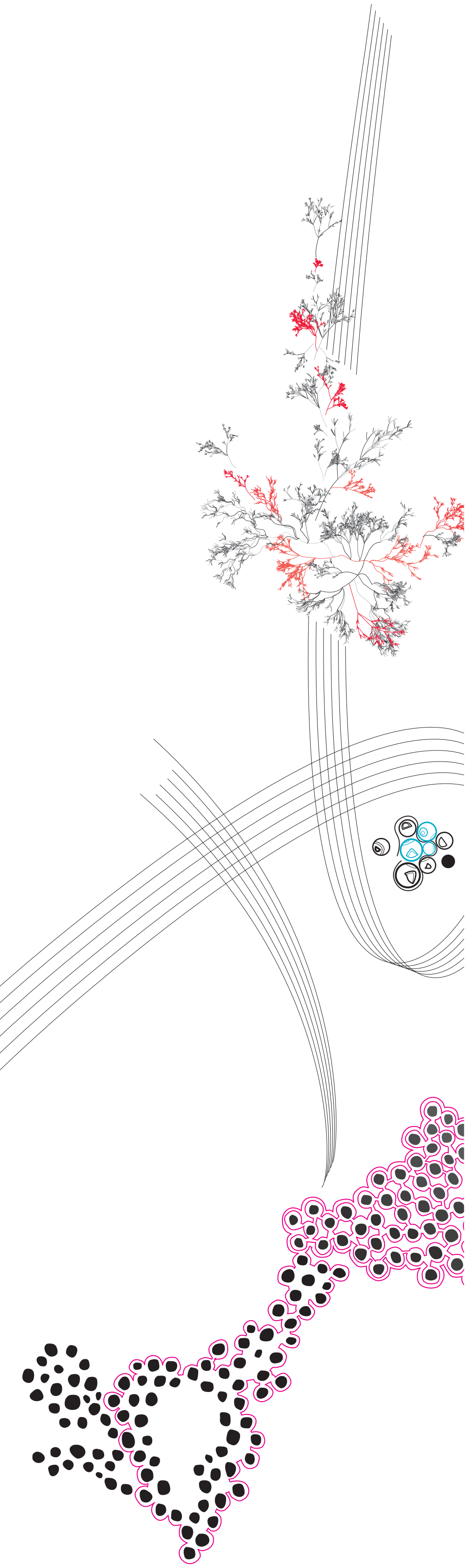

# Development of a method to assess the environmental impact of a system with a long life cycle

## A case study on train films at Fleetshield

Ellen Siebers, s1691988
October, 2022

FLEET SHIELD
EXPERTS IN FOLIETOEPASSINGEN

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# Abstract

For companies to keep up with changing environmental rules and regulations, good insight in their level of sustainability is important. One of the most widely-used methods to get this insight is Life Cycle Assessment (LCA). Using LCA, the environmental impact of a system over its complete life cycle can be calculated and evaluated.

Fleetshield is a company looking to find out how sustainable their product is. They sell films applied to trains, busses, trams and buildings to protect and enhance the surfaces. These films are products with a relatively long life cycle of over 15 years. When carrying out an LCA of such a system, its long life cycle forms an obstacle because the unknowns about the future create extra uncertainty in the results.

In this research, the potential role of LCA in assessing the environmental impact of systems with a long life cycle is studied. This is done through a literature study and a case study performed at Fleetshield in cooperation with Nederlandse Spoorwegen (NS; English: Dutch Railways). Fleetshield's film is studied as applied to NS trains and compared to its alternative, which is paint.

To start with, a conventional LCA is performed for the case study, which showed the importance of taking future changes into account. A literature study presented scenario modeling as a possible solution for this. With the insights gained in the initial LCA on the case study and the findings from the literature study, an approach was developed to generate scenarios that can be used to deal with the uncertainties introduced by the unknowns of the future. In turn, this approach was tested on the case study and the results were evaluated to come to an improved approach. This resulted in the following five-step method to assess the environmental impact of systems with a long life cycle: (i) executing a (simplified) conventional LCA, (ii) generating scenarios, (iii) modelling scenarios, (iv) interpreting results and (v) regular evaluation.

Using this method, different possible future directions are explored and their impacts on the environment can be compared. The results acquired can be used as a good basis for discussion and informed decision making. The thesis also provides a basis for further research on the use of scenario modelling for uncertainty management in prospective LCA.

# Acknowledgements

This thesis could not have been realised without the guidance and support of the people around me. First of all, I would like to thank my supervisors Willem Haanstra and Jan Braaksma for all their advice, feedback and brainstorm sessions. Without your expertise, insights and constant willingness to help, this thesis could have never become what it is now. Also, I would like to thank Marten Toxopeus for joining the brainstorm sessions that inspired new directions to explore and gave me extra motivation to work on this project.

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Ellen Siebers
October, 2022

# Contents

# Chapter 1

# Introduction

Environmental awareness is growing larger every day. Subsequently, the importance of this subject is increasing rapidly among governments, companies and individuals. Take for example the European Green Deal from 2019, with which Europe aims to become the first climate-neutral continent by 2050, with zero net emissions of greenhouse gasses [9]. To support this goal, the European Commission presented a package of policy proposals, with the goal to reduce greenhouse gas emissions with 55% by 2030, compared to the levels in 1990 [10]. These policies will affect companies and organisations, as well as the individual European citizen one way or another [47]. A method that is increasingly used for supporting sustainable transitions is Life Cycle Assessment (LCA). The European Union (EU) also cites LCA in many of their policies regarding the Green Deal [58].

LCA is a tool to assess and evaluate the impact of a system over its complete life cycle [19]. It can be used to support decision-making and is considered increasingly important for this purpose with regard to sustainability goals [58]. While conventional LCA offers a good framework to evaluate systems with a relatively short life cycle, the standard methodology does not deal with the uncertainties introduced by a long life cycle. This research explores the possibilities of using LCA when assessing the environmental impact of products with high uncertainty due to a long technical life. It is based around a case study performed at Fleetshield B.V. in cooperation with Nederlandse Spoorwegen (NS; English: Dutch Railways).

This chapter will introduce the study by discussing the background, the research problem and the research questions, followed by the relevance of the research, the approach and the limitations.

## 1.1 Background

The goals and policies introduced by the EU are just one example of the increasing attention for sustainability worldwide. The role of this subject is growing larger in the everyday business of companies, not only because of policies imposed by governments, but also because of expectations from the consumer [62]. Some companies are aiming to stay ahead of the imposed improvements.

One of those companies is Fleetshield, a Dutch firm specialized in the application of films in public transport. The largest part of their portfolio is rail transportation and also within the rail sector, sustainability is an important topic, especially since the adoption of the Green Deal [35]. Therefore, Fleetshield wants to find out two things:

1. What is the current environmental impact of our product compared to the most-used alternative?
2. What is the best direction for the future when looking at the environmental impact of the product?

There are multiple ways to determine the environmental impact of a system. One of those is the widely adopted method of LCA. Therefore, LCA would be a good tool to start with when answering these questions. Since the late 1960s, LCA has become an increasingly popular technique for assessing the impact of a system. The conventional LCA, closest to the original LCA framework, has developed into numerous directions. It has become more than a tool for simple environmental impact, yet it is still perfectly suitable for that purpose.

## 1.2 Problem statement

Conventional LCA is already well established and has been applied in real-world situations many times. The practical applications have shown where common obstacles lie and where opportunities are to expend. Thus, numerous different variations have been introduced, all based on the original LCA framework. Examples of those variations are organizational LCA, used to evaluate environmental impacts related to activities within an organization and the product portfolio [6], consequential LCA, which focuses on socio-economic mechanisms instead of technical connections between activities and processes [38], and prospective LCA, used to model future phases of technologies [2].

As will become clear later in this report, prospective LCA seems to be best applicable to the Fleetshield films. Numerous studies have been done about this type of LCA, mostly focusing on emerging technologies that have not entered the market yet [2, 53, 18]. Those studies often centre around the opportunities prospective LCA offers for improvements in the design phase by modelling the future use. In the case of Fleetshield, the main obstacle is the uncertainty arising from the long life cycle of the product, namely 18 years. This means a relatively far-ahead future has to be modeled, but the improvement options in the design phase are limited because the product already entered the market. More importantly, because of the long life cycle, much data is unknown, including some major processes such as the disposal method, introducing large uncertainties.

For LCA to be an effective tool, the results have to be thoroughly interpreted. Clear interpretation of results eases the translation into concrete improvements. Results with high uncertainties to which no attention is paid are harder to interpret and not useful in supporting decision making. Therefore, the right approach has to be applied to use LCA while effectively dealing with the uncertainties. This is certainly the case when looking at a product with a long life cycle. Conventional LCA already comes with many uncertainties, which introduce a large challenge. However, prospective LCA has additional uncertainties because of the long life cycle of the product and technological and societal development during its life. Research on dealing with uncertainty in prospective LCA is limited and examples in real-world cases of translating its results to effective improvements are lacking.

## 1.3 Research question

As explained above, shifts towards a more sustainable industry ask for effective tools to support this transition. LCA can play an important role in this, for example in answering the questions as composed by Fleetshield. However, LCA is not directly applicable to all areas yet. To answer Fleetshield's questions, first the possibilities have to be explored of using LCA for assessing the environmental impact when dealing with a long life cycle. Therefore, the aim of this research is to answer the following question:

- How can LCA be used to assess the environmental impact of products with high uncertainty due to a long life cycle?

To help answer this question and give structure to the research, multiple sub-questions are stated, namely:

1. What methods are currently used for life cycle modelling of future situations?
2. What is the state of art of prospective LCA?
3. How are uncertainties taken into account in LCA?
4. What requirements should be met when assessing the environmental impact of systems with a long life cycle?
5. How can the environmental impact of technologies with a long life cycle be assessed?

6. How effective is this approach when applied to a case study on Fleetshield's film?
7. What are recommendations for implementation of the proposed approach?

## 1.4 Relevance

This study will contribute to broad field of Life Cycle Assessment methodologies by researching the opportunities for assessing the environmental impact of products with high uncertainty due to long life cycles. This will help fill the gap in current research, where this type of uncertainty is currently underexposed. Additionally, it will provide practical value to companies or organisations that deal with products with a long life cycle aiming to determine its environmental impact.

## 1.5 Approach

The research will be built around a case study on Fleetshield's film as applied to the trains of NS. This case study will be used to investigate and substantiate the main research question of this study. Both companies will be introduced in more detail in Paragraph 1.5.1, followed by a more precise description of the case in Paragraph 1.5.2.

First, literature will be studied to get a better idea of the state of art of LCA and, more specifically, of the developments in forward-looking LCA and uncertainties within LCA. Next, a conventional LCA will be executed on the case study to get insights into the process of conducting an LCA and the challenges faced. This will also provide insight into the current impact of the film and room for improvements, answering part of Fleetshield's questions. The experience of conducting the conventional LCA will be used, together with the literature study, to come to a proposed approach for dealing with the uncertainties introduced by the long life cycle. This approach will, in turn, be tested and evaluated in the context of the case study, which could provide an answer to Fleetshield's second question. Finally, the effectiveness of the approach will be discussed and evaluated and conclusions will be drawn. This also includes recommendations for the implementation and future research.

### 1.5.1 Company profile

To get a better idea of the companies behind the case study and how these relate to each other, some background information is given below.

**Fleetshield**

Fleetshield is a Dutch company founded in 2001. The company specializes in the application of films on trains, busses, trams and metro's. Recently, building facades were added to their portfolio. The films are used to embellish surfaces and to protect from UV-radiation, graffiti or other damages. They provide clients with the most suitable film for their specific project, from the initial advice through to the montage. Although it is a small company in number of employees, it works together with large suppliers and clients throughout Europe. With the slogan "Fleetshield protects, enhances and preserves" the company sees film as the solution that enables surfaces to look as new and remain that way for a long time. This way, the life cycle is extended and less maintenance is required.[14]

**Nederlandse Spoorwegen**

Nederlandse Spoorwegen (NS) is the largest railway operator in in the Netherlands, founded in 1938 [46]. In 2019, before the Covid-19 lockdowns, NS brought approximately 1.3 million passengers from A to B throughout the Netherlands and in some cases in neighbouring countries [44]. Over 18000 employees work for NS in the Netherlands throughout many different departments and the company works together with numerous different suppliers and other partners [43]. One of those suppliers is Fleetshield, which supplies film for several train modernisation projects both for the interior and exterior of the rolling stock. Fleetshield provides NS with the most suitable combination of film and laminate and makes sure the right cut-outs are made and delivered. NS itself oversees the montage and the maintenance.

The mission of NS is to "make the Netherlands sustainably accessible, by everyone and for everyone". They define a sustainable business as fossil free, circular and green. This is translated to multiple sustainability goals NS has set for the near future. One of those goals is to be entirely circular in 2030. This means circular purchasing, maximizing the (re)use of materials and creating zero waste everywhere throughout the company. This also means their business partners are expected to contribute to these goals.[42]

### 1.5.2 Case study

In 2005 Fleetshield and NS crossed paths when NS was looking for alternative to their paint system, protecting the exterior of the train. Film offered the solution they were looking for. Since then, multiple series of trains have been finished with a layer of film after their midlife modernization, to be used for another 18 years. Currently, one series of trains, called VIRM 2/3 (or VIRM23), is being modernized after 18 years of service, to be able to roll through the Netherlands for another 18 years. The exterior conservation system on this train series is being finished with film. Very similar to this series is the VIRM1 series, for which the entire conservation system consists of paints. The core of both train models is exactly the same, but VIRM1 has been purchased a few years before VIRM23, so the midlife modernization happened earlier as well. Therefore, different design choices were made for the modernization and the exterior of VIRM1 contains no film, while VIRM23 does. This makes for an interesting comparison. In this research, the environmental impact of the conservation systems of trains with film applied (VIRM23) and without film applied (VIRM1) will be investigated and compared.

## 1.6 Limitations

In this thesis, the use of LCA will be researched in the context of systems with a long life cycle and therefore high uncertainty. It potentially contains some limitations. First of all, this research will be supported by a practical application to a case study on the films provided to NS by Fleetshield. Because this is a very specific product, the findings cannot necessarily be used on all types of products. Also, the LCA in the case study is executed for Fleetshield, which is not the typical company to initiate such a study because it is not the manufacturer of the product, nor the end-user. Therefore, Fleetshield has limited influence on the life cycle of the product. Nevertheless, they do operate from a unique position that allows them to analyse the product over its entire life cycle, because they have knowledge of the current technology and its use and foreseeable future innovations. The LCA could result in recommendations for Fleetshield that are different than they would be for other initiators. Additionally, although the LCA is a quantitative study, the overarching research in this thesis is qualitative. This means it includes a certain amount of subjectivity. Lastly, there are time restrictions to this research, which results in simplifications in some parts.

## 1.7 Report structure

The research questions are guiding the structure of this report, with the Fleetshield questions being used in between to help answer the academic questions. The points of discussion raised by the Fleetshield questions are partly answers to the main research questions. Figure 1.1 gives an overview of the outlines of this report and how each questions plays a role in a different chapter.

In Chapter 1, the context and problem have been introduced as well as the approach to tackle the problem. A literature study to find out more about the theoretical background is carried out and described in Chapter 2. The first three sub-questions are treated here. In Chapter 3, the first part of the case study is reported. The results of this guide to Chapter 4, in which a new approach for scenario generation is designed. The approach is designed to be generic and not case specific, so where Chapter 3 zooms in on the case study, Chapter 4 zooms out again. The newly designed approach is then applied to the case study in Chapter 2.3, where the report zooms in again. Although this report contains separate chapters for the discussion and conclusion, the results of the case study are discussed within Chapter 3 and 2.3. The discussion in Chapter 6 is focused on the results of the academic question, and adopts a broader view than just the case study. The same goes for Chapter 7, where conclusions to the overall research question are drawn and recommendations are made.

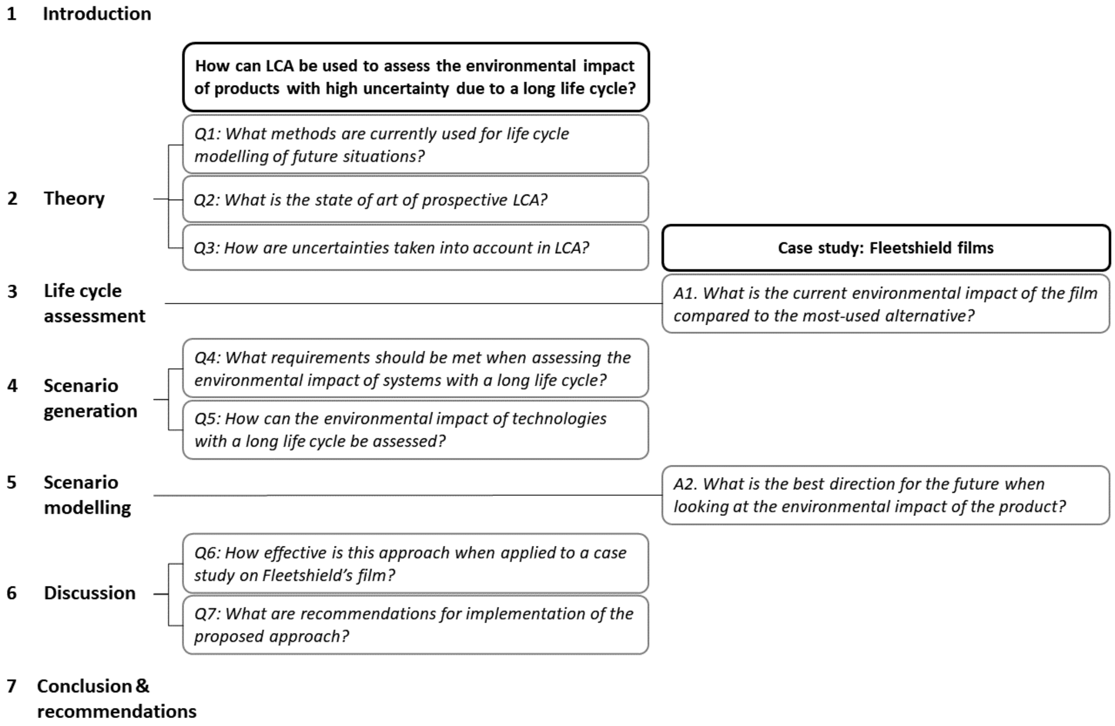


Figure 1.1: Structure of the report

# Chapter 2

# Theory

To be able to answer the research question, it is important to first establish what is already known and what has already been done in this field. This chapter sets out the current techniques for assessing environmental impacts and the state of art of prospective LCA. Also, uncertainties that are common within LCA are discussed as well as the manners in which people have dealt with these before. The findings will later be used when executing the LCA for the case study and determining how to deal with the uncertainty in modelling for future situations.

## 2.1 Measuring environmental impact

As the effects of global warming are becoming more visible, governments are implementing new environmental laws and regulations. For example, new EU regulations require companies with over 250 employees to report on their environmental impact starting in 2023 [12]. Therefore, the interest in methods of environmental impact measurement is increasing vastly.

There are different ways to measure the environmental impact of a product or system. Two widely used methods are measuring the circularity and life cycle assessment (LCA). Measuring the circularity finds its source in the idea of a Circular Economy (CE) where the use of virgin resources is limited by reducing, reusing and recycling while creating value for the economy [51]. It measures what goes into a system and what goes out, ideally bringing it down to zero. Everything that happens in between is a black box. With Life Cycle Assessment, the impact of a product can be measured over its entire life cycle, taking into account all processes from start to finish. The output of an LCA gives insight into the accumulated impact of the product but also into the impacts of single processes and everything in between.

This research focuses on using LCA as a tool for assessing the environmental impact. Therefore, this chapter dives into the general methodology, common obstacles faced when conducting an LCA and recent developments in this field.

### 2.1.1 General LCA

An early form of LCA has first been used in the late 1960s and it has developed into a broad method of assessment since then [21]. Nowadays, it is a widely used method to quantify and assess the impacts made by human beings through products and services [8, 45]. This quantification and assessment can be used to identify points of improvement, as a tool to support decision-making, for marketing reasons or to learn about environmental issues in general [68].

LCA is a method that allows the practitioner to make a quantitative assessment of the environmental impact of the entire life cycle of a product or system. This is done by modelling all energy and material flows and processes in the lifespan of that product or system and translating those to different environmental impacts. Specialized software, databases and expertise on the subject are required, making it an elaborate method. For official assessments, ISO certification is available [33].

There are many different types of LCA, including environmental LCA, cost-based LCA, organisational LCA, safety LCA and many more. This study will focus on environmental LCA. All types use the same four-step approach as described by the ISO 14040 standard [33]: a goal and scope definition, inventory analysis, impact assessment and interpretation. Figure 2.1 shows an overview of the standard phases of LCA.

