasingly popular (Kousemaker, Jonker and Vakis, 2021). An LCA estimates and quantifies the environmental impact of a system, by mapping energy and mass balances (Kousemaker, Jonker and Vakis, 2021). This system encompasses the five life cycle stages, raw material extraction, production, distribution, use and disposal (Subramanian *et al.,* 2020). In LCA studies, circular economies (CE) are becoming increasingly applied, where upcycling is used for the closing of material cycles (Dieterle, Schäfer and Viere, 2018). The conventional cradle-to-grave approach, which is the environmental impact created by products or activities ranging from the beginning of its cycle to the disposal, is turning into cradle-to-cradle, which is is the principle of turning the end of life of a product cycle back into material to the same or another system (Dieterle, Schäfer and Viere, 2018). Data quality and reliability of LCA studies have been improving in recent years (Björklund, 2002), along with more research into chemical recycling (CR) of plastics (Davidson, Furlong and McManus, 2020) (Palme *et al.,* 2017). An example case of such chemical recycling by using LCA studies has happened in lower olefins, which are the second most resource and emission intensive products in Germany's manufacturing sector, which has shown a viable increase in sustainability when replacing the conventional fossil feedstock with renewable or secondary feedstock (Keller, Lee and Meyer, 2020). In this paper, a research for improving communication of LCA results is conducted, of which the details are explained in the problem analysis section.

2 Problem analysis

2.1 Problem owner analysis & problem statement

The problem owner is Ecoras, which is a company that consults industrial organizations that want to reduce the environmental footprint of their processes. They provide insights into the value chain of industrial processes of their clients, by taking a critical look at raw materials and secondary material flows. One of the methods used to map these value chains is a life cycle analysis. There are documents which guide the creation of LCAs by a number of standards, which is later explained in the theory section. These documents do not state a general format in communicating results. This is a grey area where Ecoras experiences problems. In existing literature and reports, they often experience that wrong interpretation of results can occur, due to for example chain insights that are hard to grasp by hidden assumptions in the reporting process. Such hidden assumptions can happen in bar charts, which may contain underlying information that is often not (clearly) communicated. Furthermore, a complete chain overview is often missing, which may cause the audience to misinterpret the system, and thus its results. Hence, the problem statement is described as follows:

Ecoras does not have a readily available transparent way of presenting LCA results to their clients and/or investors of clients.

2.2 Stakeholder analysis

Ecoras is the main stakeholder, which is the problem owner. They have a high interest in the outcome of the research, due to the potential direct application of the formatting of results for their clients. They have a high power with regard to the integration of the results due to the degree in which they decide to apply it in practice.

The clients they work with are also stakeholders. Their clients can understand the results better when the value chain is conveyed in a manner that optimizes the grasping of chain insights. However, the power of the clients in the research are limited, due to their somewhat more distant relation.

Lastly, other companies using life cycle analyses as methodologies in the consulting of customers are interested in the formatting, should this become a widely applied format that is deemed convenient with regard to the transferring of results. However, external companies do not have a say in the decision making process of Ecoras and their clients, and therefore they have a low power.

To visualise the aforementioned stakeholders, a Mendelow's Diagram is shown below (Mendelow, 1991). Each stakeholder is represented with regard to their power and interest. The interrelationships between the stakeholders are depicted with arrows.

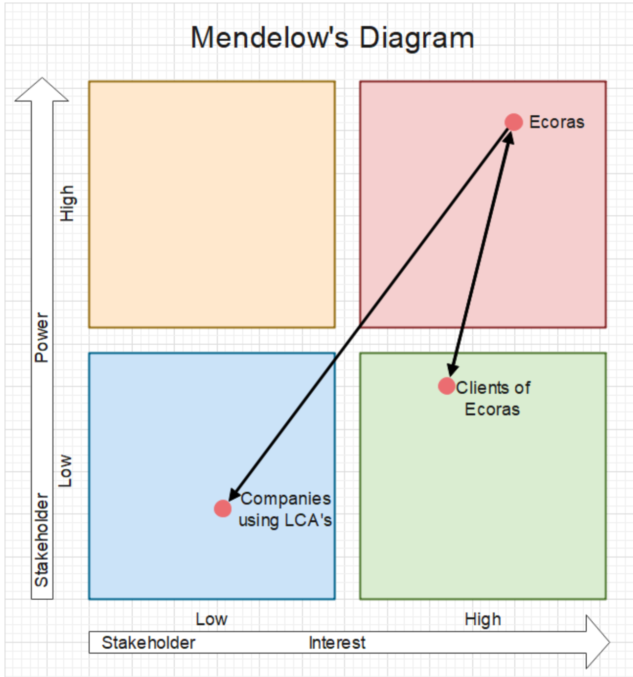


Figure 1. Mendelow's diagram, depicting the power and interest of the stakeholders of the research, as well as the interrelationships between the stakeholders (Mendelow, 1991).

2.3 Research objective

The research objective is derived by combining the essence of the problem statement and stakeholder analysis, where the SMART method is used to state an effective objective (Bjerke and Renger, 2017) (Doran, 1981). The research objective is described as follows:

The research objective is to identify improvements in the executive/management summary of LCAs, that minimizes the possibility of misinterpretation of results and optimizes the communication of assumptions and chain insights.

2.4 Research questions

By answering the main research question, the research objective is answered. Furthermore, the answering of the sub questions cascade into answering the main research question. The main research question is described as follows:

What improvements in the executive/management summary of LCAs can be identified that minimizes the possibility of misinterpretation of results and optimizes the communication of assumptions and chain insights?

By confronting the research objective with the research perspective, a theoretical research framework can be created (Verschuren and Doorewaard, 2010). This research framework is depicted below in figure 2, with subdivided categorizations a through c.

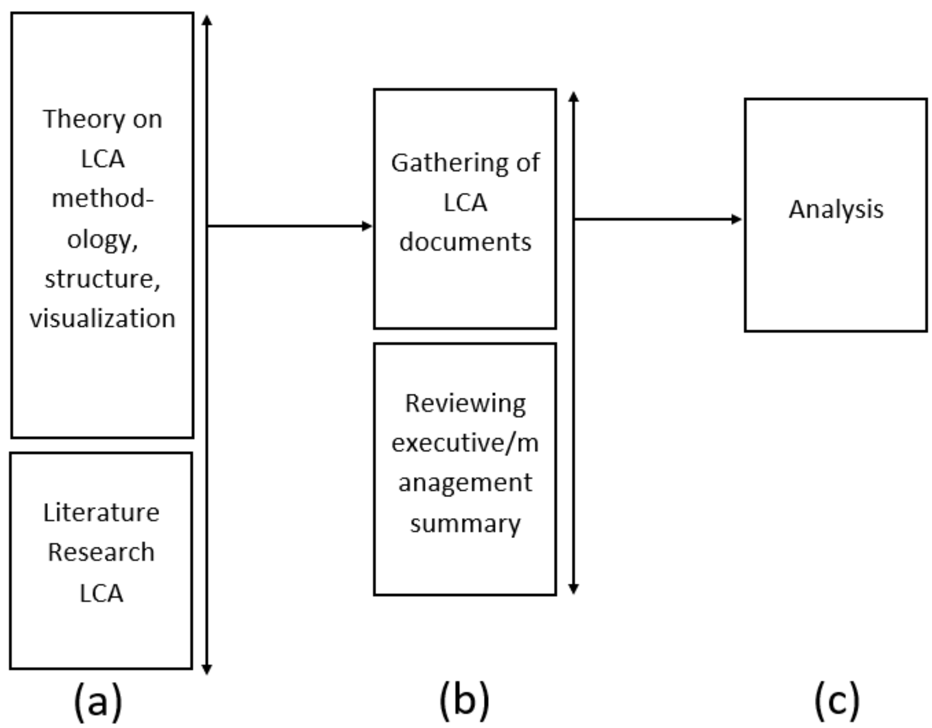


Figure 2. Research framework, consisting of key concepts of the research project and the assumed relationships between these concepts.

