Development Towards Circularity for the Flexible Film Supply Chain in the Netherlands

A Mixed Methods Approach from a Systems Perspective

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Master's Thesis

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Summary

A large part of the Dutch plastic waste is currently incinerated, with a high amount of greenhouse gas emissions as a consequence. If recycling is done efficiently, it could provide environmental benefit over energy recovery through incineration, especially in a low carbon economy where renewable energy generation becomes the new status quo. This study focusses on one of the most used types of plastic for packaging: flexible film. The aim of the research is estimating the degree of circularity in the flexible film supply chain from a systems perspective. Moreover, the focus is on discovering how the current techno-institutional regime involving the flexible film supply chain can be protected from techno-institutional lock-in: a situation where innovation towards a circular supply chain is opposed through reinforcing socio-economic, institutional and technical structures. To explore this, a mixed method approach is applied, covering several qualitative and quantitative research methods. First, the current flexible film supply chain is examined by means of desk research. This analysis indicates that it is economically more advantageous to incinerate than to recycle flexible films under current conditions. A material flow analysis is performed to uncover the current flexible film material flows in the Netherlands. It shows that the ratio between recycled and reapplied flexible film and the amount incinerated is different than expected. A much higher proportion seems to currently be incinerated than suggested by national statistics. Furthermore, the material flow analysis shows that much of the recycled content supply remains unused, as the demand for recycled flexible films is currently higher than demand. The main supply chain actors are interviewed for their perspective on the influential factors for innovation for circularity in the supply chain. The interviews are analysed by means of comparative cognitive mapping. Results showed that the actors perceived high dependency on governmental institutions for accelerating innovation, more so than interdependency within the supply chain. Furthermore, the demand for recycled flexible films seems to be one of the most crucial factors, with recycled flexible film quality as a close second. Aggregated institutional factors appear to have the most influence on the demand for recycled flexible films, compared to socio-economic and technical factors. The construction of the current techno-institutional regime visualizes the crucial role of the institutional system in initiating and accelerating circular innovation through governmental (policy) triggers. Desk research is done to discover trends for and relationships between the relevant factors mentioned by the supply chain actors. Subsequently, the flexible film supply chain and the relevant influential factors are simulated for different scenarios towards 2025 by means of dynamic modelling. The results show that only in the high scenario, demand exceeds supply, resulting in a positive stimulus for achieving more circularity within the supply chain. Moreover, in the high scenario, the reapplied recycled content increases significantly, which shows a positive development on the ratio between incinerated and reapplied recycled content. The same trend is visible in the low scenario, but to a much lower degree. Moreover, only the high scenarios display an eventual decrease in the accumulating stockpile of unused flexible film supply. Based on the results of the different methods, it can be concluded that the current flexible film supply chain shows less circularity than Dutch national reports suggest with their values for recycled content. Nonetheless, some positive trends are visible, that push the supply chain towards circularity. In the short term, institutional factors seem to be most important here, due to their influence on recycled flexible film demand. The government aims to achieve a 30% recycled content, compared to overall annual production, for each type of plastic in 2025. This can only be achieved when the influential factors develop as estimated in the simulated high scenarios, especially in terms of institutional factors. Due to the crucial role of institutional triggers and policy implementation in this context, it is strongly recommended that governmental action is taken for providing a level playing field within the plastic industry. This can, subsequently, break reinforcing technological and socio-economic loops and initiate change within these structures hindering innovation. In this way, the development towards a circular flexible film supply chain can be stimulated and a techno-institutional lock-in is avoided.

Keywords

Circular Supply Chain — Plastic Recycling — Flexible Film Recycling
Techno-Institutional Lock-In — Techno-Institutional Complex — Techno-Institutional System

Preface

Before you lies the master’s thesis 'Development Towards Circularity for the Flexible Film Supply Chain in the Netherlands: A Mixed Methods Approach from a Systems Perspective'. This research was carried out as part of my graduation from Leiden University and Delft University of Technology for the master's degree in Industrial Ecology. The focus of the study is on the flexible film supply chain in the Netherlands and the relevant factors associated with it. The aim is to create circularity within the supply chain in the build-up towards a circular economy in the future. The study was partly carried out as part of an internship at EGEN BV. From timeframe of this research is from January to August 2021.