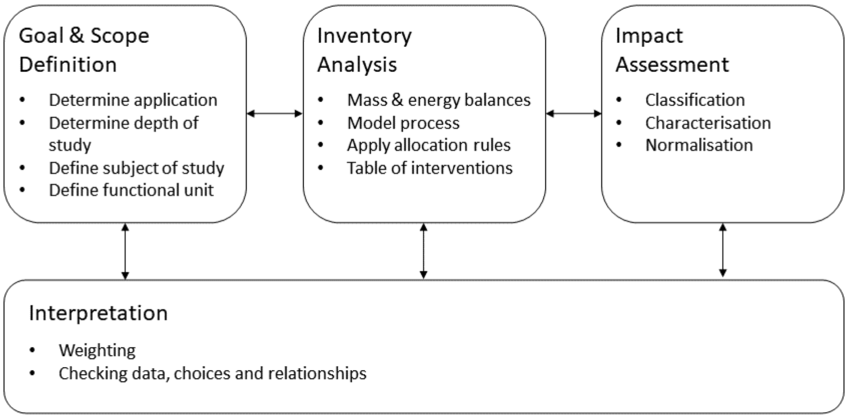


Figure 2.1: The LCA framework as defined in ISO 14040 [33]

While the initial step is not the most time consuming, it is an important one to carefully conduct. The goal and scope definition guides all methodological choices in the LCA [68]. Schrijvers et al. have shown that the goal 'to assess the environmental impact' can lead to at least five different methods [60]. Clear and consistent definition is important and the scope should be carefully matched with the goal [67].

During the inventory phase, all data is collected and an overview of the entire value chain is mapped and modelled using a Life Cycle Inventory (LCI) database, such as Ecoinvent [8]. There are multiple dedicated LCA software programs available to create such a model. Examples are SimaPro, GaBi and OpenLCA. These programs are a major help in translating the LCI input to the exact outputs for the Life Cycle Impact Assessment (LCIA).

All elementary flows defined in the LCI are converted to environmental impacts in the LCIA [8]. Impact assessment methods (IAM) are used to convert this data. There are different IAMs that are widely used, some of the most common being CML2001, ReCiPe, Environmental Footprint Methodology and TRACI. Each method includes their own impact categories, where the number of different categories differs between the methods. Nonetheless, the methods use the same kinds of categories and those can often be related to three main areas of protection: human health, natural environment and natural resources [54]. A clear distinction can also be made between midpoint categories and endpoint categories. Midpoints show impacts on single environmental issues, such as ozone depletion and land use, whereas endpoints focus on issues from a higher level, often comparable to the main areas of protection mentioned above [55]. Midpoints can be converted to endpoints, as they are also seen as a connection within the cause-effect chain of an impact category [3]. Midpoints and endpoints can both contribute in a useful way. The most important things to be considered are that using midpoints reduces uncertainty compared to endpoints, although the use of endpoints makes for simplified interpretation [3, 39, 55].

Although often mentioned as the final step, interpretation happens in all phases of LCA. It is part of the iterative process that connects all phases. Nevertheless, a large part of the interpretation does happen at the end and forms an important link between the results and the decisions made by stakeholders [36]. With the goal and scope in mind, both the LCI and LCIA are critically evaluated [59].

### 2.1.2 Challenges in LCA

Challenges occur throughout the process of conducting an LCA. Every phase of the assessment induces different obstacles. Djekic et al. identified multiple scientific issues that occur when performing LCA in the food supply chain [7]. Several are applicable to LCA in general and are recognized by other researchers in other fields as well [37, 5, 32, 49]. Limitations from system boundaries are considered a challenge, as well as defining the most appropriate functional unit, data collection, appropriate allocation approach, lack of transparency and choice of impact categories. These ultimately all come down to uncertainty, which is further discussed in Section 2.2.

Aside from the methodological challenges described above, there are also challenges with the implementation and use of LCA results. Although companies are aware of the benefits of LCA, the actual implementation of the results is lacking, for which one reason is the communication barrier [66]. Also, the focus of current research is mostly on improving the analysis part of LCA, and not so much on the actions that should follow afterwards [26].

## 2.2 Uncertainty in LCA

Uncertainty is present in all phases of LCA [4, 24, 28, 63]. Consequently, it plays an important part in the validity of the results and the trust in those. If uncertainties are not taken into account when interpreting results from an LCA, the conclusions might be misleading [5]. By quantifying the uncertainties, the conclusions of an LCA can be presented with more confidence and credibility, giving it an important role in strategic decision making and strengthening LCA as a tool to support decision-making [41, 64]. It helps to understand the robustness of the results. Therefore, this chapter dives deeper into the role of uncertainty in LCA.

### 2.2.1 Defining uncertainty

Uncertainty can cause problems in three parts of an LCA: at the input, when translated from input to output and at the output [23]. To understand the exact influence of uncertainties, it is important to first give a clear definition.

Though the term can be defined in different ways, experts most often define uncertainty in LCA as unknown data, being the lack of data or wrong or ambiguous data [23, 56]. Assessing the uncertainty in results does come with some obstacles. One of those is the confusing, inconsistent terminology [23, 41]. A term often confused with uncertainty is variability, while variability is different because it refers to heterogeneity of values. Nevertheless, there is often overlap between the two terms and various researchers name variability as one of the sources for uncertainty [13, 23, 41].

Besides variability, many different sources of uncertainty in LCA have been identified over the past three decades. Some examples are quality of inventory data ([1, 27]), unknown future changes ([45]) and simplified model assumptions ([24, 63]). Björklund defined a whole list of different types of uncertainties, including model uncertainty, mistakes and estimation of uncertainty itself [4]. A more comprehensive classification is now often adapted, in which the uncertainty is divided into three types: parameter uncertainty, methodological uncertainty, and epistemological uncertainty. Parameter uncertainty, sometimes also called data uncertainty, includes all uncertainty that arises because of incomplete knowledge of true parameter values [28]. Methodological uncertainty, also known as scenario uncertainty, originates from methodological choices made by the practitioner, such as the allocation approach and the LCIA method used [5, 61]. Uncertainty related to the lack of knowledge about the product that is being assessed, is referred to as epistemological uncertainty [56]. This three-type classification will be used for this report and is summarized in Table 2.1.

Table 2.1: Classification of uncertainty as adopted from Huijbregts et al. [28]

| **Type** | **Uncertainty due to...** |
|---|---|
| Parameter uncertainty | incomplete knowledge of parameter values |
| Methodological uncertainty | methodological choices made by the practitioner |
| Epistemological uncertainty | lack of knowledge about the product |

### 2.2.2 Recent developments

The importance of assessing the uncertainty in LCA is recognized increasingly [31]. This was not always the case, even though its significance was already recognized in the early 90s [4, 23]. Nevertheless, in the early 2000s the assessment of uncertainty was still an underexposed topic in LCA [57]. There was a lack of data available and no dedicated LCA software supported uncertainty calculations [23, 41]. This lack of both created a vicious circle, because people saw no need to create software for no data and vice versa [23]. However, LCA software developers are now supporting Monte Carlo analysis, paving the way for further accessibility of uncertainty assessment. Nevertheless, no standardized methodology for including uncertainty assessment in LCA is in use yet [61].

In recent years, various studies have been done to quantify uncertainty using statistical approaches, including analytical techniques such as stochastic multi-attribute analysis [50] and null hypothesis testing [25]. Within this list of analytical approaches, Mendoza Beltran et al. made a clear distinction between exploratory and confirmatory methods [41]. The first being relevant for early stages of analysis to identify the uncertainties, and the latter following in later stages to determine the level of significance [41]. However, because analytical methods are often unavailable, the numerical simulation in the form of Monte Carlo analysis is widely used to include uncertainties in LCA [22].

The statistical approaches are mostly used to deal with parameter uncertainties. Methodological and epistemological uncertainties are often dealt with using scenario analysis [18, 48, 64]. Though all uncertainty is relevant, as endorsed above, the epistemological uncertainty is especially interesting for this specific study. This will be further elaborated on in Section 2.3.

### 2.2.3 Management of uncertainty

The use of these methods, especially the statistical ones, is complex [41]. As mentioned before, often insufficient input data is available and standard LCA software offers limited support. There are few examples of these methods applied to real case studies and the documentation is scattered and unclear [41]. Furthermore, giving more space to the uncertainties would introduce more technical jargon and make the results less accessible by non-experts [23].

As Funtowicz and Ravetz stated [16]: "High quality does not require the elimination of uncertainty, but rather its effective management". Therefore, it is important to communicate uncertainties clearly, adapted to the target audience. According to Rosenbaum et al., an effective uncertainty communication strategy can be drafted based on three steps: the target audience and their familiarity with LCA should be identified, the exact information to be communicated should be identified and an idea should exist of how the results can be presented [56].

## 2.3 Forward-looking LCA

When assessing the impact of a product with a long technical life, it is important to take into account future changes to the product and the environment it is used in. Ideally, such an assessment leads to opportunities for environmentally conscious design choices early in the design process. However, at this point in time, very little about the future is known with (high) certainty. This raises a challenge also referred to as the Collingridge dilemma. This dilemma can be visualised using Figure 2.2, showing the design freedom is at its height when the knowledge and technological diffusion are at their lowest point [2]. While the low technological diffusion leaves much space for change, the lack of knowledge introduces epistemological uncertainty making it hard to determine what change results in the best outcome.

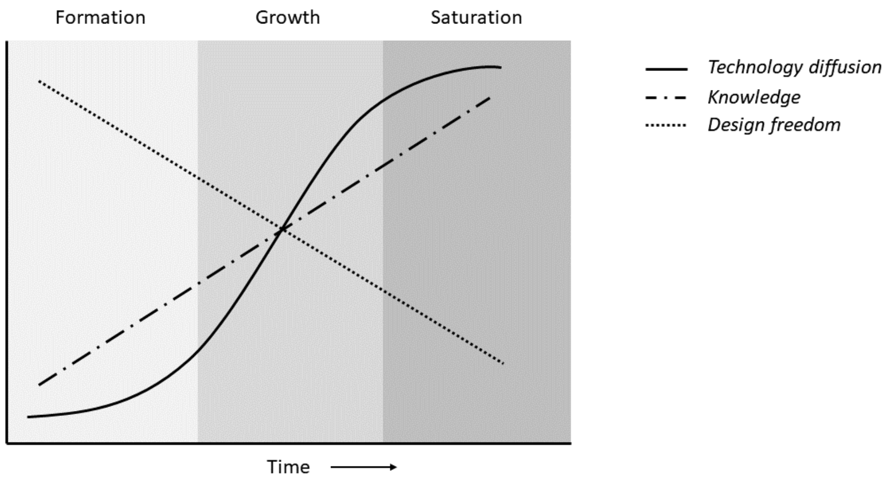


Figure 2.2: Relation of the diffusion curve relates to the knowledge level and design freedom, adopted from Arvisson et al. [2]

For systems with a long life cycle, epistemological uncertainty exists on top of the uncertainty that is already present in all LCA. As can be concluded from Figure 2.2, the highest epistemological uncertainty exists in early design phases and remains higher for a longer period of time when the life cycle is longer. This makes it impossible to create 100% reliable models of the future. Nevertheless, scenario modelling can provide a way to use LCA as a tool to base decisions on [64]. Mendoza Beltran et al. divide the different types of scenarios that can be used into two: cornerstone scenarios and "what-if" scenarios [40]. Cornerstone scenarios are used to describe future situations that are unknown or new, taking into account all parameters together [64]. "What-if" scenarios are more similar to a sensitivity analysis comparing specific alternatives by changing specific parameters [48].

### 2.3.1 Ex-post versus ex-ante

LCA modelling for future situations has been around for some time now. The types of LCA most suitable for this study are ex-ante LCA and prospective LCA. Both are used in the assessment of emerging technologies and focus on the modelling of situations before they occur (ex-ante), as opposed to modelling the product after it has been in use for a relatively long time (ex-post), which is often the case for conventional LCA [18]. While Van der Giesen et al. observe the two terms to be regularly used to describe the same, they also state clearly that ex-ante LCA is used for technologies before these are introduced to the market. Prospective LCA, on the other hand, can also apply to technologies that are already established to review its environmental impacts at a certain point in the future [18]. By this definition, prospective LCA is most applicable to this research. However, the concepts used in ex-ante LCA can still be very helpful as well, since for both ex-ante and prospective LCA more epistemological uncertainties are introduced than for ex-post LCA.

### 2.3.2 Prospective LCA

In ex-ante LCA and prospective LCA case studies, researchers often establish the current stage of development as starting point for solving the problem. They describe this in terms of Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) [2],[18],[30]. First introduced in the context of LCA by Gavankar et al. in 2014, both measures are closely related and present a scale from 1, conceptual development, to 10, mass production [17]. It should be noted that this often regards new, emerging technologies. However, such a scale could be applied to technologies passed the introduction to the market as well, to determine the current life stage.

Multiple recent researches identified different challenges with ex-ante and prospective LCA [53, 18]. Most relevant to this research are the choice of impact categories, the fact that most existing LCI databases are based on historical data causing a lack of primary data, the temporal mismatch between foreground and background data and the lack of common methodology. As opposed to ex-post LCA, the uncertainty analysis of prospective LCA might need to focus on more than the 'known unknowns' [18]. Feduzi and Runde describe 'known unknowns' as a hypothetical event imaginable by the decisions maker. The other option is an 'unknown unknown': a hypothetical event the decision maker does not even consider because they cannot imagine it happening [11]. In prospective LCA, 'unknown unknowns' can be a large contribution to the epistemological uncertainty.

## 2.4 Modelling for long life cycles

Challenges introduced by epistemological uncertainty in prospective LCA are additional to the challenges that exist in all LCA, such as the methodological choices made by the practitioner. In the previous section several of those challenges have been identified. Also, scenario modelling has been named as a method to deal with epistemological uncertainty. In order to use scenario modelling, there are also some challenges to overcome, most notably the lack of methodology, data and transparency. Existing literature gives some suggestions as to how to deal with those.

### 2.4.1 Lack of methodology

There is no common methodology for scenario modelling in prospective LCA. Most of the prospective LCA's focus on technologies that are not market-ready yet, with a relatively low TRL and MRL. So, the methodologies described are not directly applicable to the case of a product such as the film. Also, the assessed product is often a consumer product, unlike the film. However, the principles of these methodologies can be used. One of those is the systematic approach as proposed by Van der Hulst et al., providing a method consisting of three phases to assess future impacts of emerging technologies. Though the method is not finalized and tested in different situations yet, the steps used in this approach, could also be applied to the generation of different scenarios [30]. Furthermore, Negishi et al. propose an approach in the context of dynamic LCA for buildings in which multiple perspectives on the time dimension are identified [45]. These perspectives can possibly be applied in all time-dependent LCA.

### 2.4.2 Lack of data

Suggested sources for the required data are scientific articles, patents, expert interviews and roadmaps [2, 30], as well as shared socio-economic pathways and integrated assessment models [40]. Furthermore, learning curves and experience curves are considered possible data sources [30].

In case expert interviews are used as a source of data, Van der Giesen et al. suggest to use responsive evaluation, as described by Guba and Lincoln, to come to final scenarios [18]. This method consists of four steps, in which first all stakeholders are identified and their claims, concerns and issues are accumulated. The second is to present those to other stakeholder groups and let them respond and discuss. Third, all unsolved claims, concerns and issues require additional information to be collected and finally the new information from step three should lead to negotiations, in turn leading to a consensus [20].

### 2.4.3 Lack of transparency

To minimize inconsistencies and improve transparency of the LCA, Mendoza Beltran et al. suggest to differentiate between scenario generation and evaluation [40]. Scenario generation being the establishment of assumptions about the future situation, and scenario evaluation being the assessment of these assumptions [15].

# Chapter 3

# Life cycle assessment

In the previous chapter, relevant aspects in literature on LCA in general, as well as prospective LCA and uncertainties in LCA are described. This shows that there has been research towards forward looking LCA and that uncertainty remains a large obstacle in all LCA, but even larger in prospective LCA. To become more familiar with the process of conducting an LCA and to experience what the major obstacles are, first a conventional LCA is executed. This is done within the case study for Fleetshield. With the conventional LCA, only the current situation is under investigation. The aim is to answer Fleetshield's first question on how the film in the current situation compares to the most common alternative, being paint. Also, the opportunities to improve the environmental impact of both are explored.

This chapter follows the four-step structure of LCA by starting with the goal definition, followed by the inventory analysis. Next, the characterised and normalised results are presented in the environmental profile and finally those results are discussed and improvements are suggested.

## 3.1 Goal definition

As described in Section 2.1, an LCA starts with a goal definition. In this goal definition, the application, the subject and the depth of this study will be stated from the perspective of an LCA commissioned by Fleetshield.

### 3.1.1 Application

The goal of this LCA is to get an overview of the environmental impact of using film on passenger trains as part as the conservation system and comparing this to the impact of the 'traditional' method of only using paint coatings. The aim is to find out where the excessive impacts are, at what places the impact can be reduced and in what ways it can be reduced. The results are to be used to improve the product and the process and inform companies involved with the production, use and disposal of rolling stock about this. The research is initiated by Fleetshield, in cooperation with the University of Twente and NS. The latter is the user of the product and can provide useful insight into the use and disposal phases. Other relevant stakeholders are the manufacturer of the film and production partners of Fleetshield responsible for the assembly.

### 3.1.2 Subject of the study

The subject of study is the conservation system of an NS train. Two different conservation systems are compared by looking at two different train types currently in use by NS. Both train types have the same dimensions but different years of being modernised. This causes train type VIRM1 to have a traditional conservation system which consist of multiple layers of paint and type VIRM23 to have a conservation system that includes Fleetshield's film. From now on, this report will speak of VIRM1 and VIRM23 to distinguish the two alternatives.

Both alternatives are compared by looking at a single carriage from cradle to grave. In practice, different types of carriages are used in different combinations, as shown in Figure 3.1. Every carriage shown in this figure has a different passenger capacity and exterior layout. In this analysis, the average of the six carriages is used when this difference is of influence.

For VIRM23, this assessment will specifically look at the 180 series film, laminated with 8993 polyester laminate, both from 3M. In reality, another type of film is used for the heads of the outer carriages because it requires more flexibility to curve around the heads. However, for simplicity, this research will only look at the film used on the largest part of the exterior area.

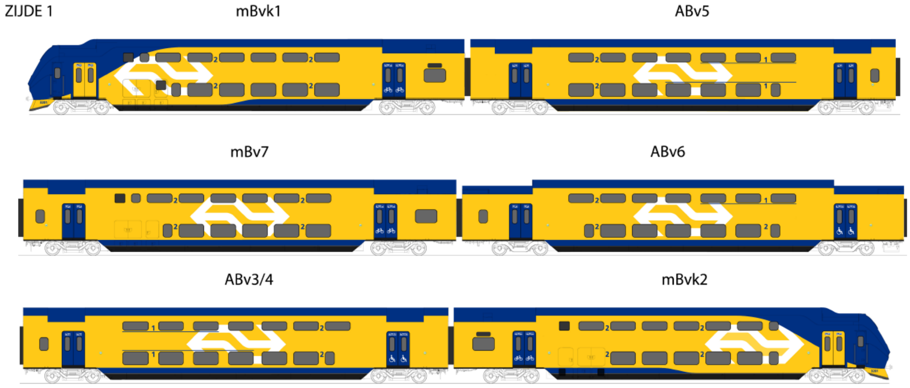


Figure 3.1: Overview of carriages of VIRM23, retrieved from Fleetshield

### 3.1.3 Depth of study

Within this study, only first order of inventory will be taken into account because the impact of second and higher order levels will be limited due to mass production. This means the resources used for production and application of the traditional conservation system and film are part of the model. Also, the cleaning processes during the use phase and the resources required for this will be considered as well as the disposal of waste during production, cleaning products and the conservation systems at the end of their lives. Figure 3.2 schematically shows all processes taken into account in this study.