The cascading of all the tasks in a category, depicted by a vertical arrow, leads to the requirements of the tasks in the follow-up category, depicted by a horizontal arrow. Hence, by reading backwards from point c to point a, a clear chronological order can be read. In other words, to achieve the task in point c, the cascading of the terms in point b is required. This phenomenon of unravelling the research framework assists in the creation of sub questions. The sub questions are described as follows:

1. *What LCA content should be presented in order to minimize the possibility of misinterpretation of results and optimize the communication of assumptions and chain insights in the executive/management summary?*

2. *What LCA structure should be used in order to minimize the possibility of misinterpretation of results and optimize the communication of assumptions and chain insights in the executive/management summary?*

3. *What LCA visualisation methods should be presented in order to minimize the possibility of misinterpretation of results and optimize the communication of assumptions and chain insights in the executive/management summary?*

3 Body of knowledge

3.1 Theory

Life cycle assessments are increasingly becoming more standardized by documents coming from regulatory organizations, attempting to increase the level of acknowledgement and comparisons of LCA studies. On the other hand, they are a family of modelling studies, not a single one, which means that LCAs are not always comparable. Thus, communication of case specific LCA mechanics is of importance for the recipient to understand the studied results, limits and implications (Røyne *et al.*, 2019). Therefore, the theory section addresses some main aspects enlightening this, found in the literature research.

3.1.1 Regulatory documents and organizations

The International Organization for Standardization (ISO), standardizes LCAs in two documents (ISO 14040 and 14044, 2006). In these documents, LCAs consist of four phases, namely the goal and scope definition phase, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase and the interpretation phase (ISO 14040 and 14044, 2006), visualised below.

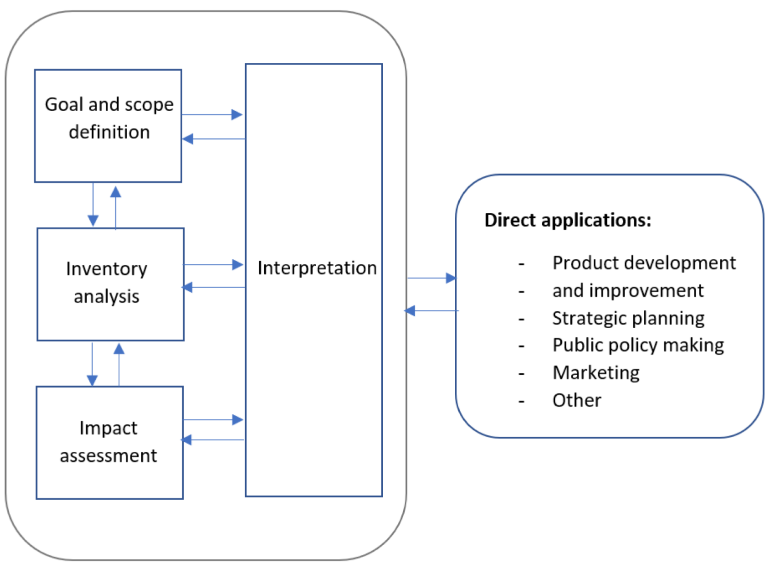


Figure 3. Life Cycle Analysis phases according to ISO standards (ISO 14044 and 14040, 2006).

The ISO standards provide requirements for each phase of the LCA, including a set of principles and a framework (ISO 14044, 2006). In addition to the ISO standards, the International Reference of Life Cycle Data System (ILCD) handbook provides technical guidance for governments and businesses on LCA practices (European Commission, 2010). Furthermore, the plastic LCA method of the Joint Research Centre provides a methodological framework for LCA studies of plastics from different feedstocks (European Commission, 2021). In short, multiple regulatory practices attempt to standardize LCAs to the extent possible where LCA studies can be more easily acknowledged and compared (Peters, 2016).

3.1.2 LCA approaches and impact assessment disparities

It is important to realise that an LCA is not a single, unique, objective assessment, rather, it is a family of assessments. Disparities exist between them due to the many modelling choices, the first of which is to decide between an attributional life cycle assessment (ALCA) or consequential life cycle assessment (CLCA). It is of importance to realise the discrepancy between the two, as each implies their own views and assumptions on the modelling process. Herefore, a brief explanation and discussion on the dissimilarities that are of interest in this paper is provided.

- Attributional model approach

This LCA aims to identify the share of the global activities and their environmental burdens that belong to a product system, as described by the European Commission (2020). Its life cycle inventory modelling principle is also known as "accounting" or "book-keeping" (European Commission, 2010).

- Consequential model approach

The European Commission describes a CLCA in the ILCD handbook as follows: "This LCA aims to estimate how the global environmental burdens are affected by the production and use of the product investigated."

In short, an ALCA assumes that there is no decision control between the selected system and the outside world, whereas CLCA does make this assumption (Kousemaker, Jonker and Vakis, 2021). Avoiding virgin production as a result of recycling can thus be introduced in a CLCA, whereas this is not the case in an ALCA. It becomes apparent that ALCA and CLCA have a different view on the life cycle stages, where CLCA has a more comparative nature, assessing changes in flows due to decisions (WBCSD, 2014). The goal of the study therefore has a say in the approach that is to be executed, either attributional or consequential. Additionally, the different impact assessment methods determine where environmental impacts are allocated, and where the system boundaries reside.

Method	Attributional LCA	Consequential LCA
Simple cut-off	X	
Economic cut-off	X	
Cut-off plus credit	X (Modules A-C)	X (Module D)
Material losses	(X)	X
Virgin material use	(X)	X
50/50 methods	(X)	X
Quality-adjusted 50/50		X
Circular Footprint Formula		X
Price-based allocation	(X)	
Price-based substitution		X
Price-elasticity methods	(X)	X
APOS	(X)	

Table 1. Environmental impact allocation methods and their respective belonging to attributional and/or consequential life cycle modelling. (X) indicating partial belonging, X indicating full belonging (Ekvall *et al.*, 2020).

The methods allocate the impact of recycling in very different ways. The case study of Ekvall *et al.* (2020), further emphasises this phenomena. In the study, low-alloyed carbon steel was evaluated over an entire product life cycle in terms of CO_2, where only the life cycle stages of disposal, recycling and virgin product were considered. The use phase is assumed to be passive (no environmental impact of any kind) and the manufacturing of the end-product is assumed to be neglectable. The result is figure 4, highlighting the difficulties in quantifying the benefits of recycling in life cycle modelling. Keep in mind that there is no wrong method, they only emphasize different aspects in the studied system (Ekvall *et al.*, 2020).

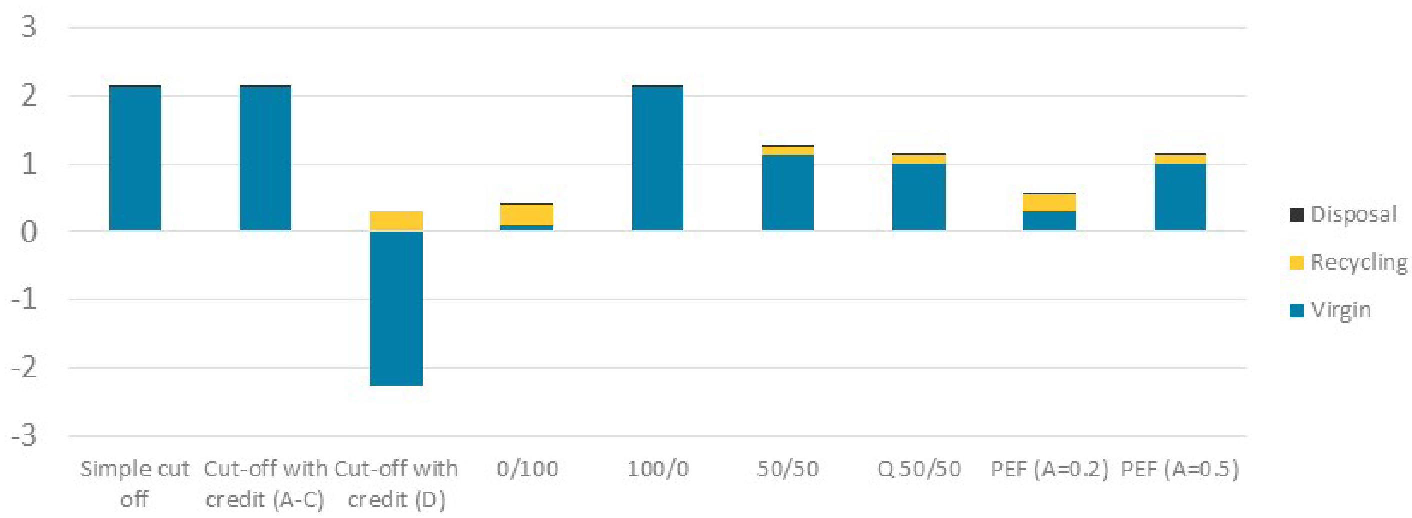


Figure 4. Climate impact in kg CO2 eq. per kg hot-rolled strip produced by SSAB, and its dependence on the selected method for allocating the impact of recycling. Manufacturing and use of the product in which the steel is used has been excluded (Ekvall *et al.*, 2020).