First of all, I would like to emphasize that this study taught me a lot about doing research, the complexity of a mixed method approach and the importance of interdisciplinarity in phenomena such as the plastic problem and sustainability in general. Sustainability has always been an important part of my day-to-day decision making. During the Industrial Ecology study program, I was able to delve into the field of my ambition and I gained the knowledge and skill to make a real difference towards a sustainable future. With this thesis project I was able to take the first practical steps towards a sustainable contribution to society and nature, besides some other interesting projects that came along during the study program. Not only am I very proud of this achievement, but it also motivates me to continue this path in my personal life and carrier after my graduation. The reason that I was able to make a practical difference with this study is, among other things, because of the network EGEN BV provided, which has enabled me to make connections with important players within the flexible film supply chain. In addition, I will present the results of my study to the supply chain actors, who have shown to be eager to incorporate the findings in their supply chain collaboration. This means that my study, in addition to a contribution to the scientific knowledge gap with regard to this topic, can make an actual contribution in practice.

Many passionate, instructive, but also strenuous days passed during the execution of this research. Completion of the study would not have been possible without the constructive feedback and guidance of my supervisors Aad Correljé and Ester van der Voet, for which I would like to thank them massively. My internship supervisors, Tjerk Wardenaar and Twan van Leeuwen, also played a crucial role during this research process. Not only did they provide me with insights and feedback for my thesis, but they also managed to make the past six months a fun time for me. Especially because of the complex circumstances due to Covid-19, where working from home was rather rule than exception, they made my daily activities a lot more enjoyable, for which I want to express my gratitude. Furthermore, I would like to say many thanks to all the respondents who contributed to this research and who always responded quickly and extensively to my e-mails with additional questions. Moreover, I want to thank the Foundation for Packaging and the Environment (SVM) and Leiden University Fund (LUF), who offered me a grant for the research proposal, which I submitted prior to this study. They not only made this research possible, but also stimulated me to take it to a higher level. I look forward to presenting the results for the delegation of SVM and LUF in the nearby future. Last but not least, I would like to thank my dearest love, Michiel, and my beloved sisters, Esra and Ila, for listening to my very long sermons and enduring my tantrums during the past eight months. It has all contributed to the greater good.

For now, I wish that you, the reader, enjoy reading this report. The study hopefully provides you with insights that you may or may not have been looking for.

Mirra Luijten

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List of Abbreviations

Abbreviation	*Explanation*
CCM	Comparative cognitive mapping
DFR	Design-for-recycling
DKR	Deutsche Kunststoff Recycling
DKR 310	Sorted mono flow of plastic films
DKR 350	Sorted Flow of mixed plastics
EEE	Electrical and Electronic Equipment
HDPE	High-density polyethylene
LCA	Life Cycle Assessment
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
NRK	The Federation of the Dutch Rubber and Plastic Industry
MDPE	Medium-density polyethylene
MFA	Material Flow Analysis
PE	Polyethylene
PCPPW	Post-consumer plastic packaging waste
PCR	Post-consumer recycled
PIR	Post-industrial recycled
PMD	Plastic packaging, metal packaging and drinking cartons
PP	Polypropylene
rLDPE	Recycled low-density polyethylene
rPE (films)	Recycled polyethylene films (including a small content of PP)
SCM	Supply Chain Management
WIP	Waste Incineration Plant

1. Introduction

In the oceans and seas, the amount of plastic waste is increasing (Verrips et al., 2017). The plastics float, sink and eventually break down into small pieces, called microplastics, or even smaller particles, known as nano plastics (Smith, 2018). This phenomenon of floating plastics in the oceans and seas is popularly called the "plastic soup" (Verrips et al, 2017). The amount of plastics entering the Dutch market is increasing every year (Corsten et al., 2010). About 32% of the plastic waste streams comes from packaging (CE Delft, 2019). From 2013 up until 2017, the amount of plastic packaging waste has increased 10%. Of the 512 kilotons of plastic packaging waste in 2017, approximately 243 kilotons were marked recycled (CE Delft, 2019; Achilias et al., 2007).