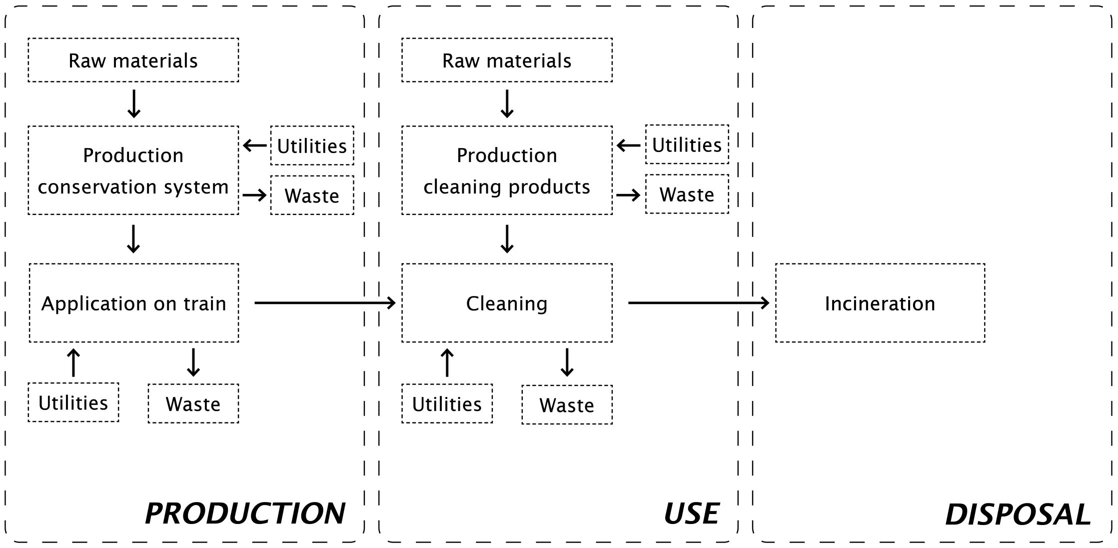


Figure 3.2: General overview of the assessed system

Parts not taken into consideration are the repair of film and coatings and the packaging used during transportation in the production phase because the masses of those are very small compared to others and there is no reliable data on exact numbers available. Furthermore, the distance for transportation between different locations during production has shown to be almost equal for both alternatives and is therefore left out. Also, the energy required for driving the train has not been taken into account because the weight difference between the two alternatives, which could be a reason for a difference in electricity consumption, is minimal.

The results are valid for EU countries. A lot of companies within this region work together on projects and rules and regulations are based on EU guidelines. The temporal validity of this research is 5 years.

### 3.1.4 Functional unit

The functional unit used in this analysis is one passenger kilometer (pkm). This is chosen because part of the goal of this analysis is to inform the industry about the environmental impact and sustainable improvements, and this unit is often used for LCA's regarding transportation. In case of the NS train, the average capacity per carriage is 108 persons. The average distance a train travels each month is approximately 50,000 km. This comes down to 5,400,000 pkm per month.

## 3.2 Inventory analysis

For the inventory analysis, data is collected so that input and output flows can be modelled in the form of mass and energy balances. The model for this LCA is made in GaBi software, in which the mass and energy balances, combined within the process trees, are the input and the environmental impacts are the output.

### 3.2.1 Data collection

For a useful inventory analysis, enough data must be collected and processed. In this research, data is obtained through documents and knowledge within Fleetshield, NS, Fleetshield production partners and the manufacturer. First of all, expert interviews are conducted with employees from those companies. Besides exact data, also insights into the process and future expectations are obtained through the interviews.

Whenever there is a lack of sufficient data or the exact numbers are classified, assumptions are made based on data found on the internet. For example, the exact amounts of paint used are known, but the ingredients it is composed of are classified. In this case, the safety data sheets (SDS) are used to find approximations of the hazardous materials used in the paints.

### 3.2.2 Modelling

To model the complete life cycle, dedicated software, namely GaBi is used. The majority of the flows and processes are from the GaBi database, with additions from the EcoInvent database when necessary. Below, an outline of the life cycle as modeled in GaBi is described. Also, process and assembly trees that resulted from the inventory analysis are shown.

#### Process trees

The processes of both conservation systems are shown in Figure 3.3 and 3.4 for VIRM1 and VIRM23 respectively. Those figures show the upper level of all processes to give an overview of what has been analysed. More detailed process trees, which are used as a basis for the GaBi model, can be found in Appendix A. A more detailed description of each phase and the assumptions made for the modelling are given in the following paragraphs.

#### Production

The conservation system is build up of several layers, the first being a layer of putty, followed by primer, multiple layers of base coat and, finally, a layer of clear coat or film, depending on the train type.

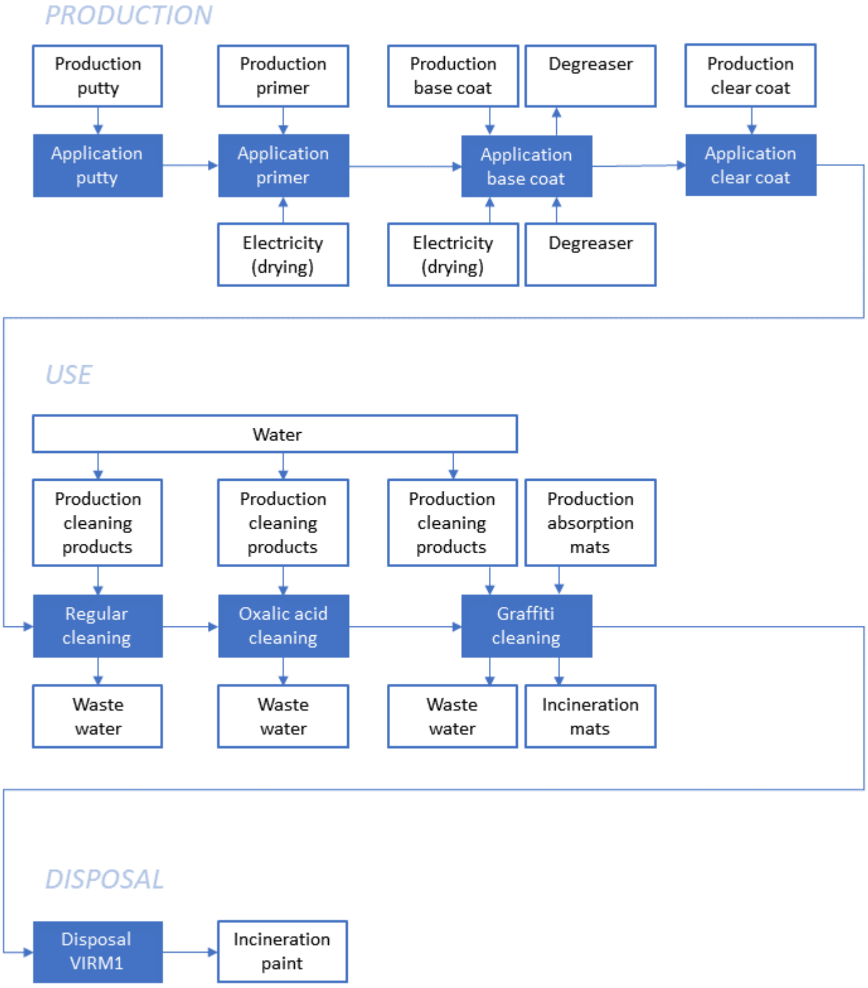


Figure 3.3: Process tree life cycle VIRM 1

Clear coat is only used for VIRM1. It is replaced by film with VIRM23. Also, during the modernization of VIRM23, a smaller amount of base coat is used. Between the application of the different paint layers, a drying tunnel is used to speed up the drying process. There is limited waste in the painting process because of the use of a 2K painting system which only mixes the required amount of coating with hardener just seconds before it is sprayed on. The film is produced in Germany and laminated by a Dutch production partner of Fleetshield. This company also plots the design, which causes some cutting waste. NS applies the finished product on their trains, where also some waste is created because of windows that still need to be cut out.

For the production phase, some assumptions had to be made, which are the following:

- Although the 2K-installation was not available yet when VIRM1 was modernised, it will be modelled as the used technique. For one because there is no information available about the previously used techniques and secondly because if VIRM1 was modernised at the same time as VIRM23, the 2K-installation would have been used.
- The given amount of putty and paint used slightly differs between VIRM1 and VIRM23. Nonetheless, the amounts of putty and primer used are assumed to be equal for both types of trains because the differences are very small.

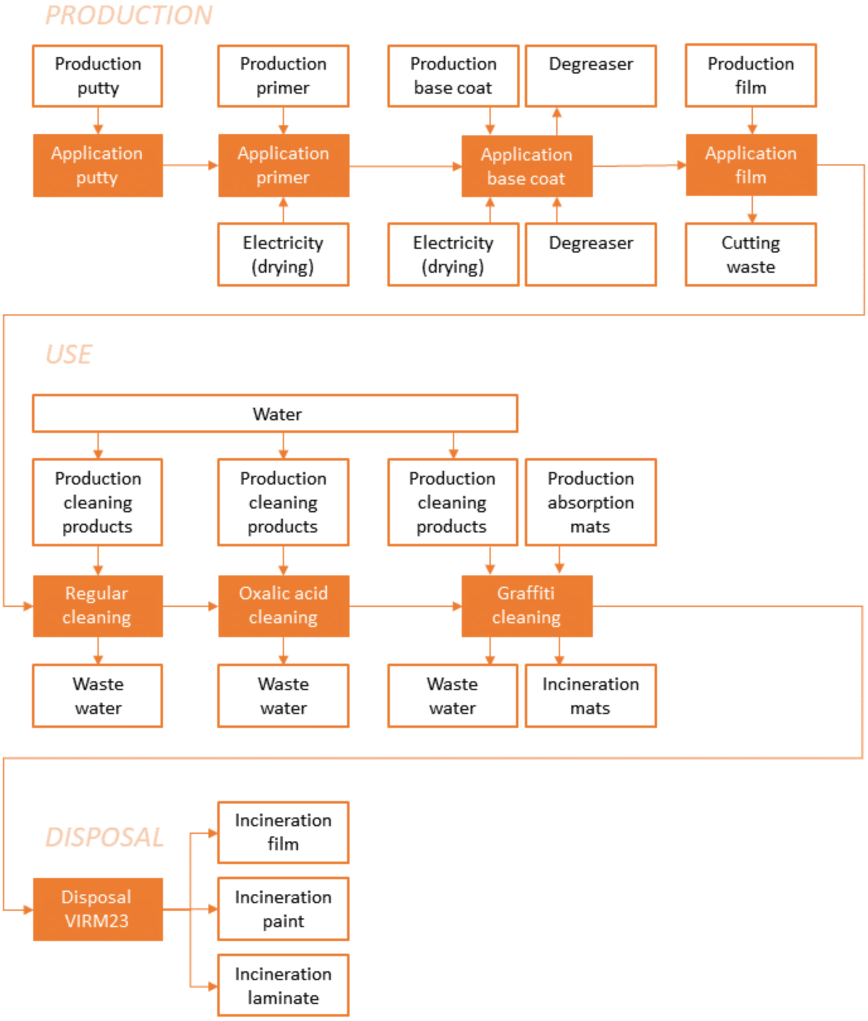


Figure 3.4: Process tree life cycle VIRM 23

### Use

During the use phase of the film, the largest part of the maintenance is the cleaning of the trains. This consists of regular cleaning, oxalic acid cleaning and graffiti cleaning. At the moment of modelling the processes, the aim of NS is to do a regular cleaning every week for VIRM1 and once a month for VIRM23. The oxalic acid cleaning is scheduled every 60 days for both trains and the graffiti cleaning is done whenever necessary. The first two processes take place using a washing machine, the graffiti cleaning is done by hand. The same cleaning products are used for both trains.

For the use phase, several assumptions are made as well, those are the following:

- The maintenance of the film and paint layer is assumed to be minimal and therefore not taken into account. This includes the paint that sometimes partly has to be replaced after graffiti cleaning.
- Also the extra movement of the train due to maintenance of the conservation system is assumed to be minimal and therefore not considered.
- In reality, the cleaning frequency is much lower because of capacity and scheduling reasons. For consistency and because it is the aim of NS, the above mentioned number of cleanings is considered.

**Disposal**

There are waste streams in all three phases of the conservation systems life cycle. Liners and cutting waste need to be disposed of during production and the same goes for cleaning products used during the use phase.

At the end of life, the train is stripped down to the core and a large part of it is reused or recycled. What is left includes the conservation system protecting the exterior of the train. No plans have been made for the end-of-life of the film yet, as this will not take place for another 18 years. However, experts presume it would be incinerated together with the steel body if it had to happen right now.

Because so little is known about the disposal phase, the following assumptions are made:

- The conservation system in assumed to be incinerated and the heat produced during the incineration is used to generate energy.
- For incineration at the end of life of the conservation system, only the elements with the largest weight percentage are taken into consideration. For the paint this is polyurethane, for the film this is PVC and for the laminate this is polyester. Although these do not account for the full weight of the product in the production phase, they are accounting for the full weight in the incineration process.
- Similar to the modelling of the incineration at the end of life, also the film liner waste created during production is modelled as pure polyethylene, while in reality this is a combination of polyethylene and paper.

**General assumptions**

Besides the assumptions per phase as mentioned above, there is also multiple assumptions that apply to the overall modelling. First of all, the expected technical life of the film is 14 years. However, the trains are used 15-20 year. No example is available of a train with film driving around for over 14 years, because the technology is too new for that. Nevertheless, a life cycle of 18 years is assumed in this model.

Furthermore, as mentioned in Section 3.2.1 part of the data is based on safety data sheets. On an SDS, only approximate weight percentages are given and since only unsafe ingredients are named on these sheets, this often does not add up to 100%. If this is the case, not 100% of the known mass of this paint is used in the model, only the percentage for which the ingredients are known. Substances accounting for less than 5% of the products weight are considered negligible.

Finally, in case of assumptions with limited substantiation, a sensitivity analysis will be conducted to find out how large the impact on the results is.

**Assembly tree**

All masses of each flow are shown in the assembly trees. The assembly trees of the conservation system of VIRM1, the conservation system of VIRM23 and the cleaning products used can be found in Appendix B.

## 3.3 Environmental profile

The inventory analysis shows where the main differences between the two conservation systems lie. This gives some indication of what results can be expected. The main differences in the production phase are expected to be caused by the different composition of the conservation system. In case of VIRM1 this means no PVC is used, but in case of VIRM23 fewer layers of paint are used which not only means less paint but also less energy used for drying. For the use phase, the distinctness is in the number of regular cleanings scheduled and in the disposal phase the types of materials to be incinerated will likely cause different outcomes.

GaBi calculates the exact outputs through classification, characterisation and normalisation. The impact assessment method used in this study to convert the results is ReCiPe 2016. This results in 18 midpoints. This section will analyse the results to find the differences in impact between the two alternatives and pinpoint the causes for these differences to be able to find out what opportunities there are for the individual alternatives to improve.

### 3.3.1 Characterisation

As explained in Section 2.1, both midpoints and endpoints can be calculated during the characterisation. For this study, only midpoints are considered because of the extra uncertainty endpoints would introduce. For every ReCiPe midpoint the impacts are calculated. Those results were analysed and the ones that stood out are discussed below.

#### Climate change

Comparing the climate change impact of VIRM1 and VIRM23, as shown in Figure 3.5, the highest impact turns out to be in the use phase. Figure 3.6 shows this is mainly due to the use of oxalic acid during the oxalic acid cleaning.

What stands out in this impact category is the impact caused in the disposal phase. When zooming in on the disposal phase of VIRM1, as shown in Figure 3.7a, the impact of the incineration of polyurethane (paint) shows to be very high. This process actually causes the highest impact in this category, but is compensated for by the generation of steam and electricity in this same incineration process. Figure 3.7b shows that in the disposal phase of VIRM23, the incineration of polyester (laminate) and PVC (film) also contribute to the climate change impact. These are not as much compensated for by the generation of electricity and steam. Therefore, the disposal phase of VIRM23 does not 'give back' as much in this category as VIRM1. Even though the impact of the production phases of both systems are similar, and the impact of the use phase of VIRM1 is much higher than the use phase of VIRM23, the disposal phase brings the total impacts closer together.

Since the regular cleaning and the polyurethane (PU) incineration cause most of the impact, the higher impact in this category by VIRM1 can be logically explained: the regular washes are four times more frequent and an extra layer of polyurethane-based paint is used in this conservation system.

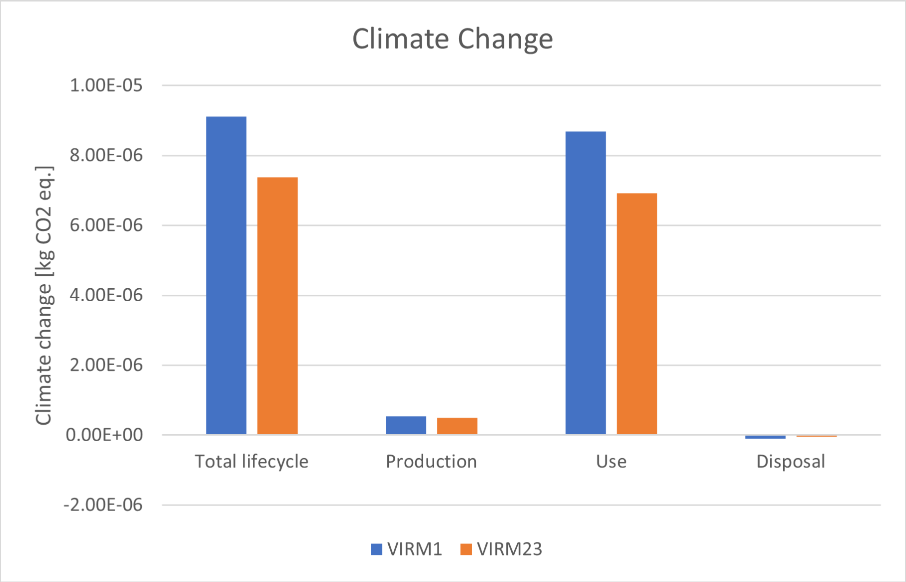


Figure 3.5: Climate change per life cycle phase VIRM1 and VIRM23

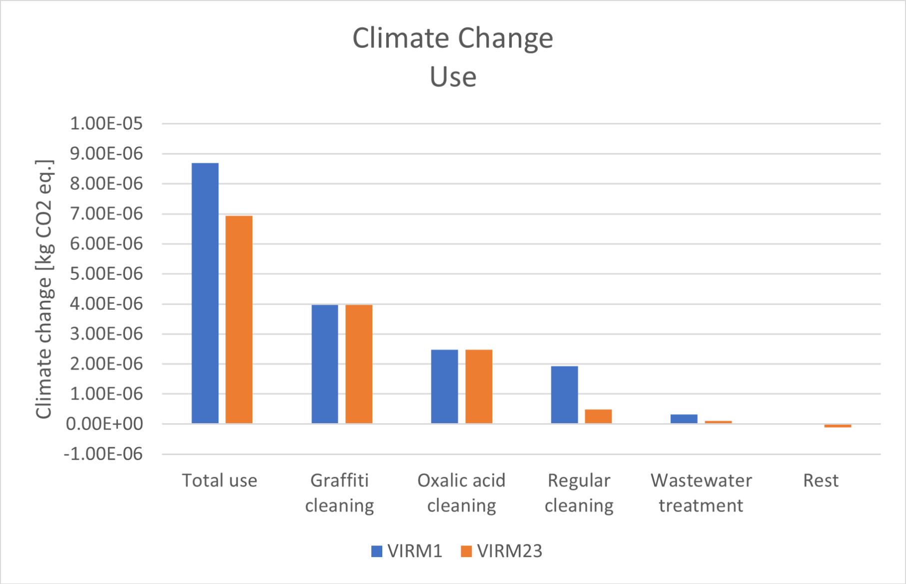
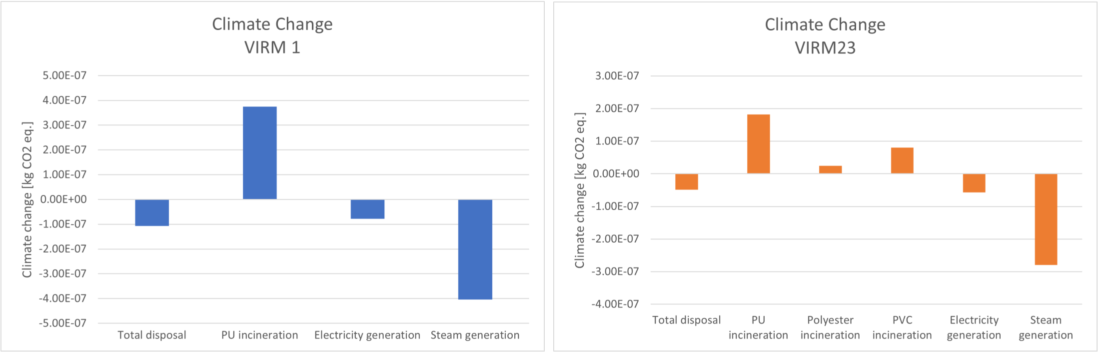


Figure 3.6: Climate change in use phase VIRM1 and VIRM23



(a) VIRM1

(b) VIRM23

Figure 3.7: Climate change impact in disposal phase

### Freshwater consumption

Figure 3.8 shows that, similar to climate change, the use phase also accounts for the highest impact in freshwater consumption. When zooming in on the use phase of both VIRM1 and VIRM23, as shown in Figure 3.9a, this is mostly caused by regular cleaning. This is expected since 600L of water is used every time the train carriage is cleaned. Although the wastewater treatment does compensate for this, the total impact in the use phase is still very high compared to other phases.

Another thing that stands out in Figure 3.8 is the production phase of VIRM23 causing a higher impact than that of VIRM1. Figure 3.9b shows that this higher impact is mainly caused by the production of the film. Diving into that, the main cause of this impact is both the production of kraft paper (the laminate liner) en the PVC production.