Hence, there exists an additional challenge in being able to transparently communicate the implications and assumptions that underlie the impact allocation methods. Interpretation of bar chart result figures may thus not be straightforward. Recipients can only reliably grasp the insights from such a diagram, once properly informed on the modelling limitations, assumptions and otherwise relative LCA methodologies.

3.2 Methods

The methods used in this paper is literature research and a review on LCA reports. The literature research is done by searching in Smartcat, Web of Science and Google Scholar, by using, amongst others, the keywords: Life Cycle Assessment, LCA summary, LCA presentation, LCA communication, LCA structure and LCA visualisation. This provides the scientific background, which is used, substituting the findings of the review of LCA documents. The LCA documents are presented in Appendix A. The findings are then evaluated on LCA structure, content and visualisation.

4 Results

Here, the findings are elaborated upon, in the three categories LCA content, LCA structure and visualisation.

4.1 LCA content

The joint research centre made statements in the plastic LCA method, referring to the minimum requirements of documentation of LCAs (European Commission, 2021). An LCA report complements the LCA study and provides, amongst others, an accurate summary of itself (European Commission, 2021), meaning that a summary is required in the LCA report. Furthermore, the summary shall be able to stand alone, without compromising any of the results, conclusions and recommendations. The summary should be written targeting a non-technical audience, to the extent possible (European Commission, 2021). It should, at minimum, consist of the following components.

- The goal and scope of the study, including relevant limitations and assumptions.
- A short description of the system boundary.
- Relevant statements about data quality.
- The main results of the LCIA.
- A description of what has been achieved by the study, any recommendation made and conclusions drawn.

Adhering to these components, with the aim to be no longer than 4 pages long, is compliant with the joint research centre in the plastic LCA method (European Commission, 2021). However, in the search for well documented LCAs, it became apparent that summaries, more often than not, do not adhere to one or more of these components. Herefore, the components are individually elaborated upon below.

4.1.1 Goal and Scope

The goal section of an LCA reports the reason for carrying out the study, the intended application(s), methodological limitations and the target audience. The scope of the study addresses the approach used to establish the functional unit (FU), reference flow, system boundary, list of impact categories, additional information, assumptions and limitations. This is a lot of information that has to be concisely presented. However, everything correlates to one another. This may be viewed as the most important phase of the LCA, as it outlines the direction of the study.

First of all, before starting with the LCA, it is important to know what the client's sustainability key performance indicators (KPI) are (Ekvall *et al,* 2020). What do they want to achieve, be transparent about, or reduce? By understanding their ambitions, one can formulate a plan that centers around their needs, ensuring that the results are relevant to them (Ekvall *et al.,* 2020). This is of course done in the initial stages of the LCA, way before any executive summary is made. However, it is the basis of the direction the LCA is going towards, and therefore crucial for the recipient to understand. Below, three different requirements on LCAs are identified as the cause and effect chain of varying application areas.

Application area	LCA used as learning process with tailor-made method(s)	LCA used as a calculation tool with predefined method
Policy-making	Develop basis for policy-decision	Required by a policy instrument
External communication	General communication on product and its environmental performance	Environmental Product Declarations, etc.
Internal use	Develop basis for strategic decisions	Day-to-day decisions

Table 2. Requirements on the method vary with the application. Red color indicates that the main requirement is to generate relevant knowledge. Blue indicates that the method must be robust and generate reproducible results. Yellow indicates that the main criterion is the ease of use (Ekvall *et al.*, 2020).

An LCA therefore has different requirements, depending on the goal and application area. The motivation of the LCA determines the KPIs, or in other words, the environmental impact categories, which are commonly determined by the needs of the client. However, impact categories can be presented using midpoint or endpoint notation, some insights on this are elaborated upon in Appendix B. The resulting methodological LCA choices centers around achieving the desired result. The functional unit, reference flow, assumptions and limitations are all determined by the intrinsic reason for carrying out the LCA. In other words, the procedures in following steps of the LCA are outlined by the goal and scope phase. The recipient should be able to grasp these (value) choices, and therefore it is a mandatory requirement for it to be stated in the management summary. Nearly all LCA summaries that are reviewed state the goal of the study. However, in some cases, the functional unit is not presented. The unit is the very basis of how the system is evaluated, and should be noted and explained (Nissinen *et al.,* 2006). In cases of multiple perspectives, e.g. a waste perspective and a product perspective, they should be explained separately. In cases of more than one perspective, they have all been explained thoroughly.

4.1.2 System boundary description

The system boundary (description) and reference flow is formally included in the goal and scope phase of the LCA report, but treated separately in the management summary, as stated by the component summation earlier.

The system boundary includes all life cycle stages that are part of the product and/or process system. The main processes in each life cycle stage, as well as co- and by-products and waste streams of the foreground system are identified, as well as the reason for and potential significance of any exclusion. A system boundary diagram can be presented, which depicts included and excluded processes. It is not mandatory to do so, but highly recommended. The reason being, is that the diagram provides a schematic representation of the investigated system. Interrelationships between processes as well as included and excluded processes can be visualised and grouped together in the life cycle stages. The function of the system boundary (diagram) in this section, is to communicate the analysed system. The recipient should thus be able to grasp the flows and get a general understanding of all the processes that are to carry out its function as defined by the functional unit (European Commission, 2021) (Cerdas, 2017). In the documents that failed to provide such a diagram, it was significantly more difficult to get an understanding of the system. Herefore, it is advised to use such a system boundary diagram in the LCA summary. Implications on this technique are elaborated upon in the visualisation section.

4.1.3 Relevant data quality statements

In the main report, the LCA practitioner should provide a table listing all processes and their situation according to the Data Needs Matrix (DNM) (European Commission, 2021). For a management summary however, this is reduced to only relevant data quality statements. Should the dataset used have quality or otherwise related implications on the results, it is useful to mention this in the executive summary for transparency. In the literature review, LCA summaries often did briefly refer to the dataset being used and its origin.

4.1.4 Impact assessment results

The impact assessment adds another layer to the life cycle inventory, which is the system mapped in a supply-chain logic, where each process in the inventory is evaluated on environmental impact. The normalised and weighted results are presented as absolute values (Castellani *et al.,* 2020), or in other words, absolute environmental sustainability indicators (AESI) (Anders *et al.,* 2016) (Moldan *et al.,* 2012), for each impact category (European Commission, 2021). Note that the impact assessment results should provide the results of the previously selected impact categories, in the goal and scope of the study.

This is the last computational phase of the LCA, where the numerical results provide the basis for subsequent interpretation. These results are often depicted in stacked bar charts and/or a final quantitative value, in the LCA report as well as the executive summary.

The issue in understanding these results however, is that it is presented in a higher aggregation level. The impact of all processes and life cycle stages are compiled into one final result, as experienced in the LCA review. Even if the recipient understands all preceding processes of the system, as schematically introduced in the system boundary description, it is still unknown how this relates to the final result. Often, conclusions and recommendations of the study are made right after, similar to the summary components as explained by the European Commission (2021).

Therefore, it may be value adding, to (briefly) decompose the results, before arriving at subsequent conclusions. Furthermore, diving into specific parts of processes that have a high impact contribution relative to other parts, clarifies the cause and effect chain of the result. As explained in the theory section, how the impact of the main flows is allocated should also be communicated in order to understand the results. This might not be in line with the goal and scope of the study. For example, say that an LCA has the purpose of identifying whether a given product has a lower environmental impact when the fossil feedstock of the conventional production process is replaced by a renewable feedstock. The final impact assessment then provides the environmental impact results in a quantitative manner, finalized with a positive or negative recommendation depending on the outcome. The conclusions depend on the impact of the system as a whole, not on single processes. However, to be able to fully comprehend this final result, the impact of single life cycle stages and/or processes should also be presented. This level of transparency is what is often lacking in LCA summaries. The reader has to take the final result for granted, while not fully understanding the composition of processes making up for the impact.

4.1.5 Description of conclusions, achievements and recommendations

The description of conclusions, recommendations, limitations and improvement potentials is the final part of the interpretation phase of the LCA. The preceding content of the interpretation phase is a list of relevant impact categories, life cycle stages, processes, elementary flows and a robustness assessment of the study. This content is addressed in the goal and scope, LCI and LCIA phases, which have already been treated in the summary as well. The interpretation thus not only reflects on the results, but all the preceding phases in its entirety (NordFoU, 2021). In some cases, this component is missing. LCA summaries often end in the presentation of the impact results, failing to address consequent concluding remarks. This part is crucial however, to answer questions posed at the outset of the LCA study, verifying whether the desired needs are achieved.