For dealing with the increasing amount of plastic waste, which is a consequence of increasing plastic production, incineration for energy recovery is often applied (RVO, n.d.). Although it is important to reduce the plastic soup in the oceans, the incineration of plastic waste does not provide the ultimate solution. The Dutch government has ambitions for nature and society to move towards a zero-emission circular economy towards 2050 (Ministerie van Infrastructuur en Waterstaat, 2019). Currently, incineration of waste provides a relatively sustainable source for energy production. Nevertheless, in the development towards a circular economy, energy production from renewable energy sources slowly but surely should become the norm. Furthermore, plastic is made from an exhaustive resource: oil. With these considerations in mind, incineration for energy recovery will no longer be applicable in a future with a Dutch circular economy.

Moreover, CE Delft previously calculated that the climate impact of the incineration of plastic in 2015 in the Netherlands resulted in the emissions of 330 kilotons CO_2-eq (CE Delft, 2019; Achilias et al., 2007). These actions interfere with the targets the Dutch government has set, to reduce greenhouse gas emissions in 2030 by 49 percent, compared to 1990 (PBL, TNO, CBS, & RIVM, 2020). In 2018, the Netherlands had one of the highest scores in greenhouse gas emissions per capita, compared to other countries in Europe (NOS, 2018). Currently, the Netherlands is still far behind schedule in its CO_2 reduction plans, despite the dip in CO_2 emissions during the corona crisis (Zoelen, 2020).

In order to deal with the problem of plastic waste, the European Parliament and EU member states have decided on a ban on disposable plastics such as plastic cups, cotton buds, plates and straws, probably from 2021 and onwards (De Afvalmanager, 2019). In the Netherlands, the State Secretary is working on a Plastic Pact, where agreements are made with various parties about the reduction and reuse of plastic. The 2013-2022 Packaging Framework is an agreement between the packaging industry, the Ministry of Infrastructure and the Environment (I&M) and the Association of the Dutch Municipalities (VNG) with arrangements for the collection and reuse of plastic packaging waste from households (Krebbekx, Duivenvoorde & Haffman, 2018; De Afvalmanager, 2019).

Nonetheless, it seems there is insufficient insight into the processing of the plastic packaging waste (CE Delft, 2019; Corsten et al., 2010). The Court of Audit even estimates that about 60% of the total annual plastic production is incinerated (Geurtsen, 2019). This seems to indicate that the remaining 40% is recycled, but RIVM (2019) estimates that, on average for different plastic types, recycled plastic content used in relation to the total mass of plastics is only 18%. In scientific literature and public debate, there is dissension about the overall environmental benefits of recycling over incineration for energy recovery (Meindertsma & Wiessing, 2017;

BNNVARA, 2018). However, the current relatively low overall environmental benefits of plastic recycling versus incineration, has a lot to do with several factors. These include the sorted amount, composition and quality of plastic waste (Bergsma & Bijleveld, 2017; RVO, 2016; Verrips et al, 2017; Thiounn & Smith, 2020). These factors ensure that the ultimate efficiency of recycling is often still low. However, various studies indicate that the quantity and quality of collected plastic is crucial for the ultimate environmental performance (Merrild et al., 2012; Bergsma et al., 2011).

Due to the above-mentioned need to stimulate development in the field of emission reduction and encourage less use of exhaustive resources, this research is concerned with the development of circularity of a plastic supply chain from a systems perspective. The focus of this study is on a frequently used type of plastic in the packaging industry: flexible film.

The following chapter provides a literature review for defining the research problem. Chapter 3, subsequently, elaborates on the approach of the study and states the sub-questions. Hereafter, the proposed methods for this study are summarized. Chapter 4 presents a supply chin analysis, followed by a material flow analysis in chapter 5. Chapter 6 elaborated on the comparative cognitive mapping analysis, after which dynamic model simulation if performed in chapter 7. Chapter 8 and 9 involve the conclusion and discussion, respectively.

2. Research Problem

In this chapter, the research problem is explained. First, the relevance of this study in the scientific field of industrial ecology is explained. Hereafter, several literature studies about flexible film are analysed. After this, the concept of a circular supply chain and the recycling methods of flexible film are described. Subsequently, a knowledge gap is identified, on the basis of which the main research question can be formed.