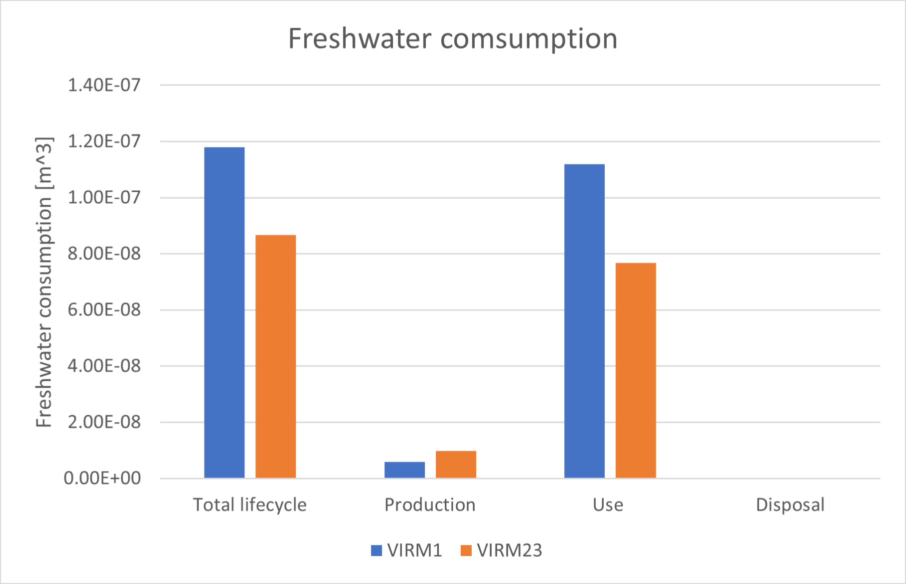
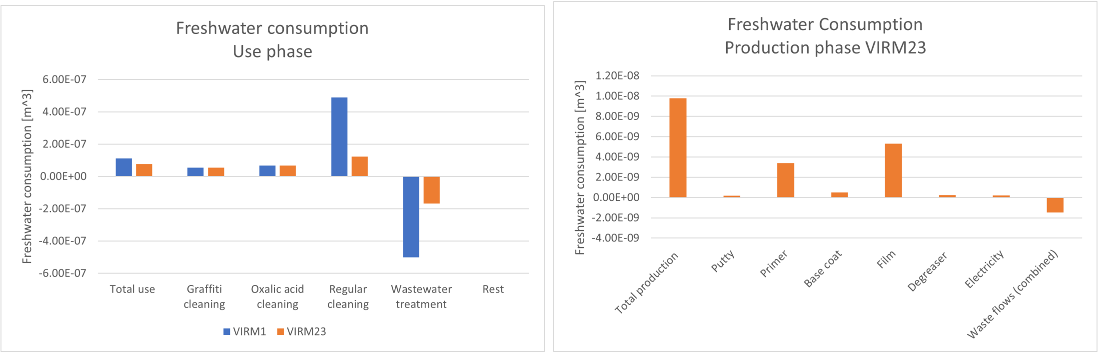


Figure 3.8: Freshwater consumption per life cycle phase VIRM1 and VIRM23



(a) Use phase VIRM1 and VIRM23

(b) Production phase VIRM23

Figure 3.9: Freshwater consumption in use and production phase

### Freshwater ecotoxicity

The normalisation, as described in Section 3.3.3, shows that freshwater ecotoxicity is the second highest impact category. Therefore, the main causes of the impact are investigated. Figure 3.10 shows that the use phase is the highest contributor for both VIRM1 and VIRM23. Zooming in on that in Figure 3.11 shows that the main causes are the regular cleaning and the graffiti cleaning. In both cases, multiple ingredients of the cleaning products (EDTA, ethoxylated alcohol and butylglycol) are reasons for this impact. Furthermore, in the same figure can be seen that the impact of the regular cleaning is smaller than the impact of the graffiti cleaning for VIRM23. This means that graffiti cleaning is also a process to watch, because if the regular cleaning frequency were to be decreased, the graffiti cleaning would become the largest problem.

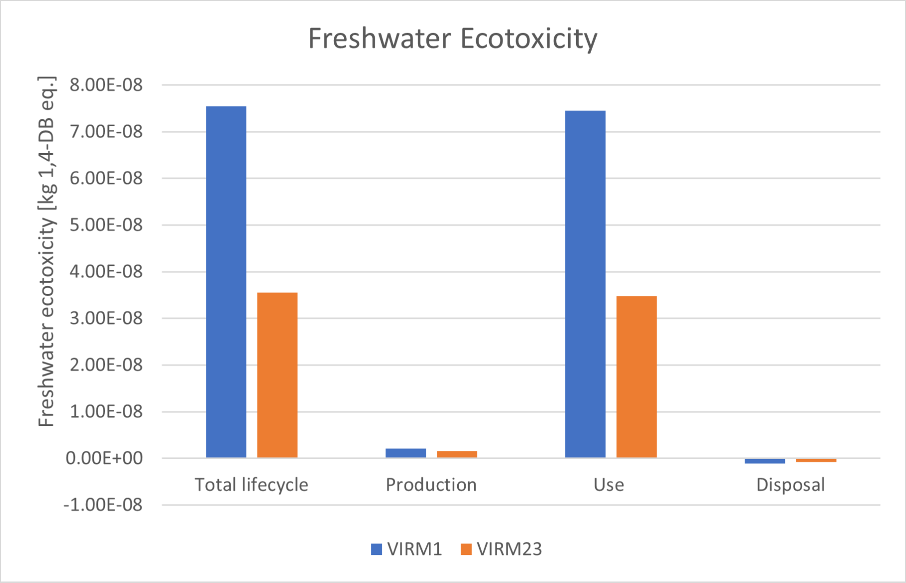


Figure 3.10: Freshwater ecotoxicity per life cycle phase VIRM1 and VIRM23

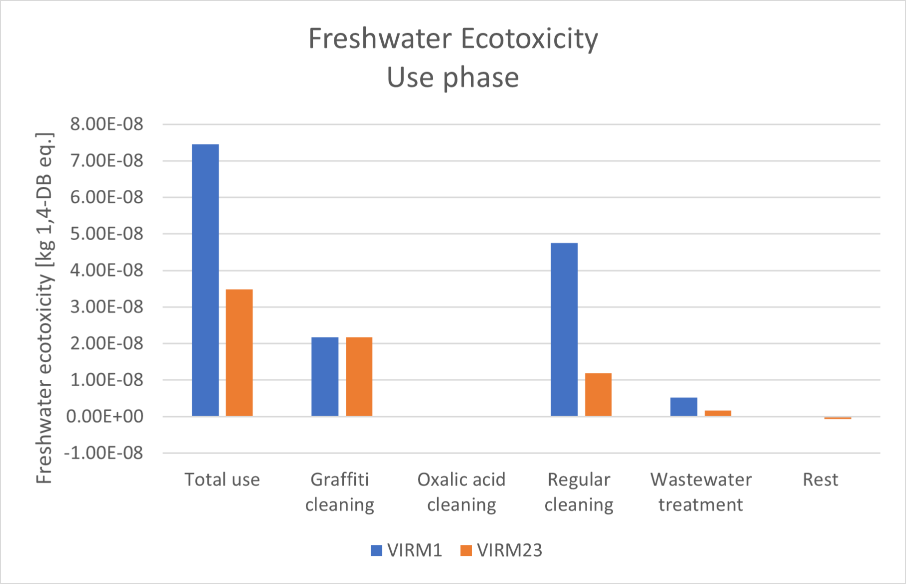


Figure 3.11: Freshwater ecotoxicity in use phase VIRM1 and VIRM23

### Freshwater eutrophication

In this impact category, the difference between VIRM1 and VIRM23 is one of the largest, as can be seen in Figure 3.12. Again, the use phase accounts for the highest impact. Figure 3.13 shows the main causes are the regular cleaning (EDTA and butyldiglycol in the cleaning product) and the wastewater treatment. Because of the higher cleaning frequency for VIRM1 and, thus, the larger amount of wastewater, this difference in impact between the two conservation systems becomes relatively large.

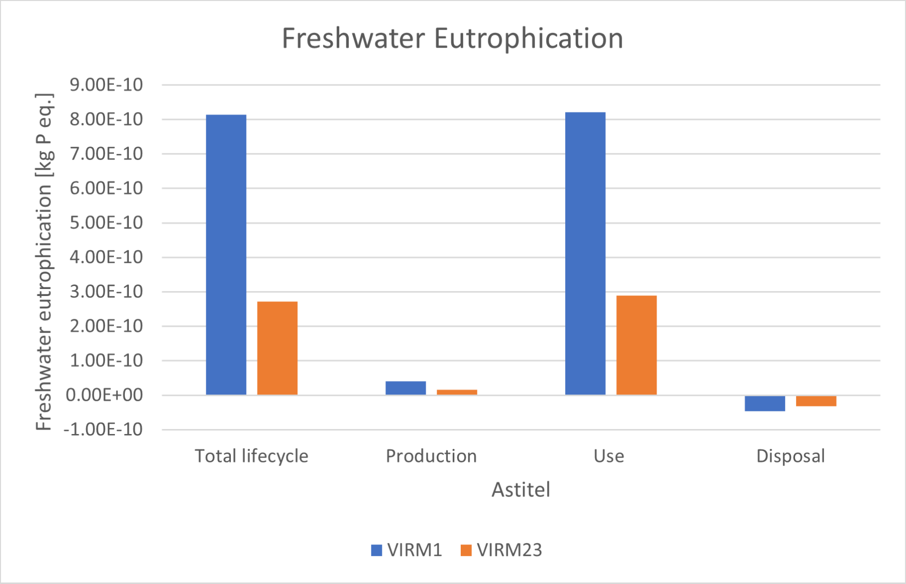


Figure 3.12: Freshwater eutrophication per life cycle phase VIRM1 and VIRM23

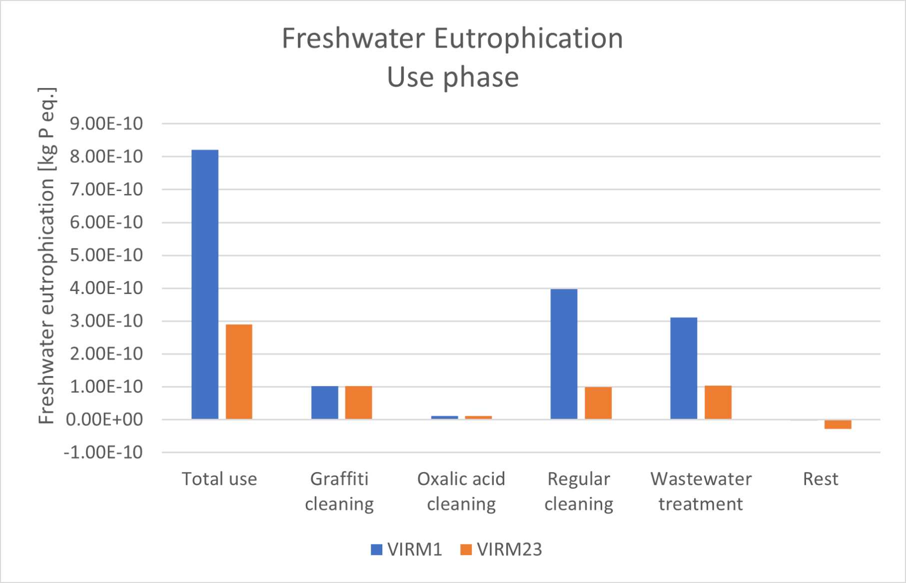


Figure 3.13: Freshwater eutrophication in use phase VIRM1 and VIRM23

**Human toxiciy, cancer**

The human toxicity (cancer) impact category is the most noteworthy. Not only does the normalisation show that this category has by far the highest impact, also the difference between VIRM1 and VIRM23 is the smallest. This can be seen in Figure 3.14. Although the use phase is again the largest cause, for VIRM23 the impact in the production phase is very close to the use phase impact.

Figure 3.15a shows that regular cleaning is causing this high impact in the use phase of VIRM1. This is mainly caused by the use of EDTA in the cleaning products. For VIRM23, on the other hand, graffiti cleaning is the largest contributor in the use phase. This is mainly caused by the use of ethoxylated alcohols in the cleaning product.

Looking at what causes the high impact in the production phase of VIRM23, Figure 3.15b shows that the film production is the main contributor. Mainly the production of PVC is not favorable for the human health.

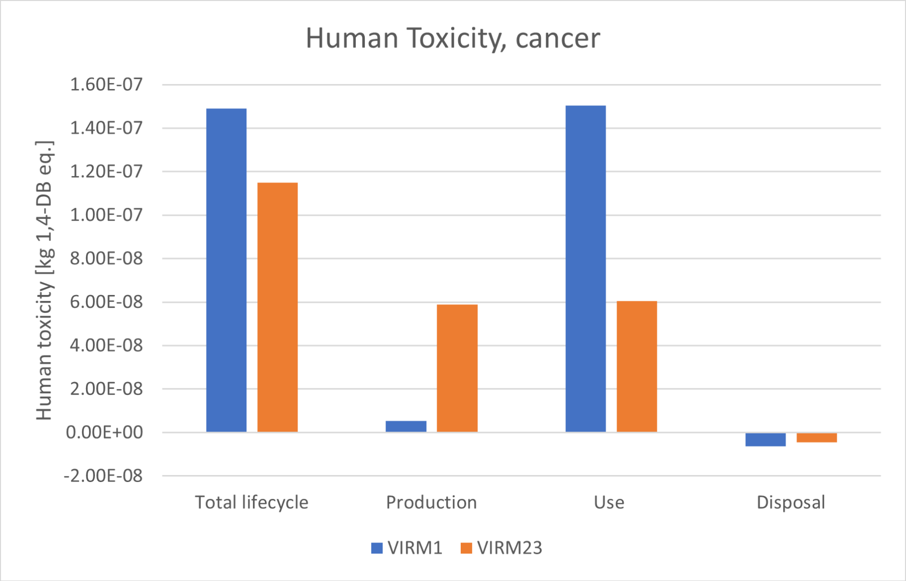
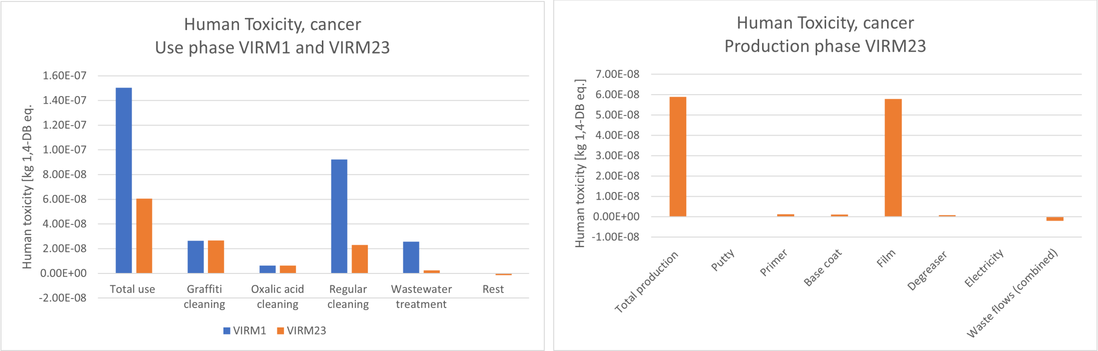


Figure 3.14: Human toxiciy per life cycle phase VIRM1 and VIRM23



(a) Use phase VIRM1 and VIRM23

(b) Production phase VIRM23

Figure 3.15: Human toxicity in use and production phase

### Land use

After the human toxicity indicator, land use shows the smallest difference between VIRM1 and VIRM23. Figure 3.16 shows that the use phase is the highest. However, again the production phase of VIRM23 causes a much higher impact than the production phase of VIRM1.

Zooming in on the use phase, as shown in Figure 3.17a, the graffiti cleaning causes the highest impact because of the ethoxylated alcohols used in the cleaning products. Since this is also used, in a smaller dose, in the cleaning products used for regular cleaning, this is also an important reason for the high impact in this phase. It should be noted that the graffiti cleaning of VIRM23 has proven to be easier than that of VIRM1. The removal is quicker and does less damage to the conservation system. In some cases, the paint of VIRM1 even has to be replaced partly after a graffiti cleaning. However, because no exact difference in numbers is known between the two, this is not taken into account in the model and, thus, not reflected in these results.

The main cause of the high impact in the production phase of VIRM23 is the production of film, as can be seen in Figure 3.17b. More specifically, the contribution of kraft paper production is relatively high. Since this is modelled as incineration while kraft paper could also be recycled, it is interesting to look at the possibilities this offers.

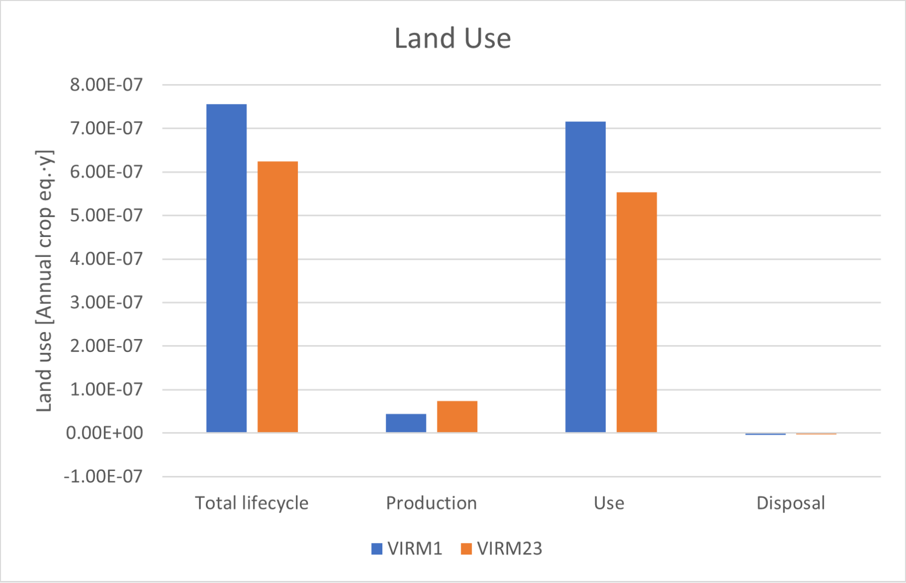
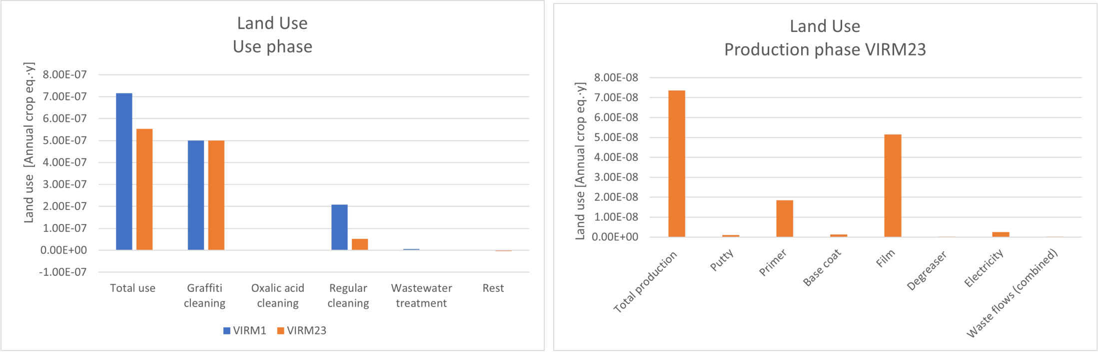


Figure 3.16: Land use per life cycle phase VIRM1 and VIRM23



(a) Use phase VIRM1 and VIRM23

(b) Production phase VIRM23

Figure 3.17: Land use in use and production phase

### Marine ecotoxicity

Looking at the normalised results in Section 3.3.3, marine ecotoxicity shows one of the highest impacts compared to other categories. In both alternatives this high impact is mostly due to the use phase, as can be seen in Figure 3.18. Figure 3.19 shows that the main contributor for VIRM1 is the regular cleaning (EDTA) and the main contributor for VIRM23 is the graffiti cleaning (ethoxylated alcohols).