Reflecting on what the results impose and/or confine and what the limitations and corresponding recommendations are, ensures that the consult is tailored to the client's demand, reducing misconceptions and misinterpretations. For example, associating the environmental performance results to possible management interventions or other relevant procedures in line with the goal and scope definition can be value adding in this regard.

4.1.6 Additional findings

One of the issues in understanding the content that is presented in the review of LCA summaries, is the degree of unexplained technical abbreviations. As the summary should be able to stand alone, the client should be able to grasp these technical contents, to the extent possible, without looking elsewhere. In this regard, two categories are identified. Technical terms originating from LCA methodologies and technical terms originating from the case specific investigated system. They relate differently to target audiences, based on their experience.

Examples of such LCA abbreviations are amongst others, indirect land use changes (iLUC), international organization of standardization (ISO), life cycle inventory (LCI), life cycle impact assessment (LCIA), functional unit (FU), environmental footprint (EF) and single market for green products (SMGP). As the summary should be written, targeting a non-technical LCA audience, the abbreviations relating to LCA content should be written out completely when it is first used, to avoid being overwhelmed by technical terms, and to get, at minimum, a brief introduction on the definition.

However, the technical terms originating from case specific systems might already be known by the LCA requester, and thus may be redundant to write out or elaborate upon. In understanding the reviewed LCA summaries, it was often hard to grasp the essence due to the multitude of these unexplained abbreviations. Examples of such abbreviations are, amongst others, palm oil mill effluent (POME), low density polyethylene plastic (LDPE), deep green utility (DGU) and power take-off (PTO). As the perspective of the recipient is someone with no knowledge of the investigated system, it addresses the issues imposed with reproducibility. This is inherently value laden by the LCA requester, and depends on the intended use of the LCA report (Galindro, 2019). As a rule of thumb, it may be useful to write out these abbreviations when it is first used, and to elaborate on them, should they be at the center of the study.

4.2 Structure of the Executive/Management Summary

From the LCA content section, it becomes apparent that an LCA is a process that is built up further at each stage. Therefore, one can not simply state the final results with no further explanation. The structure should thus be built in such a way that the reader is taken through the LCA process, starting at the origin. The LCA practitioner executes an LCA following the goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation phases in chronological order. The summary should therefore concisely reflect these phases in the same manner. However, this is not always done in empirical LCA summaries. In some cases, functional units are introduced before the goal of the study is presented. In other cases, system boundary diagrams are introduced before functional units are presented. Some components may be even completely left out, like a description of conclusions. To avoid these inconsistencies in the order of presenting results, a structure is proposed as follows, building on the findings in the LCA content section.

- The goal of the study, including:
    - Relevant project context
    - Target audience
    - The reason for carrying out the study
    - The intended application

- The scope of the study, including:
    - Functional unit(s) with explanation/motivation
    - Relevant impact categories
    - Assumptions & methodological limitations
    - System boundary description

- The inventory analysis of the study, including:
    - A system boundary diagram, depicting the main processes in each life cycle stage
    - Brief description of data source (quality if relevant)

- The impact assessment of the study, including:
    - An explanation of impact allocation on processes
    - The final impact assessment result (bar chart), presenting at minimum the relevant impact categories defined by the scope of the study
    - A brief decomposition of the final result

- The interpretation of the study, including:
    - A description of what has been achieved
    - Any conclusions that are drawn
    - Recommendations
    - Limitations and improvement potentials

An important phenomena to note is that the details of the inventory analysis are not presented. The inventory analysis is only represented by the, somewhat schematic, system boundary diagram. This diagram depicts generalized processes, leaving out all the detailed sub-processes that make up the generalized process. For example, a manufacturing process can consist of, amongst others, pretreatment of feedstock, purification steps, catalyst usage, total electricity usage and maintenance. This is elaborated upon in the LCA report, but missing in the summary. It is not feasible to go through every single sub-process in a summary, due to the limited time frame and increasing complexity. However, to be able to understand the final impact assessment results, it is proposed to briefly decompose the impact, addressing the most impactful processes that contribute to the final result. In this manner, an additional degree of transparency is introduced, allowing the reader to gain more insight in relevant processes.

4.3 Visualisation

From the reviewing of LCA documents, two distinct visualisations are found to be dominant in the management summary. They are elaborated upon separately, as they each serve to communicate their own message. The first of which is the visualisation of the investigated system, often referred to as system overview or system boundary diagram. The second visualisation is the presentation of the results of the LCA, often in the form of a vertical bar chart.

4.3.1 System boundary diagram

The function of the diagram is to provide a schematic representation of the investigated system (European Commission, 2021). A general supply-chain logic is followed, addressing all the stages of the life cycle of the investigated product or process, being the raw material extraction, manufacturing, distribution, use and disposal/recycling stages. The diagram indicates which material flows and processes are included and excluded from the analysis in the LCA, which should be in line with the purpose of the LCA. Examples of system boundary diagrams that are investigated are provided throughout this section to support claims and reasoning. A brief introduction is provided to grasp the essences of the diagrams that are necessary to understand the communication issues.

The first diagram is made by Ecoras, investigating the environmental impact of a chemical recycling plant (CRP), in which mixed plastic waste (MPW) is being chemically converted into a BTX (benzene, toluene and xylenes) mixture. A byproduct from the chemical conversion is carbon gas, which is used to generate energy. The document emphasizes on the opportunities of the CRP plant to avoid fossil BTX production from naphtha (as this is now replaced by the BTX production from MPW), as well as avoiding fossil energy production (referring to the energy captured from carbon gas). This system is then assessed with respect to a waste management perspective and a BTX production point of view. As the two perspectives are fundamentally different, two functional units are defined as follows.

- FU of the waste perspective

Waste management of 1 kg of sorted mixed plastic waste (DKR 350) in Europe.

- FU of the product perspective

Producing 1 kg virgin grade B,T and X for use in Europe.

The two perspectives are investigated by comparing the new scenario (the CRP plant case) with the so-called business-as-usual scenario (the conventional way of producing BTX and the conventional way of incinerating MPW to produce energy). The system boundary diagram of this case is presented below.

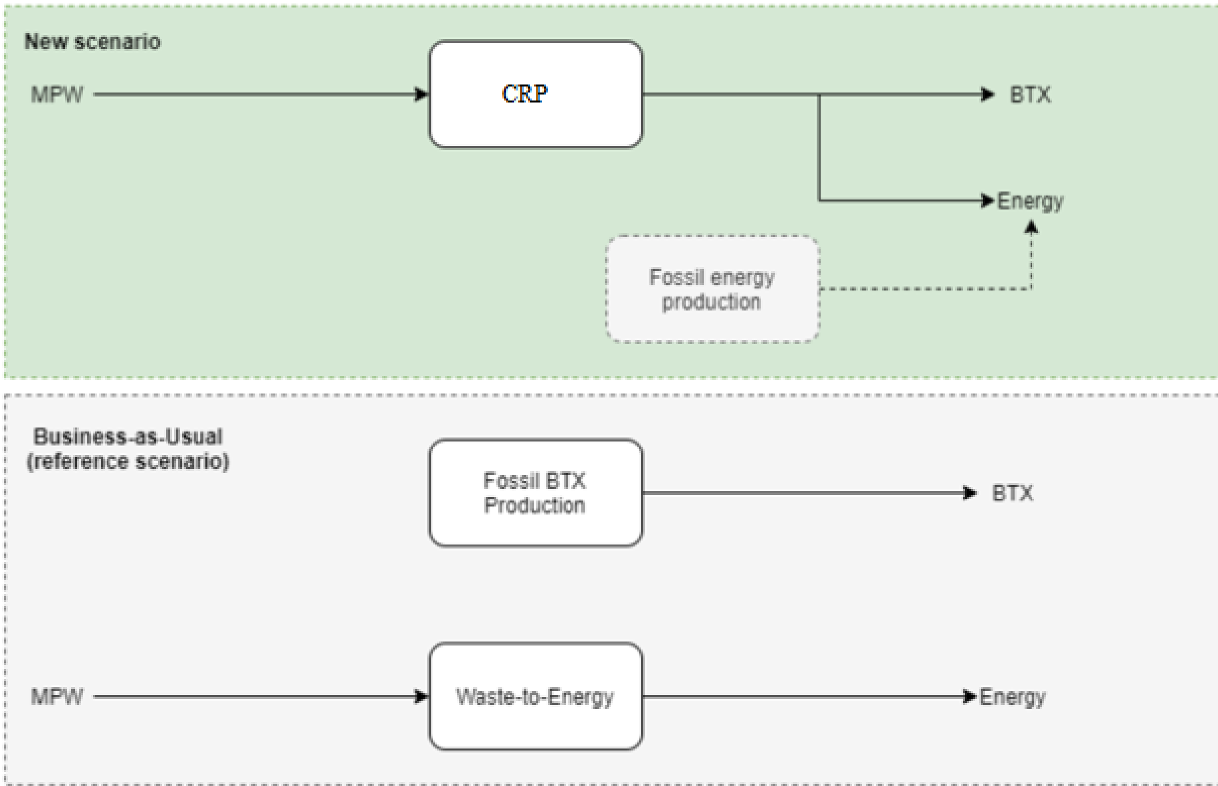


Figure 5. General overview of the investigated system. In the upper box the general steps are shown for the CRP process, which takes place at the Chemical Recycling Plant. The system starts when the plastic arrives at the factory gate. It then follows the conversion in the plant, of which the end products are BTX (mix) and energy in the form of renewable carbon gas as co-product. In the business-as-usual scenario, the BTX is produced via a fossil production route. MPW is transported to a waste to energy plant, where the plastic is incinerated for heat and electricity production (Ecoras, 2021).