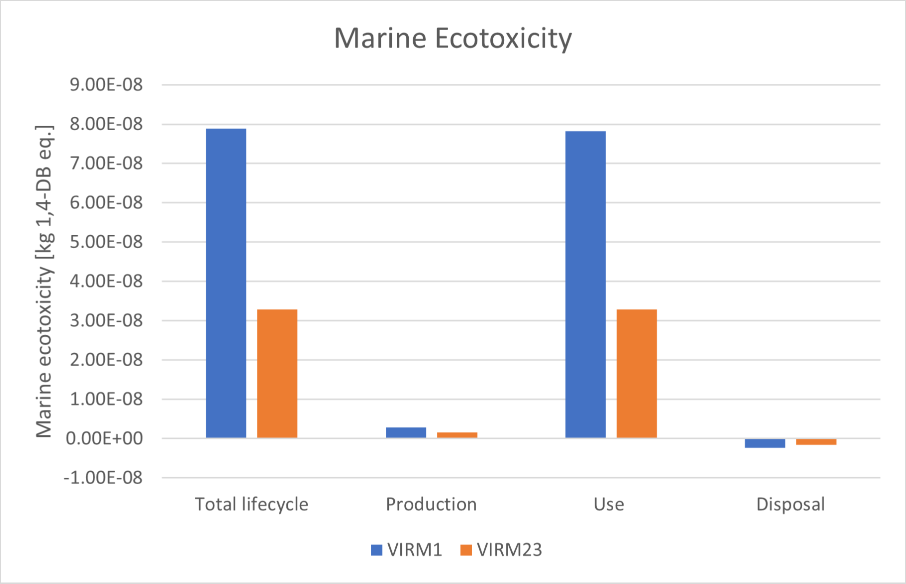


Figure 3.18: Marine ecotoxicity per life cycle phase VIRM1 and VIRM23

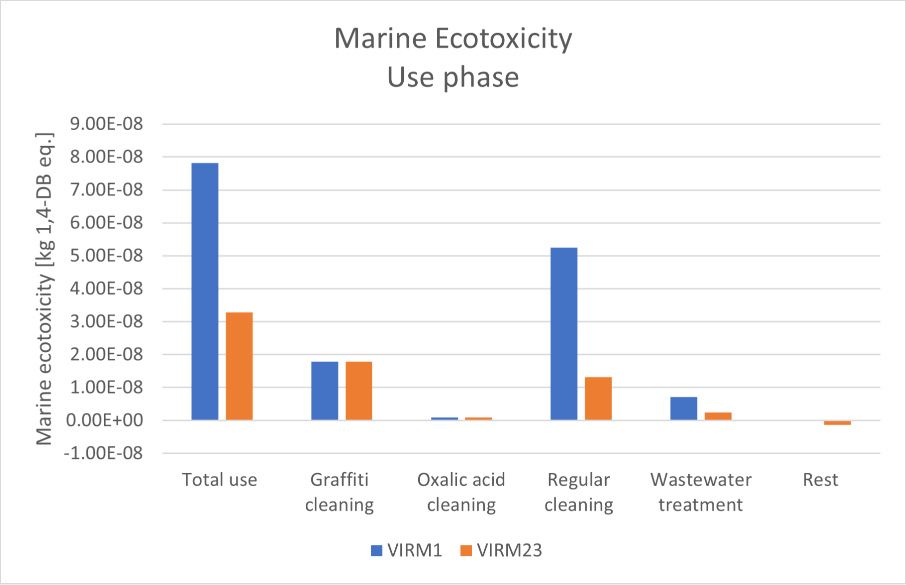


Figure 3.19: Marine ecotoxicity in use phase VIRM1 and VIRM23

### Terrestrial ecotoxicity

Terrestrial ecotoxicity is the impact category with the largest difference between VIRM1 and VIRM23. Figure 3.20 shows that this is not only due to a large difference in the use phase, but also because of a negative impact for VIRM23 in the production phase. Despite the confusing choice of words, this is actually a positive point. Figure 3.21 shows that this is for a large part due to the generation of steam and electricity during waste incineration. Also, the production of film gives a negative impact. During this process, waste liner and cutting waste are incinerated, with steam and electricity generation as side product as well.

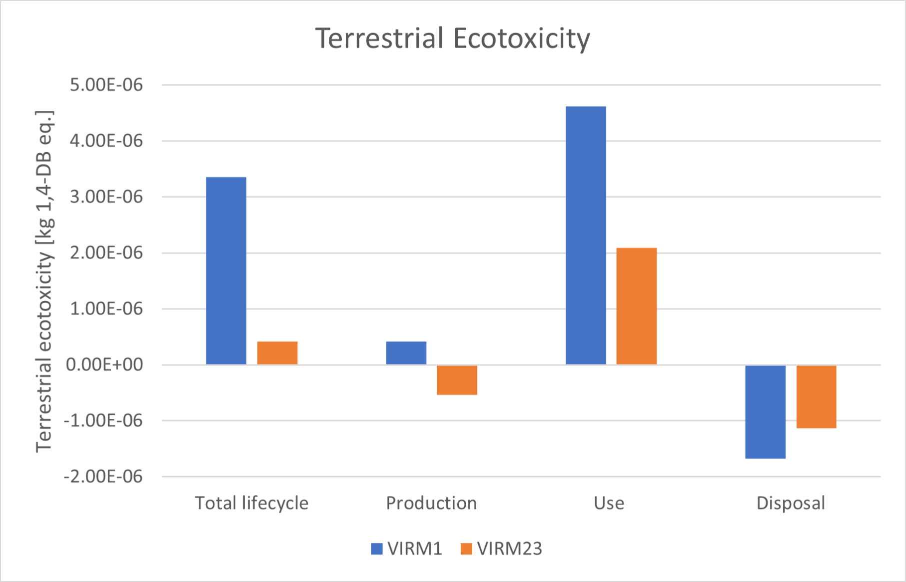


Figure 3.20: Terrestrial ecotoxicity per life cycle phase VIRM1 and VIRM23

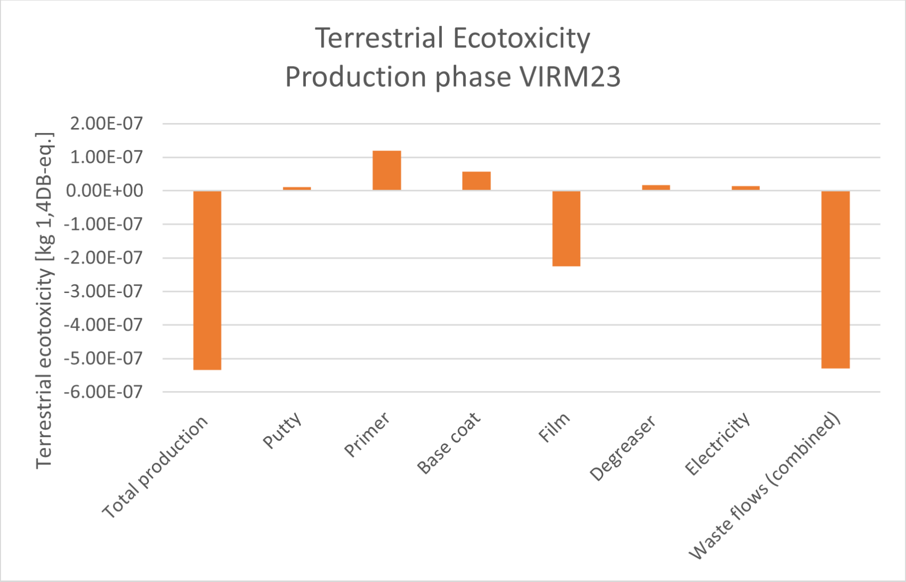


Figure 3.21: Terrestrial ecotoxicity in production phase VIRM23

### 3.3.2 Checking assumptions

The LCI contains a lot of assumptions for the composition of the paints. To verify if those assumptions are just, an alternative model is created using the paint processes from the GaBi database. Comparing the alternative to the original model, the results are almost the same, so the assumptions seem to be grounded.

### 3.3.3 Normalisation

To be able to make a good comparison between the different impact categories, the results are normalised using the ReCiPe normalisation factors of 2016. Those are based on the Europe and World reference inventories in SimaPro [29]. The ReCiPe 2016 normalisation factors are used to normalise all results. This enables a comparison between the different impact categories. The main findings from this normalisation are presented below.

### VIRM1

Starting with the normalised results of VIRM1, Figure 3.22 shows that human toxicity (cancer) is the highest impact category, for the most part caused in the use phase. For almost all impact categories, regular cleaning alone accounts for more than half of the impact. In some cases, graffiti cleaning or oxalic acid cleaning have a relatively large impact as well, but the production and disposal phase are rarely large contributors to an impact category.

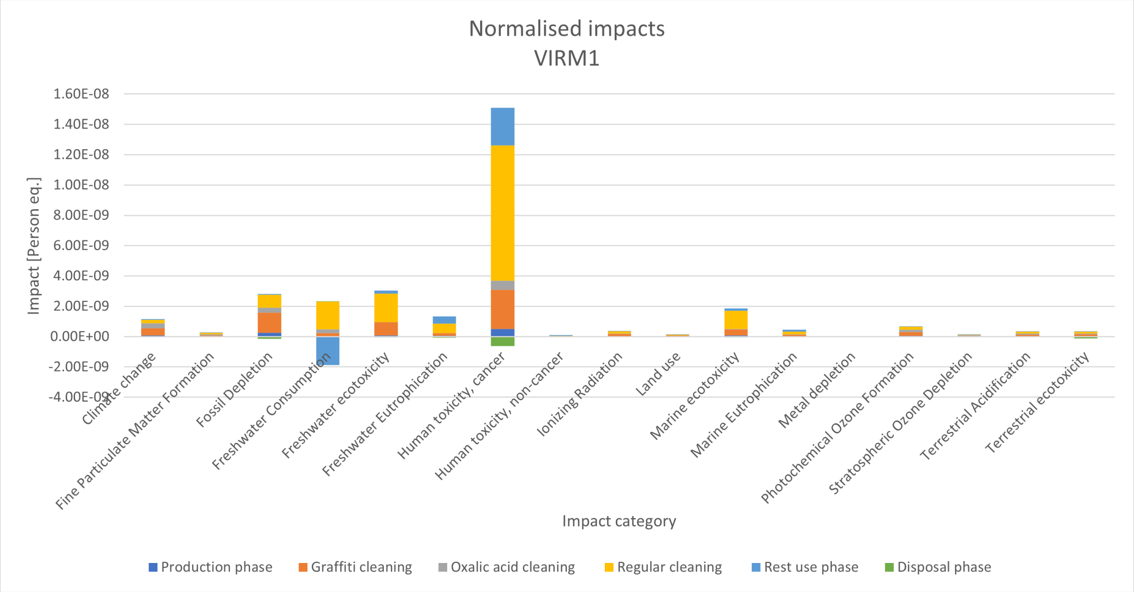


Figure 3.22: Normalisation per impact category VIRM1

### VIRM23

The normalised results of VIRM23, as shown in Figure 3.23, show the largest contributors are different processes from those of VIRM1 in all impact categories. Although the distribution of largest to smallest impact category is similar, in case of VIRM23 the main contributors are the production phase and the graffiti cleaning. The main reason for this difference in the production phase is the production of film, as discussed in Section 3.3.1.

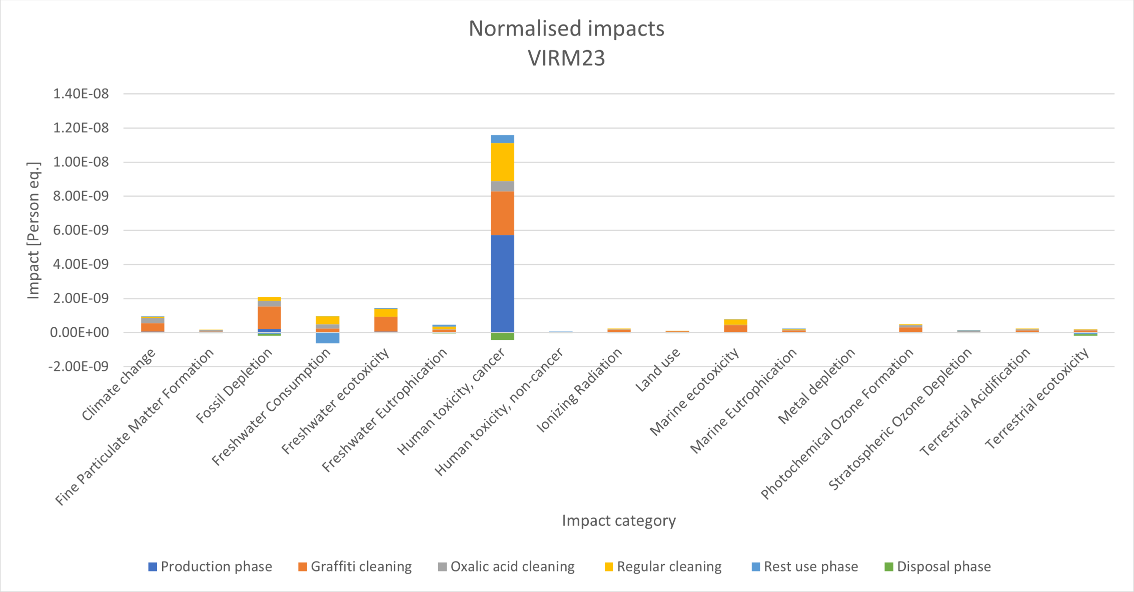


Figure 3.23: Normalisation per impact category VIRM23

### Comparing VIRM1 and VIRM23

Using Figure 3.24, the impact of both conservation systems can be compared per impact category. This shows that VIRM1 has a higher impact in every category. Also, the five impact categories that show the highest impacts when normalising are almost the same for both conservation systems, even though the causes for those impacts are different. For both, human toxicity (cancer) is by far the highest impact category, followed by freshwater ecotoxicity for VIRM1 and fossil depletion for VIRM23. In case of VIRM1, fossil depletion is the third highest and marine ecotoxicity the fourth. For VIRM23, freshwater ecotoxicity comes third and climate change comes in fourth. The fifth highest impact for VIRM1 is freshwater eutrophication. For VIRM23 this is marine ecotoxicity. In both cases, the lowest impact when normalising is metal depletion.

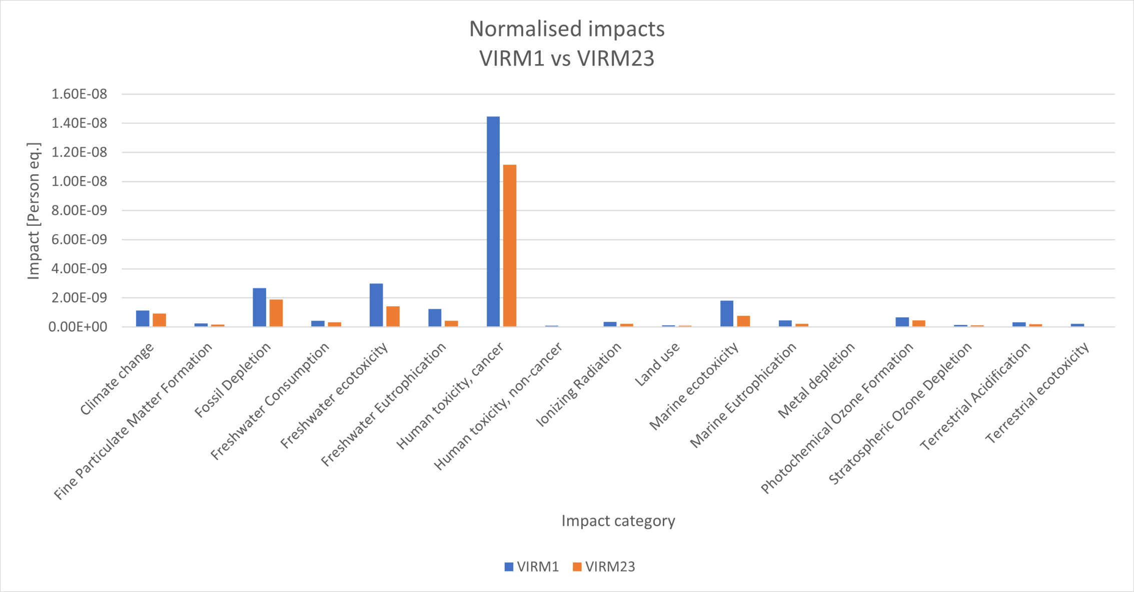


Figure 3.24: Normalised results VIRM1 and VIRM23 compared per impact category

Furthermore, it is interesting to look at the normalised results per phase, as shown in Figure 3.25. Although the use phase causes the highest impact for both, the difference between the total impact in the use phase and the production phase for VIRM23 is relatively small. This is mostly due to the much higher impact in the production phase, caused by the production of the film, and the lower impact in the use phase because of a lower washing frequency.

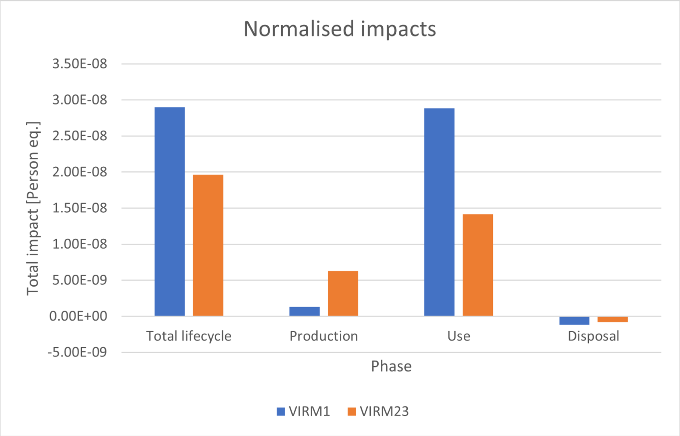


Figure 3.25: Normalised results VIRM1 and VIRM23 compared per life cycle phase

### 3.3.4 Weighting

Weighting can be used to apply value judgement to the results of the LCA. It is a controversial step because the conclusions of the LCA can be influenced by this. So, the weighting factors, or the decision to weight in general, need good substantiation. It is an optional step. It allows you to add the results of different impacts together [52]. Because the ReCiPe authors only created weighting factors for the endpoints and not the midpoints and no substantiated weighting factors are available, the results for this study are not weighted. It will be a little harder to compare, but it will also be the most realistic and transparent.

## 3.4 Evaluation & improvements

In this section, the results of the environmental profile are discussed and evaluated to draw conclusions from that can answer Fleetshield's question. Also, some points of discussion regarding the methodology are brought up to bring nuance to the results.

### 3.4.1 Interpretation of results

In every impact category VIRM23 does better than VIRM1. This is mainly caused by the use phase of VIRM1, which is the largest contributor in every impact category. Zooming in, the ingredients that are most often responsible for this are EDTA, butyldiglycol and ethoxylated alcohols in the cleaning soap used during regular cleaning and the use of ethoxylated alcohols in the graffiti cleaning product. It should be noted that the amounts of these substances used are worst case scenarios. The safety data sheets used as a source for these numbers only specify a range of weight percentages. When checking what the influence is of using the 'best case scenario', the EDTA and butyldiglycol only show small differences in almost every category and a difference of respectively 7% and 9% for freshwater ecotoxicity. The influence of ethoxylated alcohols is larger in three categories: a difference of up to 21% for freshwater ecotoxicity, freshwater consumption and land use.

Nevertheless, a lower cleaning frequency could drastically decrease the impact of VIRM1 in most impact categories. This can be achieved in multiple ways. For example, the design on the train could be altered so that dark colors are used in the places that attract most dirt or NS could decide that the appearance of trains is less important. Then, the main cause of impacts will most likely become the graffiti cleaning, as can be seen in the results of VIRM23. Either using less of this cleaning product or changing the product to a more environmentally friendly alternative will decrease the impact.

When looking at VIRM23, where the frequency of regular cleaning is four times lower, the use phase is not the highest contributor in every impact category. The production of the film causes the production phase to be the highest impact in several categories, most noticeably because of the use of PVC and kraft paper. The reuse or recycling of the kraft paper liners could be a solution to bring these impacts down. Also, non-PVC films are a possible solution for bringing the overall impact down. The effects of these measures are further explored in Chapter 5. Additionally, to also decrease the impact in the use phase, the same measures can be taken as for VIRM1, especially concerning the graffiti cleaning. It is likely that a more environmentally friendly product can be used on VIRM23 because the graffiti does not bite into the film.

Overall, VIRM23 comes out of this analysis as the more environmentally friendly alternative, despite the use of PVC in the film. However, if the cleaning frequency of VIRM1 were to go down as well, this would no longer be the case. As mentioned before, during a lifetime of 18 years, the amount of water and products used for cleaning a train plays a very large role in the environmental impact.

### 3.4.2 Points of discussion

When interpreting the results, some aspects should be taken into consideration. First of all, this LCA is based on a simplified model, made in limited time and, more importantly, with no access to detailed lists of materials. This means it is based on many assumptions. However, a sensitivity analysis has been conducted to justify those assumptions. To do so, the input number of a substance is both multiplied and divided by ten to see if it creates a noticeable difference in results. This is not the case.

Secondly, The current model has a very simplistic end-of-life phase. Very little is known about what happens to the film at that stage. Also, the use phase is very long and a lot could change in the coming years that is not modelled for the current situation. Scenario modelling can be used as a tool to draw relevant conclusions from these life cycle phases while also taking into account the unknowns.

Furthermore, it is important to realise that environmental impact alone should never be the only aspect to base decisions on. Besides differences in environmental impact, there are also other differences between the two conservation systems that could be of influence. Examples are the appearance of the train being better manageable with film than with paint or the fact that paint is a cheaper option than film. Also, film is rarely damaged by graffiti, while paint sometimes needs to be repaired after graffiti removal, causing extra logistical and economical difficulty.

### 3.4.3 Conclusion

To conclude, VIRM23 shows better results over the entire life cycle than VIRM1 with respect to the environmental impact. This is mostly due to the very long use phase during which VIRM1 is washed four times more frequently than VIRM23. However, the use of PVC in the film on VIRM23 causes a large environmental impact, which should not be ignored. Large improvements to the environmental impact of both conservation systems can be made through decreasing the washing frequency and looking into the use of more environmentally friendly cleaning products. In case of VIRM23, it is recommended to keep a close eye on the developments of non-PVC film.

Although all these points of discussion must be taken into account when looking at the exact output numbers, this LCA is a good tool to give a general overview of the impacts, to identify the main contributors and to compare the two conservation systems. The discussion of the results shows that there are numerous causes for uncertainty, but the epistemological uncertainties caused by the long life cycle are the larger ones. In theory, there are endless possibilities for future scenarios, but the discussion also shows that some educated guesses can be made on which are more likely to happen or more interesting than others to further investigate. Therefore, a logical next step would be to further explore the opportunities scenario modelling could offer for a system with a long life cycle such as the film.

# Chapter 4

# New approach for scenario generation

The previous chapter has made clear that there is a need for modelling the future, even though limited information about this is known. Scenario modelling is a good tool be used to do so, as described in Section 2.3 and suggested in Section 3.4. Therefore, the logical next step in this research is to generate scenarios. However, there is no widely accepted approach yet when it comes to scenario generation for LCA. That is why a new approach, based on existing theory, will be developed in this chapter to later be applied to the case study.

This chapter zooms out from the case study, to find a general approach towards generating scenarios to help deal with the epistemological uncertainties. First, the requirements for such an approach are determined, based on the theory in Chapter 2 and the findings during the executed LCA in the previous chapter. Next, the approach is drafted inspired by multiple existing studies and, finally, a four-step method is developed. This final approach will be applied to the case study in Chapter 5.

## 4.1 Requirements

One cannot expect a model of the future based on limited historical data to be very reliable. When looking at Fleetshield's questions, they want to know if the direction they are heading is the right one and which alternatives are interesting to explore. So, if the goal is to determine the interesting directions, very reliable results are not necessary. Most important is that the results can be easily interpreted and a broad conclusion can be drawn from it so it can substantiate discussions on the subject and provide insight in the topic, also for people who are no LCA expert.

Based on the literature and the experience gained in conducting the conventional LCA, all requirements for the approach to be developed are determined. First of all, the conventional LCA executed in Chapter 3 has shown that lack of information in one life cycle phase can influence the reliability of the entire LCA. Future changes in every phase are to be taken into account when looking at a product with a long life cycle because even phases that have already been lived through might need to be revisited again in the future. For example in the case of the train films, the exact technical life is not known. In case the technical life of the film is shorter than that of the rest of the conservation system, refurbishment might be required after several years. By the time this happens, it is likely some changes have occurred to the production processes, which will cause changes in impact on the complete life cycle. Therefore, it is important that all phases of the life cycle of the physical product are considered: production, use and disposal.

Also, to reduce unknown-unknowns, the scenario generation should start with a wide view of the entire life cycle. Since unknown-unknowns are a large part of uncertainty within prospective LCA, as explained in Section 2.3, the aim is to decrease this number of unknowns. Although it is never possible to catch all unknown-unknowns, some are more likely to be identified by considering the product and the context it is used in as a whole and looking from different perspectives [11].

Therefore, all relevant scenarios should be considered from an overarching point of view. Relevant being everything related to the product and the context it is used in.

By searching for a comprehensive set of possible scenarios, it is likely the scenario generation results in too many scenarios to work with. The theory in Section 2.3 suggests that the number of scenarios should be limited to keep the calculations and the decision-making manageable. Therefore, a selection must be made. This should happen consistently, so that the process remains transparent, as lack of transparency is a known challenge in LCA, as described in Section 2.1.

Finally, the approach is developed partly based on experiences with an LCA on train films. This experience has shown that there is a need for such an approach, which is not limited to the field of train films, or transportation. Therefore, the approach should be applicable more widely than just in this niche.

To summarize, the following requirements should be met when developing an approach for generating future scenarios for prospective LCA:

1. All life cycle phases of the physical product should be considered,
2. The scenario generation should start with a view as broad as possible, which includes scenarios regarding the development of the product itself, as well as external changes affecting the product.
3. The selection of scenarios to be modelled should be repeatable,
4. The approach should be generally applicable to systems with a long life cycle, meaning a life cycle that has never been finished yet.

## 4.2 Inspiration

The proposed method for scenario generation is based on two studies in the field of forward-looking LCA as earlier described in Chapter 2.3. The two studies give slightly different perspectives on which time-dependent parameters should be identified. The first is research done by Van der Hulst et al. about using prospective LCA for emerging technologies and the second is a study by Negishi et al. looking at the use of dynamic LCA for buildings, which are systems with long life cycles. Both approaches are made with different purposes and with goals slightly different to this study. However, their perspectives and the overlap between those perspectives are a good starting point for the scenario generation approach.

### 4.2.1 Prospective LCA for emerging technologies

As mentioned in Chapter 2.3, the systematic approach of Van der Hulst et al. consists of three steps and focuses on emerging technologies. These are used to identify technological developments and determine the modelling method. The first step is to define the current level of development. The second is to determine development levels of the technology and manufacturing readiness, which is subdivided into three mechanisms: process changes (changes to the processing methods), size scaling (changes to the physical dimensions of the product or equipment) and process synergies (minimization of final waste stream). Van der Hulst et al. limit this second step to the development stages before industrial development. The third and final step is to take into account external developments. According to Van der Hulst et al., this step starts at industrial production. [30]

Although the approach is developed for technologies in early stages of development, the identification of different technological developments can also be applied to film, even though this product has already entered the market and is past early production phases. However, defining the current level of development is keeping the focus purely on the development phase of the product, while the first requirement states that all life cycle phases should be included. Therefore, the first step of Van der Hulst et al. is not used for the design of the new scenario generation approach.

The next steps, on the other hand, are considered a good base for the new approach. The second and third steps are interpreted as internal and external developments, respectively. Internal developments are defined as being factors that can be influenced by the LCA client, such as maintenance. External developments are outside the reach of this client, for example regulatory changes.

### 4.2.2 Dynamic LCA for buildings

Negishi et al. describe a step-by-step approach to develop dynamic LCA for buildings. Within this approach, they distinguish three different points of view when it comes to the time dimension of buildings; the level of the building, the level of the end-user and the background system.[45]

Although buildings are not the subject of this research, nor is dynamic LCA, the points can be translated to a broader view and be applied to any product or system with a long life cycle. The product level would include construction, maintenance, replacement and refurbishment for example. For the end-user level one could look at change in function or requirements. The background includes changes in regulation or changes in the energy mix.

## 4.3 Approach

The two studies described above both look at a similar problem from a different point of view. Van der Hulst et al. divides the problem according to different stages of development. This can be translated into changes that can be influenced by the client, internal developments, and changes that cannot be influenced by the client, now called external developments. Negishi et al. focus on the different aspects of a system in which change can occur: the product, the end-user and the background. The two approaches show much overlap, but both also bring in new aspects. Individually, the approaches would not meet the first two requirements. The approach by Van der Hulst et al. only includes one life cycle phase and with Negishi et al.'s approach the lack of distinction between internal and external developments might cause some aspects to be overlooked. However, they complement each other well.

Using a combination of both approaches for the identification of possible scenarios would mean requirement 1 and 2 are met. An overview of how the two can relate to each other is shown in Figure 4.1 in which the boxes show different areas of possible change. This overview can be used as a basis for scenario generation from a view as complete as possible, taking into account the entire life cycle. This configuration is made with the Fleetshield case study in mind. Depending on the client, the boxes might be moved around between internal and external developments. Note that the boxes are just guidelines and there might be more or other boxes applicable to different systems.

To determine which boxes should fill the overview for a specific case, the goal for that case should be specified before the actual scenarios are generated. This goal definition should include criteria so it can also be used to base the selection of final scenarios on, and it should determine when enough scenarios have been selected. Considering all this, the proposed approach for generating scenarios for LCA modelling of the future is the following:

1. Define the goal and criteria to be met by the scenario generation,
2. Determine which areas of possible change are applicable to the case by filling out the overview,
3. Use the overview to generate scenarios,
4. Select the final scenarios to be modelled using the criteria from the goal definition in step 1.

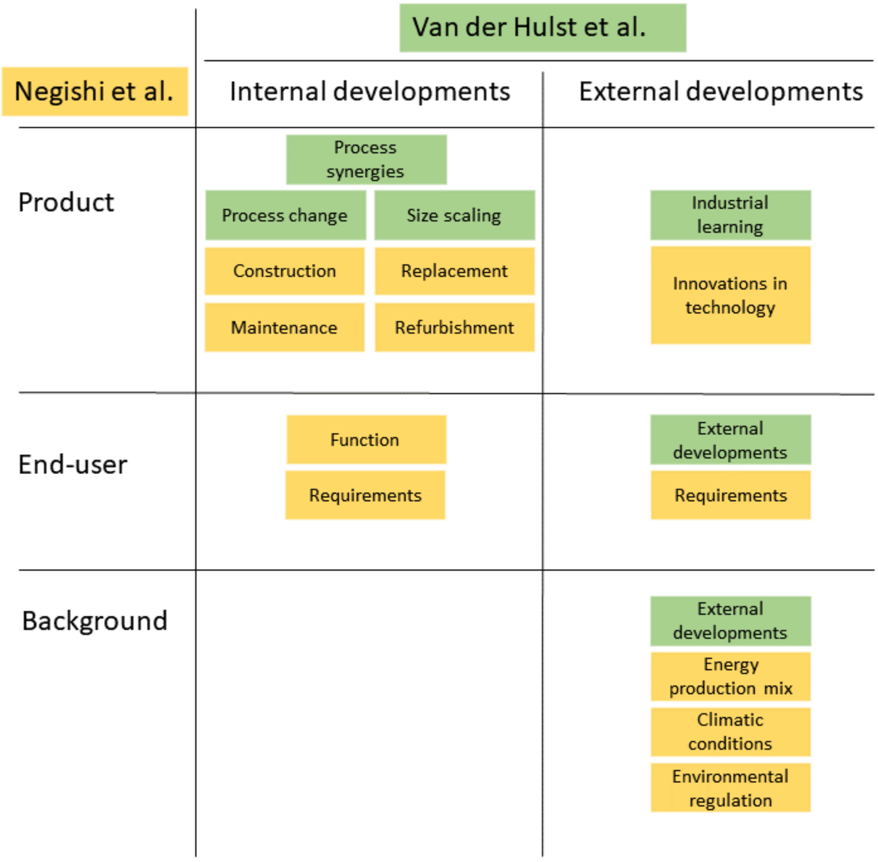


Figure 4.1: Overview of combined perspectives on temporal parameters

# Chapter 5

# Scenario modelling

The newly developed approach for scenario generation described in the previous chapter will be applied to the case study in this chapter, investigating the possible future directions of VIRM23. The case study serves as an example to demonstrate the application of the approach by aiming to answer the second question submitted by Fleetshield regarding the possible directions for the future of their product. Also, the application in a real-world situation can teach valuable lessons about the effectiveness of the approach and the possible improvements to be made. It can be used to base recommendations for future implementation on.

In this chapter, first the scenarios will be generated and selected. Subsequently, the the environmental impact results of different scenarios will be presented, as well as those of combinations of different scenarios. Furthermore, the results of those scenarios are interpreted, conclusions are drawn and recommendations for Fleetshield are based on it. The effectiveness of the new approach itself will be discussed in Chapter 6.

## 5.1 Scenario generation

The scenarios are generated according to the approach proposed in Chapter 4. This means the goal is defined first, including the criteria to be met. The areas of possible change are the ones shown in Figure 4.1 in the previous chapter. Scenarios are generated based on this overview and a final selection is made with the goal definition in mind.

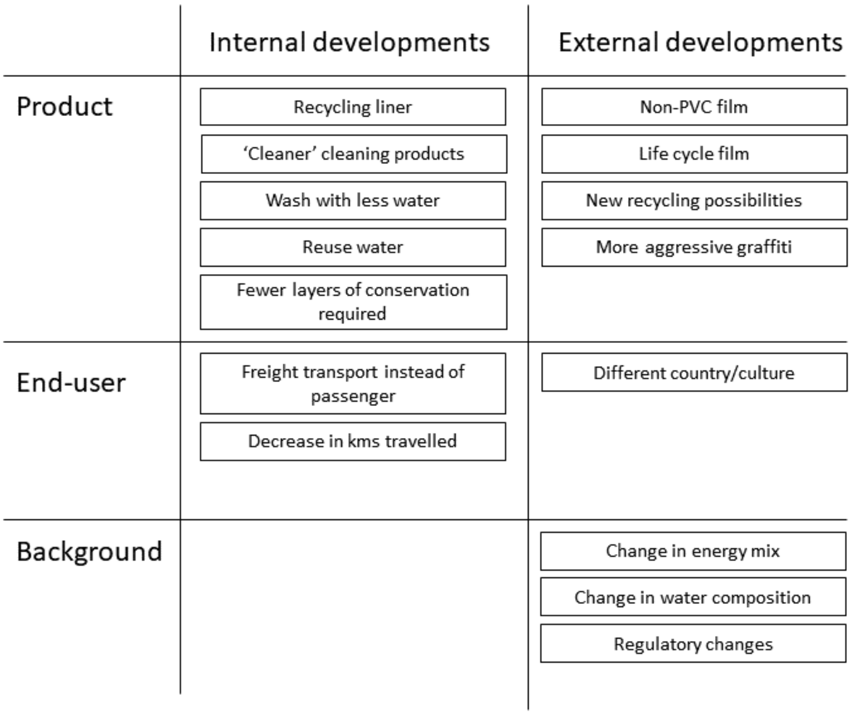
### 5.1.1 Goal definition

The goal of the scenario modelling is to get insight into possible ways forward for Fleetshield and their product regarding its environmental impact. Also, NS wants to limit their environmental footprint and is seeking ways to do so. Therefore, the clients in this case are Fleetshield and NS. From their perspectives, the areas of possible change are filled in. Furthermore, their input is important for the final selection of the scenarios. Another criterion is that enough data should be available to create a realistic model. Some possible scenarios will have a better basis for modelling than others, for example, because there are comparable processes currently used. Other scenarios will have no way of saying what it will look like, which makes it very complex to create a model at this time. So, the criteria to judge the generated scenarios on are the following:

1. Fleetshield and NS should be consulted about the possible scenarios and their preference should be weighed in for the final choice of scenarios,
2. It should be possible to create a model based on data of similar processes that currently exist.

### 5.1.2 Scenario generation

Based on the overview with areas of possible changes in Figure 4.1, the scenarios are generated. All boxes are used as starting points for drafting different options. The drafted options are based



| | Internal developments | External developments |
|---|---|---|
| Product | Recycling liner<br>'Cleaner' cleaning products<br>Wash with less water<br>Reuse water<br>Fewer layers of conservation required | Non-PVC film<br>Life cycle film<br>New recycling possibilities<br>More aggressive graffiti |
| End-user | Freight transport instead of passenger<br>Decrease in kms travelled | Different country/culture |
| Background | | Change in energy mix<br>Change in water composition<br>Regulatory changes |

Figure 5.1: Creation of scenarios

on findings described in Chapter 3 and conversations with experts. The result can be found in Figure 5.1 and descriptions of every scenario shown in there are listed below.

- **Recycling liner** Not all liner currently used can be recycled, even though it is all disposed of after a relatively short time. The film has a liner that is polyethylene (PE) based and cannot be recycled. For the laminate a kraft paper liner is currently used, which is recyclable, however it is not actually being recycled yet. In theory, the kraft paper liner can also be used for the film and all can be recycled.

- **'Cleaner' cleaning products** New cleaning products might come to market that have less of an environmental impact. Alternatively, a decision could be made to use less cleaning product.

- **Wash with less water** There could be multiple reasons for deciding to wash with less water. For example, other cleaning products might require less or the standard of appearance is altered.

- **Reuse water** A lot of water is used in the entire life cycle. Part of it can possibly be reused.

- **Fewer layers of conservation required** VIRM23 still includes most of the layers of the traditional conservation. Innovation might give film the opportunity to take over the function of (part of those) layers in the future.

- **Freight transport instead of passenger** A change of function for the train is not the most likely scenario, but not impossible. If NS decides to use the train for freight instead of passengers in the future, this might have consequences for the environmental impact. For instance, freight might require fewer cleanings because appearance is less important.
- **Decrease in kms travelled** More dirt collects on the train as it travels more. If the number of kilometers traveled per year decreases significantly, less cleaning might be required.
- **Non-PVC film** The PVC film showed high impacts. There are developments in this field and it is likely that non-PVC films will enter the market in the coming years.
- **Life cycle film** It has not been proven yet that the film used on VIRM23 will reach a life cycle of 18 years. It could be possible that it needs replacement before that.
- **New recycling possibilities** At the moment, there is no way of recycling the PVC film. New techniques could be developed, making this possible in the future.
- **More aggressive graffiti** Most graffiti currently used does not cause permanent damage to the film. Possibly, a more aggressive variant becomes available, complicating the graffiti cleaning.
- **Different country/culture** Cultural changes could occur in the context in which the trains are used. For example, if they are sold for use in another country. This can result in changes for both the use and the disposal phase.
- **Change in energy mix** It is likely that changes to the energy production mix will occur. This will influence every phase of the life cycle, but the use phase in a more continuous manner.
- **Change in water composition** A change in water composition would influence the impact on the environment because of the large amounts of water used throughout the systems life cycle.
- **Regulatory changes** Change in regulations could enforce changes in every life cycle phase, directly or indirectly. For example, environmental laws could change the washing procedures but could potentially also force technical innovation to speed up.

### 5.1.3 Scenario selection

In the final step of the approach, the scenarios to be modelled are selected based on the criteria in the goal definition. A first selection of scenarios is made based on the second criterion: availability of data for similar, already existing processes. The scenarios that pass this first bar are presented to the clients for a final selection. To better specify what these scenarios entail, they are brought down to parameters with different options for values. This means, the modelling will happen using 'what-if' scenarios.

The selected parameters, including the values that will be used for each, can be found in Table 5.1. Each individual option per parameter can make up a single scenario. However, different parameters can be merged into one scenario as well for more detailed analysis. The new scenarios will be used in the following chapter to compare possible future impacts.

Table 5.1: Overview of the different scenarios to be modelled

| **Parameter** | **Option 1** | **Option 2** | **Option 3** |
|---|---|---|---|
| Type of film | PVC | Non-PVC (polyurethane) | |
| Type of film liner | Polyethylene | Kraftpaper | |
| Kraftpaper disposal* | Incineration | Recycling | |
| Washing frequency | 1x/month | 1x/2 months | |
| Liters of water per regular cleaning | 0L | 300L | 600L |
| Technical life of film | 9 years (2x) | 18 years | |

*The laminate liner is always kraft paper

## 5.2 Scenario results

Looking at all scenarios individually, some educated guesses regarding the outcome can be made with the results from the first LCA in mind. However, the scenarios can also be very interesting when looking at the effects of combining multiple. This raises the following list of questions to be answered in this section:

1. What is the difference in impact per individual changing parameter as compared to the current situation of VIRM23?
2. What results in the lowest impact: a lower washing frequency or washing with less water?
3. What results in the lowest impact: 18 years of PVC or twice 9 years of non-PVC?
4. What results in the lowest impact: using a kraft paper film liner while incinerating all kraft paper or using a PE film liner while recycling the kraft paper liner of the laminate?
5. Which combination of parameters gives the lowest impact and what is the difference between this and the current VIRM23 situation?
6. What is the difference in impact between VIRM1 and the 'most advantageous' parameter combination?

To keep a clear overview of the consequences of the changing parameters in the different scenarios, not all 18 ReCiPe midpoints are discussed in this chapter. Only the midpoints that have shown the highest impact in Section 3.3.3 are presented. Those are human toxicity (HT), freshwater ecotoxicity (FEc), marine ecotoxicity (MEc), fossil depletion (FD), freshwater eutrophication (FEu) and climate change (CC). Other impact categories have been briefly evaluated to make sure no important points are overlooked, but no relevant information was found. Therefore, to make the interpretation comprehensible, only the six categories are discussed.

### 5.2.1 Individual parameter changes

The influence of changing a single parameter is shown in Table 5.2 by impact reduction in percentages. First of all, what stands out is that using polyurethane film instead of PVC film causes a large decrease in impact for human toxicity. Since this is by far the most prevalent impact category, it also creates a high reduction in the total impact of the system, even though the impact in other categories remains relatively unchanged.