This is a typical example of a system boundary diagram seen in LCA documents, where a new scenario and old scenario is presented in order to make comparative assertions. However, interpretation of this diagram is not straightforward. Fossil energy production is visualised in the new scenario as being avoided, whereas fossil BTX production is not visualised in the same avoided manner. Misconceptions therefore might arise on what is or is not included in the system boundary. Furthermore, from the diagram alone, the life cycle stages are not distinctively mentioned with respect to being inside or outside the system boundary. Out of the five stages, only manufacturing is visually represented. Throughout the LCA report itself, the stages are exhaustively explained and elaborated upon, but the recipient can not grasp this from the diagram.

Following the waste perspective, the MPW input is benchmarked and environmentally assessed, whereas by following the product perspective, BTX is benchmarked and environmentally assessed. The system boundary diagram should be read in a different manner for each perspective. Following the waste perspective, both scenarios are managed by benchmarking 1kg MPW as input, where the resulting amount of BTX produced in the new scenario is compared with the impacts of the same amount of BTX produced in the conventional scenario.

However, following the product perspective, the output of 1kg BTX is benchmarked and environmentally assessed. The amount of MPW needed to produce 1kg of BTX is therefore the input to the conventional scenario. One can therefore not simply shift the direction in which the flows are read, due to the change in input and output of MPW and BTX. This phenomena of using one system boundary diagram to visualise two inherently different perspectives may thus result in an overcomplicated process of interpretation.

In a similar study, Quantis, which is an environmental sustainability consultancy company, adopted a different manner to visualise their system boundary diagram. They investigated the environmental impact of chemically recycling MPW into low density polyethylene (LDPE) plastic. In a waste perspective scenario, the chemical recycling of MPW is compared to landfilling and incineration. In a product perspective scenario, the production of LDPE by means of chemical recycling of MPW is compared to the production by means of mechanical recycling of MPW and conventional fossil production of LDPE. They too, provided two distinct functional units for each perspective.

- FU of the waste perspective

Waste management of 1 kg of sorted mixed plastic waste in Europe.

- FU of the product perspective

Producing 1 kg LDPE for use in Europe.

The waste and product perspectives are now presented separately, in the two system boundary diagrams below.

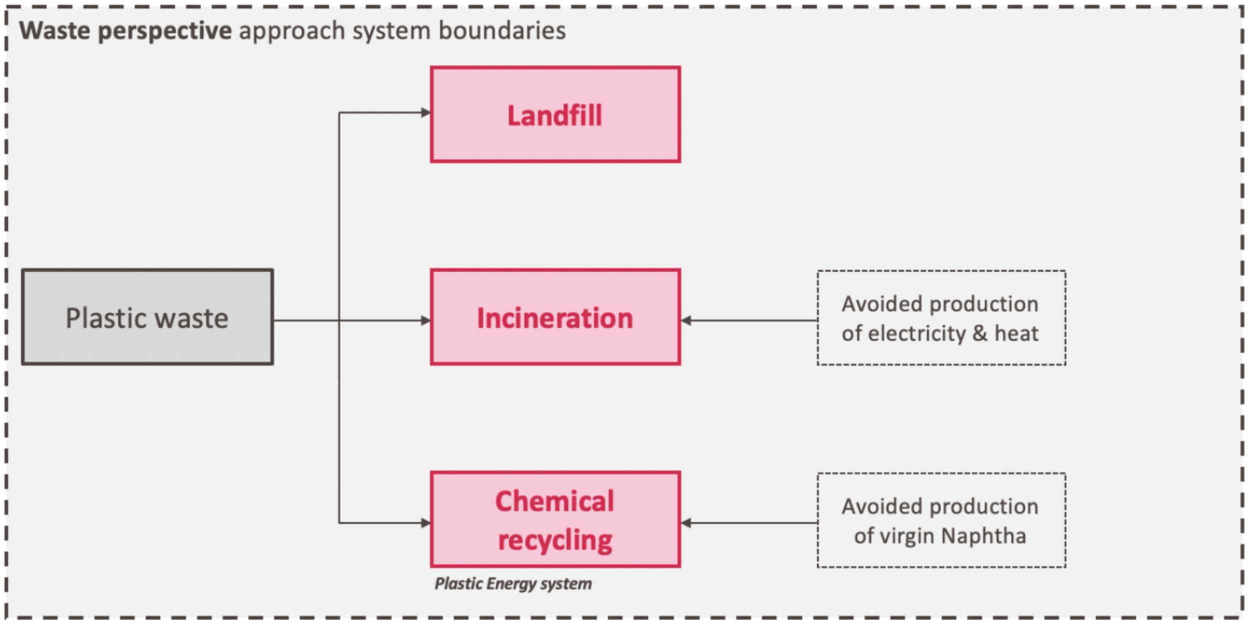


Figure 6. Life cycles of waste perspective scenarios evaluated in this study. Red boxes indicate the main system, grey ones the feedstock used (Quantis, 2020).

Notable in the waste perspective diagram above, is that the reference scenarios (incineration and landfilling of MPW) are now visualised together with the new scenario (chemical recycling of MPW).

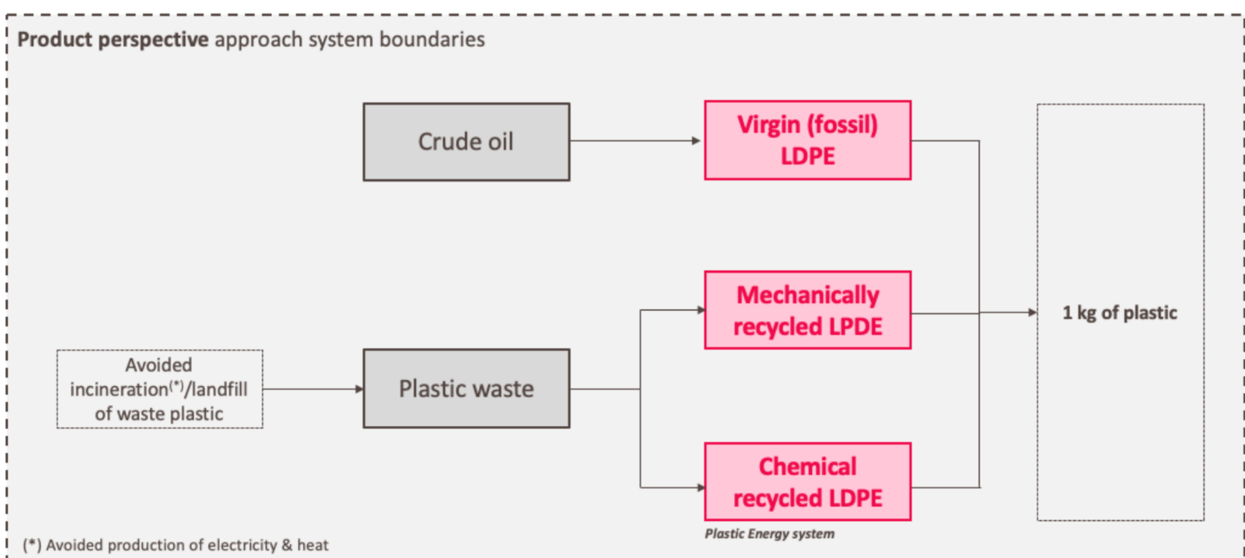


Figure 7. Life cycles of product perspective scenarios evaluated in this study. Red boxes indicate the main system, grey ones the feedstock used (Quantis, 2020).