Secondly, lowering the washing frequency causes a large decrease in impact in every category and can be considered an important parameter. Also the reduction of water used per cleaning causes some changes, mostly for freshwater eutrophication.

Third, the influence of changing the technical life is close to 0%. Even though the modelling of the 9 year technical life includes adding an extra production and disposal phase, the small difference in impact that is created by this is nullified by the large impact of the use phase.

Lastly, it is important to note that changes in impact below 5% are too small to draw conclusion from. The likeliness of this being caused by inaccuracies, in for example assumptions, is too high.

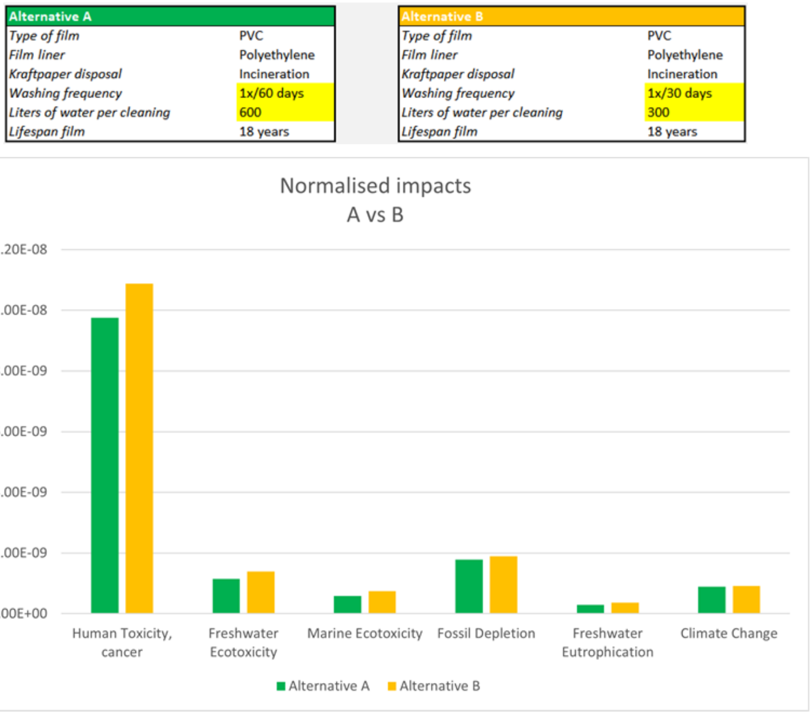
Table 5.2: Impact reduction per category for individual parameter changes

| | Impact reduction | | | | | |
|---|---|---|---|---|---|---|
| **Changing parameter** | **HT** | **FEc** | **MEc** | **FD** | **FEu** | **CC** |
| Non-PVC instead of PVC | 50% | 0% | 0% | -1% | 2% | 0% |
| Kraftpaper instead of PE | 1% | 1% | 1% | 0% | 1% | 1% |
| Kraftpaper recycling instead of incineration* | 1% | 2% | 2% | 0% | 2% | 0% |
| Washing 1x/2 months instead of 1x/month | 12% | 18% | 22% | 6% | 31% | 4% |
| Using 300L instead of 600L | 2% | 2% | 2% | 0% | 13% | 0% |
| Using 0L instead of 600L | 5% | 3% | 5% | 1% | 25% | 1% |
| Technical life of 9 years instead of 18 years | 0% | 0% | 0% | 0% | 0% | 0% |

*Laminate liner only

### 5.2.2 Washing

Comparing the impact of washing less frequently with the impact of washing with less water gives the results shown in Figure 5.2. Washing once every 60 days with 600L of water is compared to washing once every 30 days using 300L of water. It confirms the results in Table 5.2, that the impact is reduced more when washing less frequently than washing with less water. This can be explained by the fact that the cleaning products are a large cause of impact and the use of those is not reduced by washing with less water, but is reduced by washing less frequently.



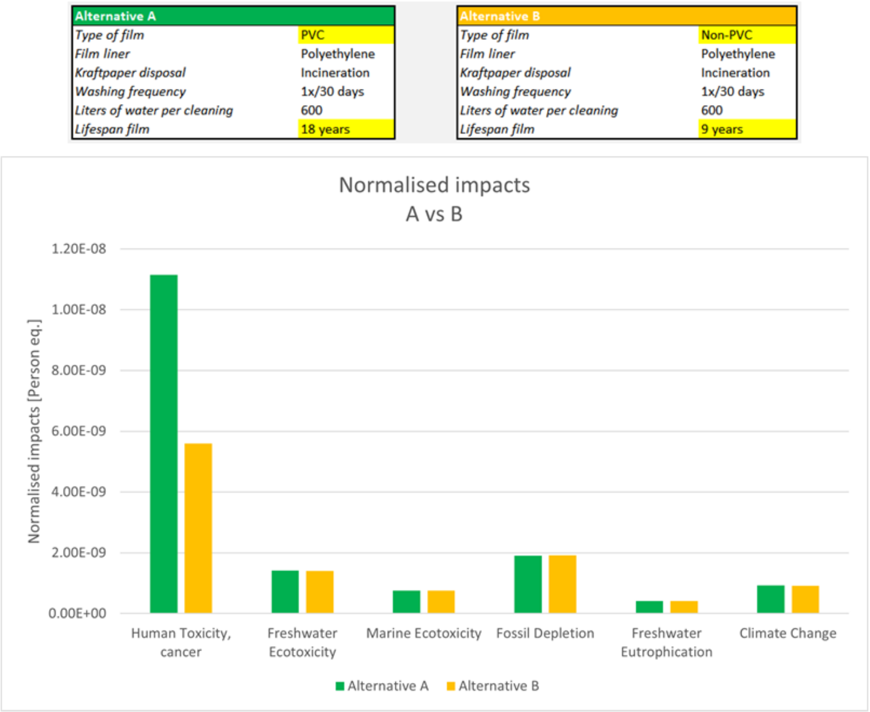
| Alternative A | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/60 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

| Alternative B | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 300 |
| *Lifespan film* | 18 years |

Figure 5.2: Normalised results for washing scenario

### 5.2.3 Technical life and type of film

Table 5.2 has shown that changing the technical life while not changing anything else does not cause a noticable change in impact. However, Figure 5.3 shows that the type of film used does cause a difference, mostly for the human toxicity. This can be explained by the fact that the impact from PVC production in this category is very high and replacing the PVC by polyurethane reduces the impact in the production phase so much that adding an extra production phase to the equation of alternative B still makes it the better alternative.



| Alternative A | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

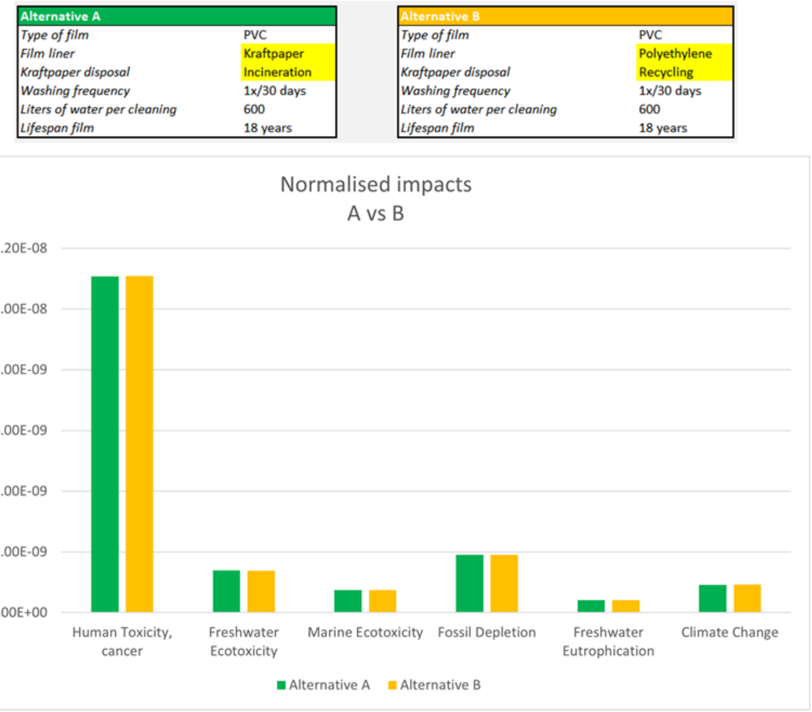
| Alternative B | |
|---|---|
| *Type of film* | Non-PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 9 years |

Figure 5.3: Normalised results for technical life scenario

### 5.2.4 Type of film liner and kraftpaper disposal

Changing the film liner from polyethylene to kraft paper while still incinerating all kraft paper does not have a much different impact from still using PE as film liner while recycling the kraft paper liner of the laminate (disposal scenario 1). This can be seen in Figure 5.4. Comparing the 'worst case scenario' to the 'best case scenario' regarding the liners, Figure 5.5 shows that using kraft paper for all liner and recycling it (disposal scenario 2) is just slightly better than disposal scenario 1. However, this difference is too small to draw definite conclusions from.

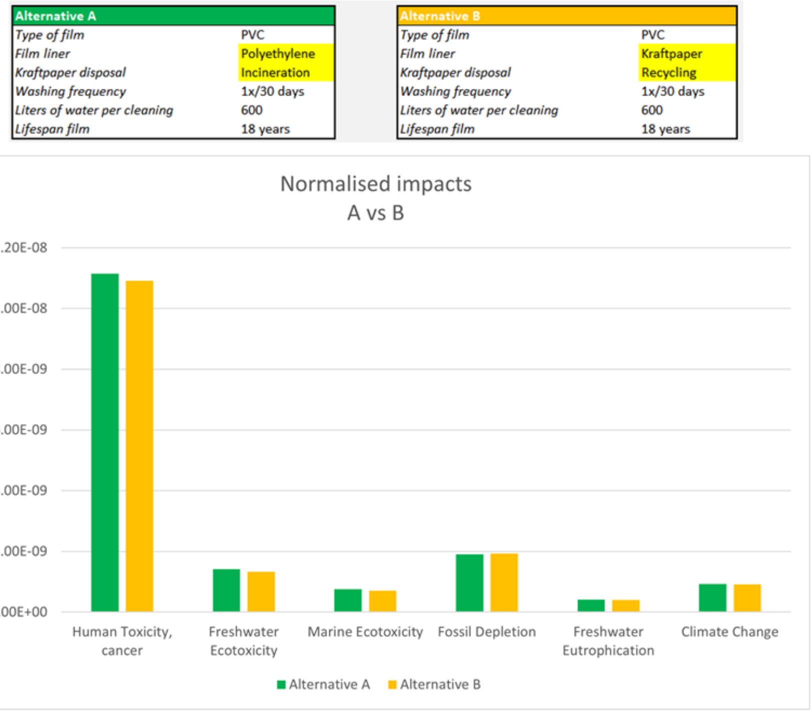
At first glance this conclusion is surprising because recycling is widely known as an environmentally friendly option. However, recycling also includes transportation to the recycling facility, processing to reusable material and production of new product. Taking all this into account, recycling is not always the best solution when looking at bringing down the environmental impact.



| Alternative A | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Kraftpaper |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

| Alternative B | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Recycling |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

Figure 5.4: Normalised results for liner disposal scenario 1



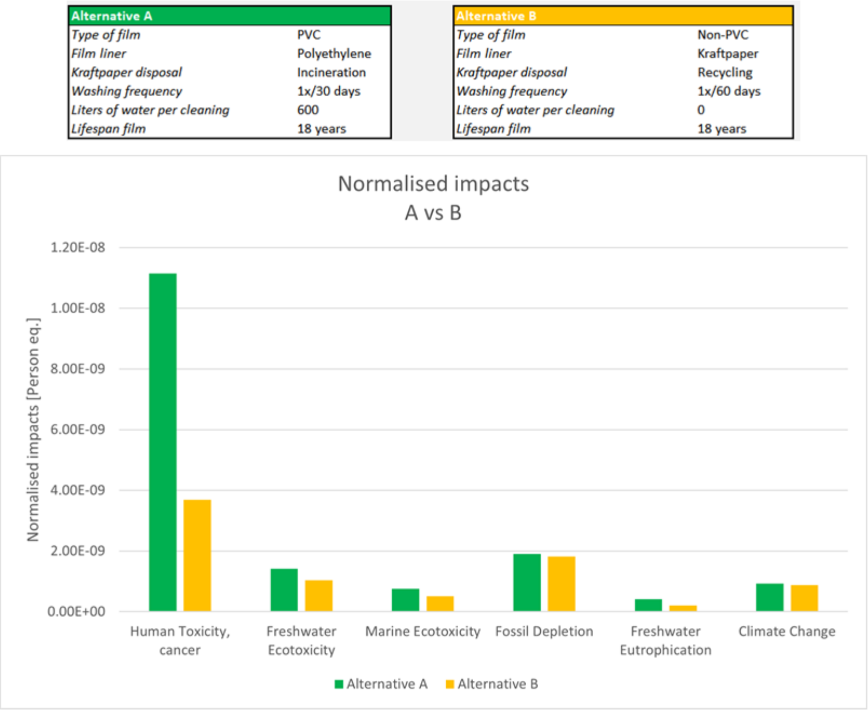
| Alternative A | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

| Alternative B | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Kraftpaper |
| *Kraftpaper disposal* | Recycling |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

Figure 5.5: Normalised results for liner disposal scenario 2

### 5.2.5 Best case scenario

Table 5.2 has shown that the best case scenario would be to use a non-PVC film, a kraftpaper liner which is recycled and washing once every 60 days with no water. The technical life of the film is of no relevant influence. Figure 5.6 shows the difference per impact category between this best case scenario and the current situation of VIRM23. The total reduction in impact of all six shown impact categories combined is 51%. When comparing the best case scenario to the conservation system of VIRM1, as shown in Figure 5.7, the reduction in impact of the six categories combined is 67%.



| **Alternative A** | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

| **Alternative B** | |
|---|---|
| *Type of film* | Non-PVC |
| *Film liner* | Kraftpaper |
| *Kraftpaper disposal* | Recycling |
| *Washing frequency* | 1x/60 days |
| *Liters of water per cleaning* | 0 |
| *Lifespan film* | 18 years |

Figure 5.6: Normalised results for best case scenario vs. current situation

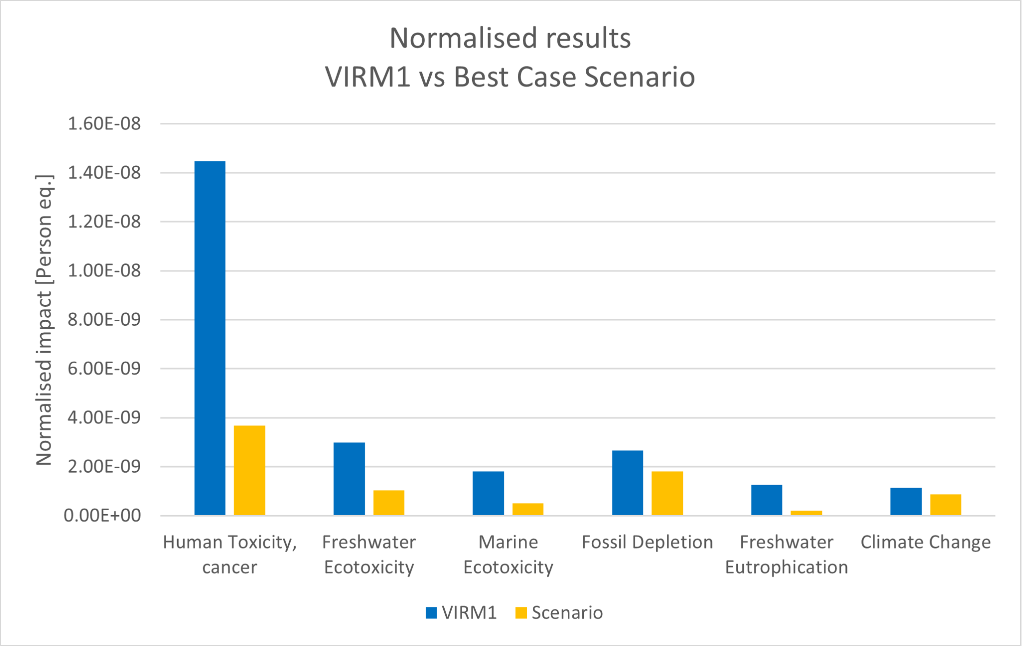


Figure 5.7: Normalised results for best case scenario vs. VIRM1

### 5.2.6 Interactive tool

Interpretation of results has been mentioned as one of the main challenges of this study in the problem statement in Section 1.2. During scenario modelling it presents itself as an obstacle once again. The scenarios provide a large amount of information but this is not easily manageable by Fleetshield since they have no expertise on the subject of LCA. This makes proper implementation of the results difficult, even more so because the uncertainties are not effectively managed. Therefore, the three steps proposed by Rosenbaum et al. for a solid communication strategy, as described in Section 2.2, are applied to the scenario results: after determining Fleetshield's familiarity with LCA and the relevant output data of the scenario modelling, an interactive tool is created to present the results.

Using this tool, Fleetshield can get a better understanding of the impact of future changes. A structured interface makes it possible to evaluate the environmental impact of all different combinations of the future scenarios. The tool is created in Microsoft Excel, which is much more accessible than GaBi, so different scenarios can be explored without requiring knowledge of GaBi or access to the software itself. A more detailed description of the interactive tool and how it works can be found in Appendix C.

## 5.3 Evaluation & improvements

Results from the previous section are evaluated and the most important points of discussion and recommendations are elaborated on in this section. These regard the model itself, the role of Fleetshield and the interactive tool.

### 5.3.1 Interpretation of results

To explore possible future prospects and their impact on the environment, multiple scenarios are created using the new approach designed in Chapter 4. Only foreground scenarios are used. Background scenarios are not taken into account. Because of this and the fact that only historical data is used, the details of the results include a fair amount of inaccuracy. However, a broader interpretation of the results can be used as a basis for discussion and to indicate the importance of certain decisions. For example, the results show that replacing the PE film liner with a kraftpaper liner does not create a large difference in impact for each of the six impact categories. The same goes for changing the disposal process of kraftpaper from incineration to recycling. On the other hand, when replacing the PVC film by a polyurethane film (non-PVC), the difference in impact is large, especially for human toxicity. Therefore, the development of non-PVC films is worth following closely. Additionally, lowering the washing frequency results in an improvement in every impact category.

Looking at different scenarios becomes even more interesting when combining the results and changing multiple parameters at the same time. This gives results that are harder to predict and it is likely that more than one thing will change in the future. It shows, for example, that it is more efficient to look at reduction of the washing frequency instead of looking at a decrease in water used per cleaning. Also, it is possible that a non-PVC film based on polyurethane will become available with a much lower expected technical life than the PVC film. When looking at the environmental impact of using this film for only 9 years and then replacing it by the same again, it is still an option worth exploring, even though the production and the disposal phase are taken into account twice. Furthermore, the impact of the best case scenario is computed. Suppose the 'best' option is available for every parameter, this would result in a 51% lower total impact than the current situation. The difference with the current situation of VIRM1 is even higher, namely 67% for six impact categories combined.

### 5.3.2 Points of discussion

The interpretation of the results above should happen with some points of discussion in mind. First of all, even though the approach for scenario generation aims to decrease the number of unknown-unknowns, it is impossible to eliminate all of them. There will always remain scenarios that are unimaginable at this time and it is possible those will be of larger influence on the environmental impact than the ones modelled now. The scenarios that are modelled are the ones that had enough data available to create a realistic model and stood out most to the clients. One example of a scenario not explored now, that potentially could be responsible for a large change in impact is the cleaning product used. It is likely that different cleaning products become available for the regular cleaning that can be used with less water and the option to use less water becomes more interesting. But because no data about these cleaning products is available for this research, the choice has been made to not integrate that into the scenarios. Another scenario not used here because of lack of data is the end-of-life scenario. Nevertheless, it is highly recommended to look into the options for this stage sooner rather than later.

Secondly, only six of the 18 impact categories are evaluated here. Although the impact in other categories is similar or lower than in these, just those six categories do not paint the complete picture. Most notably, the percentage of total impact reduction could be different when looking at all 18 ReCiPe impacts together. However, to make the interpretation comprehensible only six are taken into account.

Third, this model only shows the environmental impact. There are more factors to be taken into account in decision making. For example, the choice to use non-PVC film with a technical life of 9 years might be the environmentally preferable option, economically and logistically it is a lot less interesting. This should be kept in mind when basing decisions on these results.

Additionally, the software model created to generate the results is not available to Fleetshield and NS for changes in the future. However, it is interesting to keep track of future changes. Not only to keep the tool up to date and relevant, but also to find out how reliable the results remain over the next 18 years. Also, the results would be even more valuable when a comparison can be made with other, similar research in this sector. Creating an ecolabel to allow for standardised presentation of results could be a solution here. Now, all results are presented differently. An ecolabel could make comparison accessible and further aid the discussion around environmental impact within the sector.