In the product perspective diagram, it is apparent that the output of LDPE plastic is benchmarked for all three production cases, emphasized further by the "1 kg of plastic" notation. The separation of the two perspectives make it less complicated to grasp the process flows, relative to the diagram in which both the product perspective and waste perspective were visualised. However, in this diagram there is still no explicit visualisation of the life cycle stages of the LCA. Feedstock is presented in grey colour blocks and the main system in red blocks, insinuating that respectively, raw material extraction and manufacturing is represented. In the document, it is mentioned that the distribution, use and disposal stages are not included in the LCA, which clarifies the diagram.

The Joint Research Centre (JRC), which is the European Commission's science and knowledge service, proposed a system boundary diagram example figure, attempting to visualise the LCA stages (European Commission, 2021). In addition, it is mentioned that system boundary diagrams should group processes and activities according to the life cycle stages (European Commission, 2021). The example figure, including the life cycle stages is presented below.

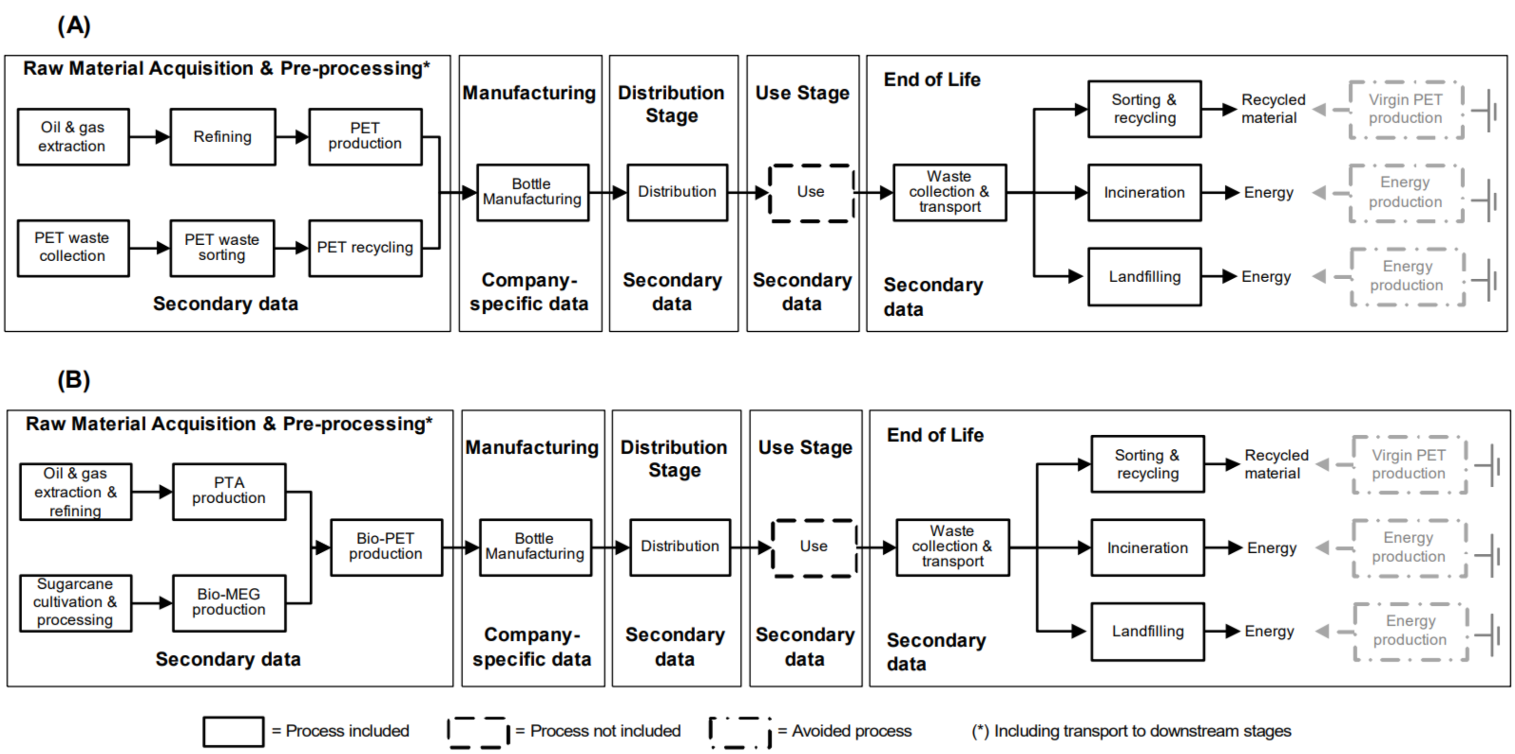
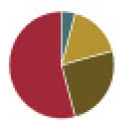
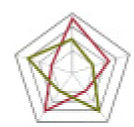
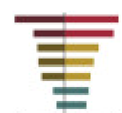
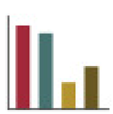
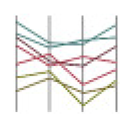
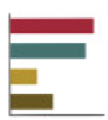
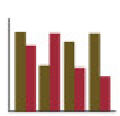
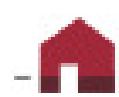


Figure 8. Example of system boundary diagrams conforming to the requirements specified in this method, for the case of partially recycled (A) and partially bio-based (B) polyethylene terephthalate (PET) beverage bottles (European Commission, 2021).

The example diagram outlines each life cycle stage, which encompasses all processes included in the system. The block chain, seen in the previous system boundary diagrams, is still visualised aesthetically similar. This visualisation technique allows for a clearer depiction of included, excluded and avoided processes. Should an LCA exclude the use and end of life stage, they can be made empty or adjusted visually in the block chain, as is done in the use stage of the example figure. This way, the recipient will no longer wonder what is or is not included in the investigated system.

4.3.2 Result visualisation

In a review paper that mapped all current LCA visualisation practices in the design process of buildings (Hollberget *al.,* 2020), it is apparent that there are many ways in which visualisations of results can be chosen. To give an example of the variety of options, a summary of findings originating from Hollberg *et al.,* (2020) is added below.

No.	Name	Icon	No.	Name	Icon
1	Pie/donut chart		**15**	Heat map	
2	Multi- pie/donut chart		**16**	Radial/spider/polar chart	
3	Sunburst		**17**	Tornado chart	
4	Vertical bar chart		**18**	Parallel coordinates	
5	Horizontal bar chart		**19**	Pictorial unit chart	
6	Grouped bar chart		**20**	Pictorial fraction chart	

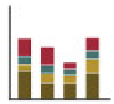
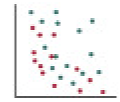
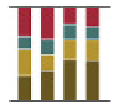
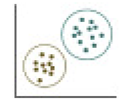
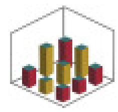
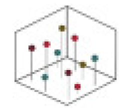
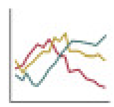
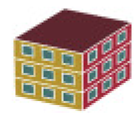
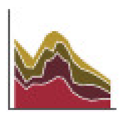
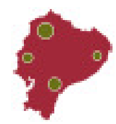
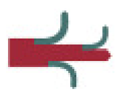
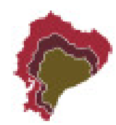
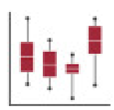
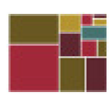
7	Stacked bar chart		**21**	Scatter plot	
8	Normalized bar chart		**22**	Cluster	
9	Multiple series 3D bar charts		**23**	3D scatter plot	
10	Line chart		**24**	3D color code	
11	Stacked area chart		**25**	Bubble map	
12	Sankey/alluvial diagram		**26**	Color map	
13	Box plot		**27**	Scale	
14	Tree map				

Table 3. Life cycle analysis visualisation types found in Hollberg *et al.*, (2020).

Considering there are many options, the (stacked) bar chart is still the most commonly used in literature. This was most dominantly seen in the LCA reviews, supporting Hollberg. The underlying reason being, is the possibility of depicting negative environmental impact credits in an intuitively understandable way (Hollberg *et al.*, 2020). For example, waste can be treated in recycling modelling through a recycling process, whereas it would otherwise have been incinerated. In consequential LCAs, the environmental impact can thus be computed by assigning waste incineration as an avoided process. In the diagram, this is visualised in negative values for the respective impact indicator. The newly created impact of recycling practices is projected in positive values, stacked on top of the avoided processes. A net resulting impact is determined by the summation of the two, often depicted as a line or point within the bar chart. Below, an example of such a stacked bar chart is provided, belonging to the product perspective of Ecoras' LCA on the CRP plant.