Furthermore, these results have most value when used over the entire life cycle. Only applying changes at this moment will not make a large difference for the environment. One should make sure the right methods will continue to be used in the future and it is important to monitor whether the predictions made in this model remain accurate and relevant. With the long life span and the large size of the organisations by which the product is used, it is a risk that the findings are applied now but forgotten over time. This would be a shame, especially considering the large impact during the use phase. This does offer interesting opportunities for Fleetshield to do more than supplying the film. They could offer advice on maintenance and cleaning and end-of-life management, adding value to the product. Also, Fleetshield could play a larger role in monitoring the cleaning process and disposal to make sure full benefit is taken from the possibilities the use of film offers. This way, they can unburden their clients over a long period of time.

### 5.3.3 Conclusion

To conclude, the scenario analysis shows that the parameters for which most improvement can be gained with respect to the environmental impact are the base material of the film and the washing frequency. Therefore, it is recommended to keep an eye on the development of alternatives for PVC film and to look into opportunities to bring down the washing frequency. Also, the results show room for Fleetshield to play a larger role in other phases of the film's life cycle.

The results are calculated with the knowledge available now. This level of knowledge will continuously change as time progresses. Therefore, it is highly recommended to reevaluate the results regularly, at least yearly. This includes reevaluating the selection of scenarios to work out. In case of the film, one of the most important scenarios to model in the near future is the end-of-life.

To visualize the impact of different decisions in the different impact categories, an interactive tool is created. Using this, different alternatives can be compared in a quick and easy manner and no in-depth knowledge of LCA software is required. Despite the uncertainties in the data, it offers a good tool for reference and to substantiate arguments in discussions.

# Chapter 6

# Discussion

This research is carried out to find out how the environmental impact of products with a long life cycle can be assessed. The focus is on the role of LCA in this process, taking into account the large uncertainty implicated by a long life cycle. Six questions are used to support this research, those are as follows:

1. What methods are currently used for life cycle modelling of future situations?
2. What is the state of art of prospective LCA?
3. How are uncertainties taken into account in LCA?
4. What requirements should be met when assessing the environmental impact of systems with a long life cycle?
5. How can the environmental impact of technologies with a long life cycle be assessed?
6. How effective is this approach when applied to a case study on Fleetshield's film?
7. What are recommendations for implementation of the proposed approach?

The questions are answered by studying literature and executing a case study for Fleetshield and one of their clients, NS. The environmental impact of Fleedshield's train film, used for the conservation of the train's exterior, is assessed and compared to the alternative product, which is paint.

In this chapter the results of this research are discussed. This does not include the results found within the case study, as those are already discussed in Section 3.4 and 5.3. The chapter starts with a discussion of the existing methods for applying LCA to products with a long life cycle, answering the first three research questions. Then, the creation of the new method for scenario generation is discussed, which includes the requirements it should meet, answering research question 4 and 5. To answer the final two questions, the application of the proposed approach to the case study and its effectiveness is evaluated and finally, recommendations for implementation are made.

## 6.1 LCA for systems with a long life cycle

A literature study reveals there are numerous ways to classify uncertainties. The classification adopted in this research is the three-type classification of parameter uncertainty, methodological uncertainty and epistemological uncertainty. For systems with a long life cycle, such as the conservation systems on trains, the epistemological uncertainty is much higher than for systems with a shorter life cycle. Executing a conventional LCA for the case study confirms that this type of uncertainty causes one of the largest obstacles in LCA for products with a long life cycle.

The case study also brings forward obstacles such as tedious data collection or an overall lack of reliable data, as well as time constraints. The latter asks for simplification of the LCA process, so a balance should be found between the level of detail and the resources put into finding these details. Furthermore, the influence of the practitioner is also ever-present and causing uncertainty in the results. These are all known challenges in LCA and are also represented in various literary sources, as described in Section 2.2. In addition to the 'general' uncertainties as mentioned above, increased epistemological uncertainty creates an even higher overall uncertainty in LCA for long life cycle products.

Uncertainty caused by unpredictability of the future does not only introduce product-related uncertainty in LCA, but also uncertainty about the context the product is used in. The literature study shows this problem is not unknown and scenario modelling is often named as a good tool to deal with epistemological uncertainty. In recent years, different future-oriented variations of conventional LCA have been designed, mostly using scenario modelling. Most applicable to this study are ex-ante and prospective LCA, as discussed in Section 2.3. However, existing literature of those mainly focuses on products in early stages of development, which are not ready to enter the market yet. This is not the case for the object of the case study, which is a product that has been on the market for several years, but has many unknowns about the future because of its long life cycle. Nevertheless, many parts of existing studies are useful to apply to this product too. The one thing missing is a method for generating the rights scenarios to use for a future-oriented LCA.

## 6.2 Design of a new approach for scenario modelling

Executing the conventional LCA not only exposes different obstacles, but also provides insight into what would be necessary to effectively assess the environmental impact of a system with a long life cycle using scenario modelling. Together with the literature study, this experience contributes to a basis for a new approach to generate scenarios. The requirements that result from this include the need for the approach to consider all life cycle phases of the physical product and the scenario generation to start with a view as wide as possible. Also, the scenario selection should be repeatable and the approach should be applicable to all systems with a long life cycle.

Inspired by existing research by Van der Hulst et al.[30] and Negishi et al.[45] a four-step approach is designed. The first step is the problem definition, the second the mapping of all areas of possible change, followed by the generation of the scenarios and, finally, the selection of the scenarios. For the second and third step, an overview can be used as shown in Figure 4.1, categorising the product, end-user and background changes by internal and external developments. The problem definition of the first step is the basis for the scenario selection in the fourth step.

Demonstrating this approach in the context of the case study provided valuable insight in the effectiveness of the approach. Evaluating this gives room for an improved approach and recommendations for implementation. In this section, the approach is evaluated and the recommendations are discussed.

### 6.2.1 Evaluation of the requirements

First of all, the requirements are used to test the validity of the proposed approach. The areas of possible change do not divide the life cycle into different phases. All categories apply to all life cycle phases, so it does provide space to consider all phases of the physical product, as stated by the first requirement. However, it is also dependent on the practitioner. When looking at the scenario generation in general, finding and creating the appropriate scenarios will always be influenced by the person executing this process and their perspectives. The influence of the creator could be minimized by, for example, using responsive evaluation as described in Section 2.3.

Furthermore, categorising the areas of possible change in internal and external developments and product, end-user and background relatedness allow for the practitioner to view the situation from different angles. By not converging to the selection of the scenarios immediately, a broad view for possible scenarios is encouraged. Although this means the second requirement is met, one can never identify all scenarios. It is plausible that in the near future new data is available that introduce a need for new scenarios or some previously generated scenarios become impossible. In several years the generation and selection of scenarios could be entirely different. This does not only apply to the scenarios but also the impact categories. In the future, advances in technology and research might ask for different impact categories that do not exist at this time [2]. Therefore, it is important that the scenario generation and selection is evaluated regularly.

The scenario selection is part of the approach to make scenario modelling manageable and the results comprehensible. Investigating more scenarios takes more time, so a trade-off should be made between effort and quality. The current approach has no limit on the number of selected scenarios. It is interesting to find either a suitable set limit for all products or find a way to determine the best limit for each individual case.

Although this approach is only tested on the case of a very specific product, the generic steps can be applied to other products as well. Only the division of suggested viewpoints as shown in Figure 4.1 might be different. The current overview might lack points relevant to other products. However, the combination of the first two steps of the approach require the practitioner to create their own version of the overview, relevant to their situation. Therefore, the approach is applicable to all systems with a long life cycle. It might even be suitable for other product types as well, such as products with a shorter life cycle but quickly changing socio-technical environment.

### 6.2.2 Evaluation of the outcome

Besides checking if the approach does what it is designed for, the case study also creates an opportunity to identify other points of discussion and possible improvements. Firstly, none of the scenarios selected for the case study are background scenarios, despite the literature emphasizing the importance of those. The selection requirement regarding the availability of data excluded all background scenarios because there is no simple way of collecting and applying this data in an LCA model. In numerous researches, the recommendation is made to look into simple ways to access and implement background data, for example, by integrating it in the LCA software databases [34, 40, 65]. This study confirms that recommendation.

Second, what-if scenarios are used in this case study to make it comprehensible. The dataset in the software, in this case GaBi, is not available to everyone and not available everywhere. Therefore, specific parameter values are selected, for which the impact and the impacts combined with other parameters are calculated. However, it is also an option to use cornerstone scenarios as discussed in Section 2.3. This would probably be a more complex process and require more complex calculations by the software. It could therefore also require more time. Nevertheless, this would provide more comprehensive insight in the possible futures as it enables to find break-even points more easily and work towards an optimum. It would be interesting to test the proposed approach in combination with cornerstone scenarios in a real-world situation as well.

Section 2.1 mentions a communication barrier as a challenge in LCA because it forms an obstacle for implementation of results. This also presents itself a challenge in the case study. A variation to the communication strategy described by Rosenbaum [56] is applied to communicate the results to Fleetshield: by identifying the familiarity with LCA within the company and determining what information is relevant to present, a visualisation of the results is made in an interactive tool. If more combinations of different scenarios are to be created within this tool, it would become more complex because of the large amount of data behind it. Integration in software could provide a solution. Another question in the interpretation and visualisation is which impacts to present. Not every impact category is equally interesting, and presenting all does not make it easier to understand, especially for non-experts. But no two situations are the same, so one impact category might be important in one situation but not at all in the other. Finding a way to provide guidance in the selection of impact categories to present could be a great addition to LCA.

All in all, the proposed approach is a useful way of dealing with epistemological uncertainties as it creates a strong basis for discussion on the topic of environmental impacts and gives useful insight into the possible futures. This is confirmed by the application of the approach on the Fleetshield case study. It provides a strong basis for investigating different directions or a combination of directions, as the scenarios in the case study in Chapter 5 also show. However, there is still room for improvement of the approach. More importantly, the steps that precede and succeed the scenario generation can make the process more robust if executed in the right way. Therefore, the approach does not only require improvement but also expansion.

### 6.2.3 Recommended approach for scenario modelling

Reflecting on the application of the proposed approach on the case study, the recommended way to apply it in the future is visualised in Figure 6.1. The proposed approach is improved and expanded to a method for scenario modelling in LCA, which includes the scenario generation and multiple other steps to make the results more valuable.

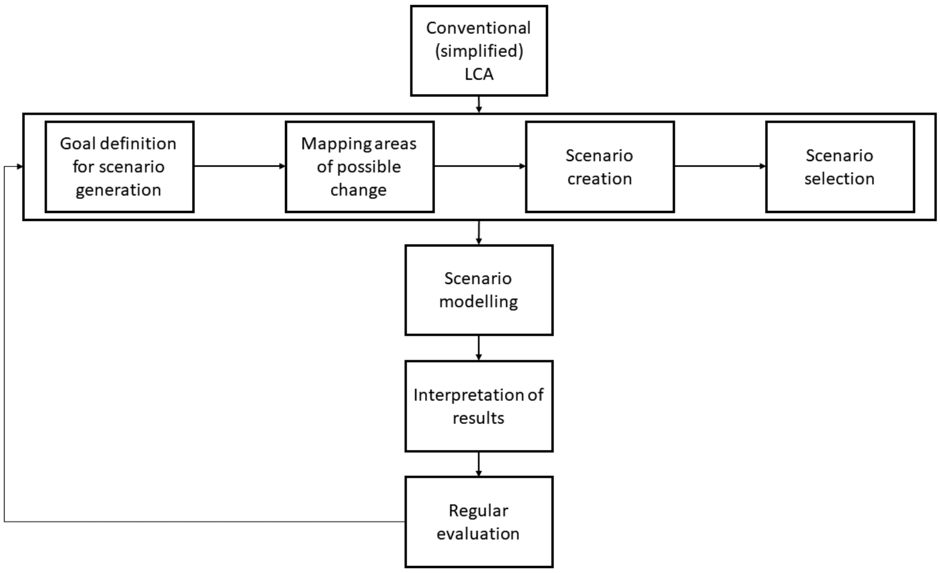


Figure 6.1: Overview of the method for scenario modelling in LCA

First of all, it is recommended to execute a conventional LCA on the product before generating the scenarios to get a good overview of the processes and the context of the product. This will allow for a good basis for the scenario generation. The conventional LCA is also a good basis for further modelling. With limited time, a simplified version of conventional LCA can be used. This will still provide the overview, but costs less time. The level of detail might not be very high, but this is not necessary because the goal is to guide discussion and not to draw hard conclusions from the numbers.

The scenario generation remains the same four-step approach as suggested in Chapter 4. Starting with the goal definition and mapping the areas of possible change for the product to be assessed, the different scenarios can be generated and finally be selected using the requirements set in the goal definition. It is highly recommended to involve different stakeholders in the scenario generation and selection so the influence of the practitioner on the outcome can be minimised.

After the scenario selection, the scenarios can be modelled using dedicated LCA software. Also combinations of different scenarios can be assessed to get a good idea of the influence of multiple changes to the life cycle impact.

As explained above, the interpretation of the results is a very important step, since it also provides a basis for how the results are communicated to different stakeholders. The right communication increases the chance for actual implementation of the results, making the LCA more valuable [26]. Therefore, the results of the scenarios should be presented in a way that is comprehensible and cannot be misinterpreted. The three-step communication strategy by Rosenbaum et al., as described in Section 2.2, can provide a good basis for this.

Finally, as already recommended in the evaluation of the initial approach, the decisions made during this process should be evaluated at least once a year because of the many unknowns that still remain and the changes in unknowns that happen over time. Depending on the speed of technological development of the product and its context this might need to happen more frequently. The influence of changes on the life cycle impact can be especially high for products with a long life cycle. Therefore, it is very important to determine if every decision is still based on valid data at a later point in time. Also, this increases the transparency within the approach, as described in Section 2.4.

# Chapter 7

# Conclusion & recommendations

Because of a shift in the industry in which sustainability plays an increasingly important role, companies are forced to reflect on their own impact on the environment and look for ways to improve. Fleetshield, a company that specializes in train films, wished to know what the current environmental impact of their product is compared to its alternative. Also, they wanted to look ahead and find out how to improve their footprint and which direction offers the best opportunities to do so.

Trying to answer Fleetshield's questions gave rise to a broader academic question that first had to be tackled. This question was related to the increased uncertainty that arises when the environmental impact of systems with a long life cycle is modelled. This became the main research question and is the following: *How can LCA be used to assess the environmental impact of products with a long life cycle?* To answer the question, a literature study was done as well as a case study on Fleetshield's film. The case study was used to find the main obstacles in LCA for long life cycle modelling and to set up requirements for a new approach for scenario generation. This approach was then applied in the context of the case study to demonstrate and test.

The case study was carried out for Fleetshield in collaboration with one of their clients, NS. The application of film as part of the exterior conservation of NS trains was compared to the alternative, an entirely paint-based conservation system. In this final chapter, conclusions will be drawn on the research for both the LCA practitioners perspective and that of Fleetshield and NS. Furthermore, suggestions are made for future research.

## 7.1 Conclusions

By first executing a conventional LCA for the Fleetshield case study, it was found that epistemological uncertainty introduced by the long life cycle of the product is the main obstacle. Only using historical data does not provide for a complete dataset for products that have not lived through their entire life cycle yet. There is a clear need for taking the future into account, because of the uncertainty caused by unpredictability of the future. LCA is a good tool to get insight in the environmental impact of a product and identify the 'weak' points in the system. However, conventional LCA alone is not enough to do so for systems with a long life cycle because of epistemological uncertainty.

The literature study showed prospective LCA to be the most suitable existing type of LCA for the case study. More specifically, the literature study brought scenario modelling, to be applied within prospective LCA, forward as a solution to the problem. However, there was no standardized method for developing scenarios for products with a long life cycle yet. Therefore, a new approach was developed based on literature and the experience gained by executing the conventional LCA. This was designed to fit all types of products with a long life cycle. It was tested on the case study for Fleetshield to give an example of the application, to validate the effectiveness and to find possible improvements for the method.

From the case study, it was learned that scenario modelling in general is a useful tool to find a basis for discussion and find direction for the near future. However, due to the uncertainty remaining high, the exact numbers resulting from the LCA still lack accuracy and no hard conclusions can be draw from them. Nevertheless, for companies like Fleetshield, exact numbers are not the goal of such an LCA, so the tool is still effective in providing insight in the environmental impact of a product. The best use of the results is for stakeholders to learn about the environmental impact and get a feeling of the impact caused by different design choices. It can provide a basis for discussion so decisions are more likely to be taken with the environment in mind. This goal can only be reached if the interpretation is done correctly, meaning the results are accessible and easy to understand even for people with limited LCA knowledge. Within the case study, this was done by creating an interactive tool.

As for the newly designed approach for scenario generation, it was found that useful scenarios were generated and the requirements were met. However, there were several aspects not part of the initial approach for which the significance was only clear after the case study. This mostly regards the steps surrounding the scenario generation, as the value of the scenario generation is increased by applying it in the right context. Especially interpretation of the results showed to be important, as this is of large influence on the goal of creating understanding about environmental impact and involving the results in decision making, as described above. So, after evaluation the approach applied to the case study, an improved version was made, which can be found in Figure 6.1.

For Fleetshield and other stakeholders the results of the conventional LCA and the scenario modelling showed where the opportunities for large improvements lie. The most important ones are the washing frequency, the composition of the cleaning products and the PVC component in the film. Also, the scenario modelling gave insight in possibilities for Fleetshield to extend their involvement with their product beyond the production phase.

This research is valuable because only limited studies on the management of uncertainties in LCA for products with a long life cycle have been done before, even though this type of products has an increased level of uncertainty compared to products with a relatively short life cycle. This helps fill a research gap and at the same time ties into well-known problems with LCA in general: uncertainty and lack of implementation. This study offers a solution in the form of a new approach and immediately implements this in a real-world situation. This not only gives useful feedback for the solution but also provides the stakeholders in the case study with relevant information.

To give a concrete answer to the research question, the research has shown that by implementing scenario modelling in LCA, potential futures can be modeled of a product with a long life cycle. This gives valuable insight in the different possible futures within its life cycle and their environmental impact.

## 7.2 Recommendations

Recommendations regarding the implementation of the results have already been described in Chapter 6. Looking at future research, this study provides a good basis to further explore the use of scenario modelling to manage epistemological uncertainty in LCA.

First of all, the approach is only tested for one specific system with a long life cycle. It is recommended to try it out on more case studies. Also, the method is created for systems with a long life cycle, but it might be useful for other systems that have to deal with high epistemological uncertainty as well. For example, the approach can also be applied to emerging technologies or systems with quickly changing socio-technical environments.

Secondly, it is recommended to look into the possibilities to use cornerstone scenarios within the new approach and in scenario modelling in LCA in general. This will require more complex data collection but could give a more comprehensive view of the environmental impact of a product.

Furthermore, more research is necessary to find a good method for presenting data to non-experts. The implementation of the results will become easier if it can be understood by everyone. A framework to guide a practitioner in how to present data would be very useful. Ideally, this includes guidance in determining what data to present, such as the level of detail or the impact categories to include.

Finally, this research only looks at environmental impact, while decisions are always based on many more aspects. Finding a way to balance the results of an LCA with other important aspects, such as economic affairs, logistics and human rights, could potentially make for a very interesting tool for decision making.

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# Appendix A

# Process trees

This data is confidential

# Appendix B

# Assembly trees

This data is confidential

# Appendix C

# Interactive tool

Figure C.1 shows part of the interactive tool created for Fleetshield. Two alternatives can be compared, for which the parameters can be altered. Also, a comparison can be made with VIRM1, for which the washing parameters can be altered as well. Changing a parameter immediately shows the change in impact through the different graphs. Those graphs include a characterisation graph for each of the six impact categories, normalisation graphs per alternative and normalisation graphs comparing the different impact categories and the different life cycle phases.

For every parameter a drop-down list is used to select the right input. Because all data used to compute the graphs is exported from GaBi and no full databases are available within the Excel document, it is impossible to offer the entire range of options. Therefore, a limited number of options can be chosen, namely the options in Table 5.1. Despite the limited number of options, the dashboard can still give a good overview of the influence of different possible decisions.

| VIRM1 | |
|---|---|
| Washing frequency | 1x/7 days |
| Liters of water per cleaning | 600 |

| Alternative A | |
|---|---|
| *Type of film* | PVC |
| *Film liner* | Polyethylene |
| *Kraftpaper disposal* | Incineration |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 600 |
| *Lifespan film* | 18 years |

| Alternative B | |
|---|---|
| *Type of film* | Non-PVC |
| *Film liner* | Kraftpaper |
| *Kraftpaper disposal* | Recycling |
| *Washing frequency* | 1x/30 days |
| *Liters of water per cleaning* | 300 |
| *Lifespan film* | 18 years |

Figure C.1: Screenshot of the interactive tool