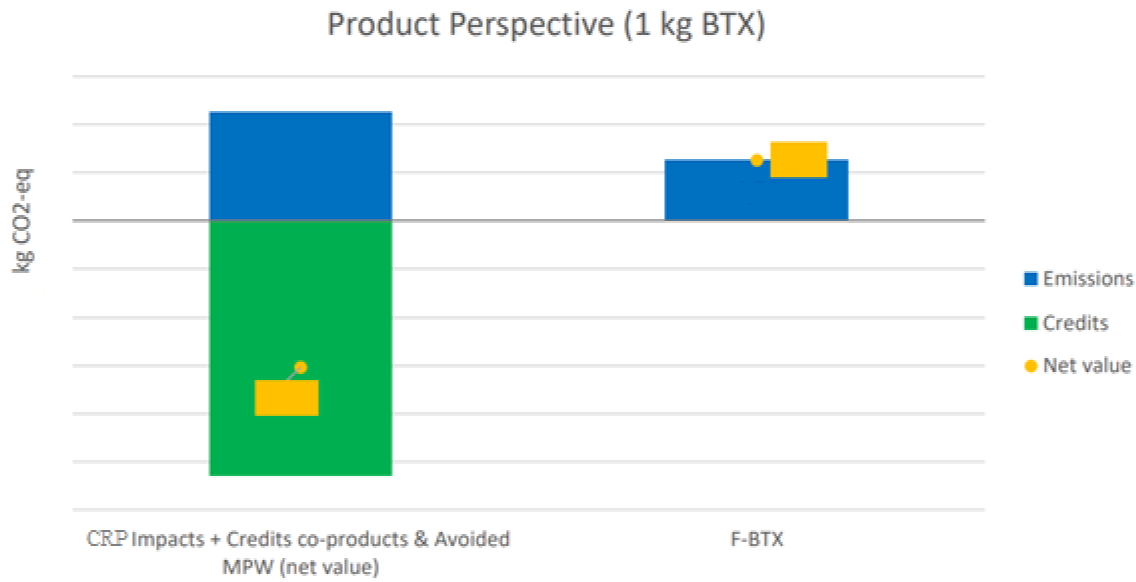


Figure 9. Results from the LCA in which the CRP process on the left is compared with the Business-as-usual on the right. For this perspective the BTX is produced via the refining of Naphtha and is referred to here as F-BTX. In blue the emissions of both processes are given. In green the credits (avoided production of substitute processes) are given. When the emissions and credits are combined the resulting impact is shown as a yellow dot in the bar (Data emitted for confidentiality reasons) (Ecoras, 2021).

These bar charts are not necessarily hard to read in itself. The problem perceived during the review of multiple of such bar charts, is the inability to know what has led to the results that are presented. The lack of grasping of the modelled system (boundaries), inventory of processes and the way in which impact is allocated. In the case above for example, the avoided environmental impact of the product perspective of the CRP plant is so high, because a relatively high amount of MPW is needed to produce 1 kg of BTX. Meaning, a high amount of avoided, incinerated MPW. This insight should be communicated in order for the audience to understand why the impacts are as they are. Furthermore, the emissions of the CRP process are in itself higher than the emissions of producing fossil-BTX, seen in the figure. However, the recipient is not (yet) informed why. The issues are thus imposed by the reader not being well enough informed of the underlying processes resulting in the outcome that is presented. Below, a stacked bar chart, elaborating on the emissions imposed by the waste and product perspectives of the CRP plant respectively, is presented.

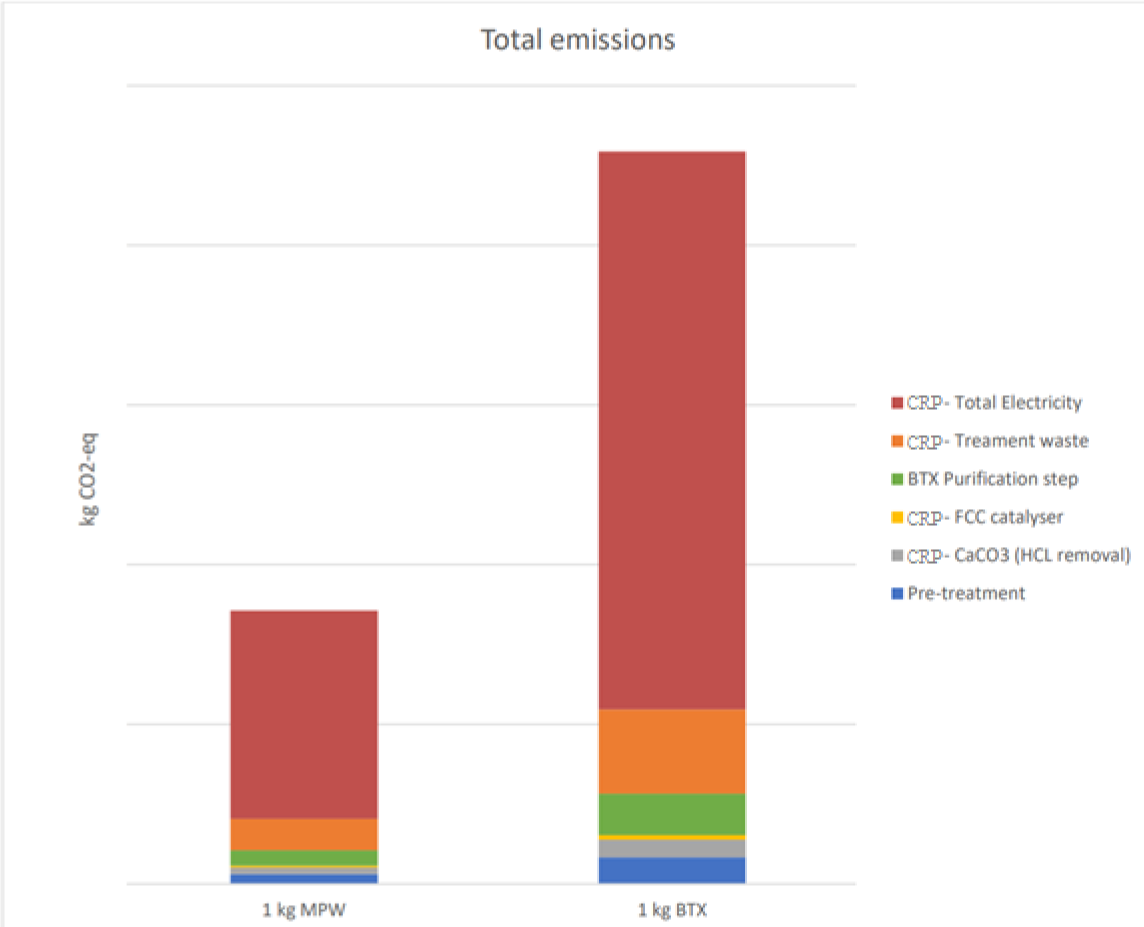


Figure 10. Total impacts of both perspectives in kg of CO2-equivalents. The left bar represents the waste perspective (1 kg MPW) and the right bar represents the product perspective (1 kg BTX). For 1 kg R-BTX, kg MPW is needed (Data emitted for confidentiality reasons) (Ecoras, 2021).

Here, the reader is informed on what the impact consists of. This figure in particular, clarifies the composition and magnitude of processes making up the total impact. However, for the purposes of a management summary, such a bar chart depicting every single process might be redundant. Relatively speaking, only the total electricity and CRP waste treatment are of importance, all the other processes are nearly negligible. Alternatively, a single sentence explaining that for example, the total electricity usage in the CRP plant accounts for 75% of all environmental impact, might clarify the essence just. After all, this diagram only depicts the emissions of the CRP waste and product perspectives, leaving out the avoided emissions and the two reference scenarios of fossil-BTX production and incineration of MPW. To adopt this detailed stacked bar chart idea for each process, four diagrams would have to be added. For a management summary addressing a non-technical LCA audience, this is too much detailed information.

5 Analysis & Discussion

Here, the main findings of the three sub questions, referring to LCA content, structure and visualisation, are combined and discussed.

5.1 General findings

As visualised in figure 4, interpretation of impact results can not be properly done by any recipient without being informed on the modelling limitations, assumptions and otherwise relative LCA methodologies. The client will require sufficient context to be able to do so. This context should be provided in an accumulative manner, going through the LCA process phases in the same structure as the LCA practitioner. The JCR provides the minimum requirements on LCA content that is to be presented. However, many LCA summaries do not abide by these requirements. LCA content is often presented in a structure which does not reflect the LCA processes. Additionally, assumptions on impact allocation are often poorly communicated. In particular, avoided processes and recycling processes. If assumptions are made, e.g. a zero environmental impact on recycled feedstock that enters the system, they have to be communicated. Each assumption induces their own implication, and to be able to understand the final result, this has to be communicated. These assumptions and limitations are not to be put into annexes or footnotes, but directly in the context of the presentation, to avoid misleading interpretation (European Commission, 2010). Findings and insights on the system boundary diagram and result presentation are elaborated separately, below.

5.2 The system boundary diagram

The system boundary diagram has a lot of potential in communicating the analyzed system in a schematic way, but induces confusion if not done properly. All life cycle stages should be presented, including the main processes of the analysed system, where it should be clear which processes are included and excluded from the analysis. In cases of multiple perspectives, and thus multiple functional units, they should be separated. The reason being, is that an overcomplicated process of interpretation is experienced when the same diagram has to be read in different manners, especially for an audience with no technical LCA expertise. An example figure of this system boundary diagram is provided in figure 8.

5.3 Impact results

Here, the impact of all processes and life cycle stages are compiled into one final result. The issue in understanding these results however, is that it is presented in a higher aggregation level than previously introduced in the system boundary diagram. The alignment with the life cycle stages and system processes fade for the recipient, as it is now compiled and not retractable. The reader therefore has to take the final result for granted, while not fully comprehending the magnitude and composition of processes making up the total impact.

Therefore, it is suggested to decompose the results, before arriving at subsequent conclusions. In the result visualisation section, this is done by depicting the impact of single processes in figure 10, which depicts single processes and their impact, relative to figure 9, which depicts the impact in its totality. Doing this however, would mean that every single process is to be elaborated upon, which would in turn induce a lot of depth and complexity. For this reason, a "hotspot identification" methodology can be applied. Elaborating not on every single flow, but strictly the most impactful ones, making up for most of the total impact. By doing this, an additional degree of transparency is introduced to the recipient, allowing them to gain more insight in the result, bringing back the missing link to the life cycle stages and its processes.

6 Conclusion

What was found in the research, is that the main issue in misunderstanding LCA results is not the presentation of the final impact. Rather, it is not being able to understand why the results are as they are. To tackle this problem, the recipients should be taken through the process of the LCA, being provided with sufficiently enough context. This is already done in full LCA reports that abide by the chronological order of LCA phases, standardized by ISO 14044. In summaries this is often attempted, but the logic is not always followed. Therefore, this paper suggests presenting the relevant LCA methodological background in a structure, similar to that of the execution of the LCA in its respective phases, while making proper use of the system boundary diagram and result visualisation. The concluding content, structure and use of visualisation techniques are presented below, as an example format of improved communication in the management summary of LCA reports.

- The goal of the study, including:
  - Relevant project context and life cycle assessment context, write out abbreviations the first time they are used.
  - Target audience.
  - The reason for carrying out the study.
  - The intended application.

- The scope of the study, including:
  - An explanation of the functional unit(s) of the study, allowing the interpretation of the analysed system with respect to this unit.
  - Relevant impact categories that are evaluated by the motivation of the study.
  - Assumptions & methodological limitations of the study.
  - A schematic description of the analysed system, referring to the flows and life cycle stages.

- The inventory analysis of the study, including:
  - A system boundary diagram. It should be visualised what flows are included, excluded and avoided in the analysed system and to which life cycle stage they belong. If more than one functional unit is present, they should be separated in two diagrams, to avoid confusion in interpretation.
  - Brief description of data source (quality if relevant). This can be done in text or visualised as in figure 8.

- The impact assessment of the study, including:
    - An explanation of impact allocation on processes. If assumptions are made with respect to allocation, in particular in recycling processes and avoided processes, they should be explained directly in the context of the presentation of the LCIA results (below), not in footnotes or annexes.
    - The final impact assessment result (bar chart), presenting the relevant impact categories defined by the scope of the study.
    - A brief decomposition of the final result. Elaborate on the most impactful processes and their contribution to the total impact in a hotspot identification logic, to assist the recipient in understanding the magnitude and composition of flows making up the total impact.

- The interpretation of the study, including:
    - A description of what has been achieved.
    - Conclusions and recommendations that are drawn, reflecting back to the goal and scope phase of the project, verifying whether the desired needs are met.
    - Limitations and improvement potentials of the study, to ensure that the client will not make management decisions based on results outside the boundaries in which it is meant to perform.

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8 Appendix

A. LCA documents

Scientific papers of LCAs were not desirable, as they often did not provide a management summary, which was essential for the evaluation. Therefore, the LCAs were found using the origin of their case specific publication, being of companies, universities and research institutes. They are provided below.

[1] Gu F., Guo J., Zhang W., Summers A.P. & Hall P. (2017). From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study.https://doi.org/10.1016/j.scitotenv.2017.05.278

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B. Midpoint versus endpoint

During the impact assessment phase of the LCA, it can be opted to work with either midpoint categories or endpoint categories. Midpoints are considered to be a point in the cause-effect chain of a category, where they focus on single environmental problems. Endpoints also reflect on environmental problems, but on a higher aggregation level (RIVM, 2018). This higher aggregation level is reached by clustering the single environmental problems into one of three endpoint categories, namely: effect on human health, biodiversity or resource scarcity (Meijer, 2021). The National Institute for Public Health and the Environment depicts this procedure in the following image.

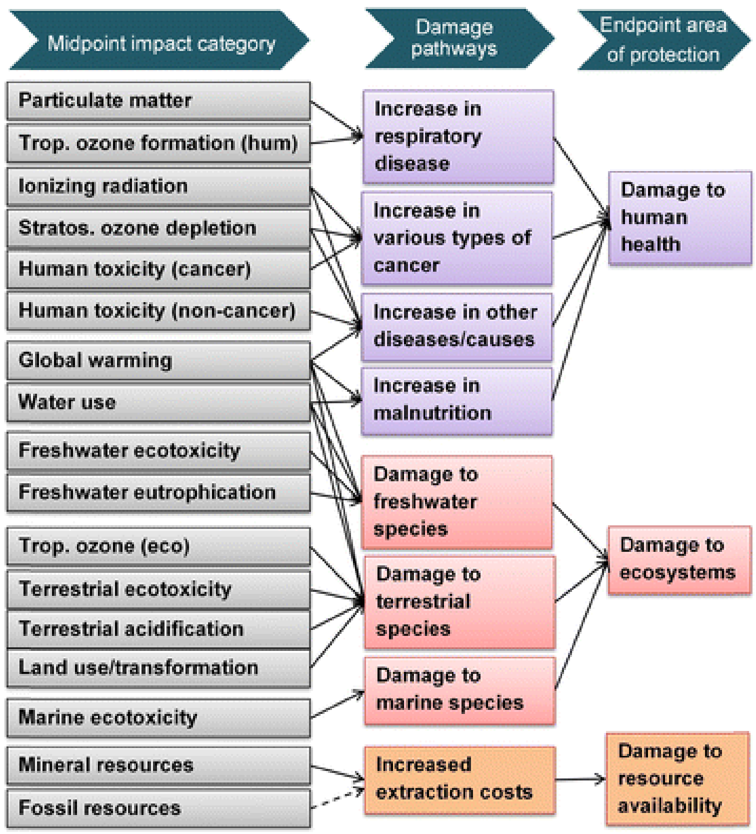

Figure 4. Overview of structure ReCiPe (RIVM, 2018).

Midpoint impact categories are detailed in the sense that they provide more information on the environmental problem relative to endpoint categories, which in reality are a summation of midpoints clustered in one of three categories. Endpoint modeling therefore is generally seen as more understandable to non-LCA experts, like decision makers (Bare *et al.*, 2000), due to the simplification factor (Beemsterboer, Baumann and Wallbaum, 2020). When extending midpoint models to endpoint models, many believe that a reduction in comprehensiveness is the result, due to additional, unsubstantiated assumptions and value choices that fill in missing gaps, which may not reflect the viewpoint of other experts (Bare *et al.,* 2000). Furthermore, an increase in uncertainties beyond the well-defined midpoint categories can result in a misleading sense of accuracy (Bare *et al.,* 2000). Many experts are of the opinion that more modeling complexity is only warranted if it can lead to an improvement in the decision-making basis (Bare *et al.,* 2000). Herefore, midpoint categories are thus generally more accurately defined, substantiated and comprehensive, relative to endpoint categories. Furthermore, without additional documentation, midpoint categories are not retractable from endpoint categories, due to the loss of details and the reduction of transparency. Thus, endpoint categories are more relatable to non-LCA experts, where they should only be used if it support decision-makers' understanding.