2.1. Plastic packaging waste and Industrial Ecology

Due to the technical nature of recycling plastic, the underlying institutional structures of the flexible film flows and the link with an environmental issue such as plastic and air pollution, this topic seems applicable in the field of Industrial Ecology. Industrial ecology is a scientific discipline focusing on sustainability problems with a systemic approach, combining engineering, social and environmental sciences (Leiden University, n.d.). Industrial ecology intends to inform decision-making for production processes by tracking and analysing resource use and flows of industrial products, consumer products and wastes (Duchin & Levine, 2006). Furthermore, it provides a perspective which helps to find visionary solutions to environmental and resource problems. This is done through accommodation of the idea that the industrial system should mimic the natural ecosystem in its overall operation (Den Hond, 2001). The focus on flexible film flows and its waste streams as well as the aim for realizing a circular supply chain, which builds on the principle of imitating natural processes, demonstrates that this research strongly links with the field of Industrial ecology.

2.2. Flexible films and plastic packaging waste

As mentioned before, flexible film is frequently used in plastic packaging. At the start of this study, the aim was to focus on low density polyethylene (LDPE) as a plastic type, instead of flexible films in general. Nonetheless, during the conduction of this study, it became clear that it would be inadequate to solely focus on LDPE, as flexible films are recycled altogether in one stream. The variety of different plastic types used for flexible film adds to the complexity of the problem under study and is therefore chosen to be considered. Therefore, the focus of the study was broadened from LDPE to flexible films[1].

Moreover, plastics can be made in various shapes and can be divided into thermoplastics (flexible), thermoset (dimensionally stable and rigid) and elastomers (elastic) (RIVM, 2019). This study is focussed on flexible films, comprising flexible polyethylene (PE) and polypropene (PP) films. PE films comprise LDPE, high density PE (HDPE), medium density PE (MDPE) and linear low-density PE (LLDPE).

[1] This also explains references to interviewed respondents already in this chapter.

2.2.1. PE Films

First, the most used type of plastic in flexible films in the Netherlands is LDPE (RIVM, 2019). LDPE films are also one of the most frequently used plastics in packaging overall. (Karami et al, 2018; Comtesse, n.d.; De Afvalmanager, 2019). The material is an oil-based polymer and it is the most used industrial thermoplastic material in packaging. Plastic bags, garbage bags, cling films and films for nutritional packaging are also made of LDPE (Karami et al, 2018; Comtesse, n.d.; Boragno et al., 2012; De Afvalmanager, 2019). The popularity of LDPE for packaging is a result of its good mechanical properties. It is very flexible, water resistant, easily processable and chemical resistant (Karami et al, 2018; Comtesse, n.d.).

Secondly, HDPE is the plastic foil type that can be recognized by the crackling character of the film (KIVO, n.d.-c). The advantages of HDPE film can be found in its resistance to many industrial and living chemicals and to the corrosion of strong oxidants, organic solvents and acid-based salts. Moreover, it is waterproof, non-hygroscopic, relatively strong, UV resistant. Another major benefit of HDPE film is that little material is needed to make a product, meaning that relatively little energy is needed for production. Moreover, the overall production of HDPE film causes less CO_2 emissions than other packaging materials since the material is light and has so little volume (KIVO, n.d.-c). Nonetheless, flexible HDPE only makes up a small proportion of flexible plastics in the Netherlands (RIVM, 2019).

Third, MDPE has properties intermediate between low-density polyethylene and high-density polyethylene (Cavitymold, n.d.). The production of this material finds its origin in the need for a plastic that is a little stronger than LDPE, and a little less rigid than HDPE. Although not as common in use as LDPE and HDPE, MDPE finds use in applications like pond liners and other low to moderate performance uses. In such applications, it is useful as a physical barrier and moisture resistant (Cavitymold, n.d.).

Lastly, LLDPE displays a little advancement over LDPE (Cavitymold, n.d.). Although it is not as high in density as HDPE, it offers a lightweight plastic with similar density to LDPE, but with more strength. Moreover, LLDPE can achieve thinner films than LDPE. The commercial advantage is being able to get material with superior properties, without the expense required to make the polymer less branched. Applications of LLDPE include plastic bags, pouches, and moulded parts like toys (Cavitymold, n.d.).

Unfortunately, national documents and research reports often do not mention LLDPE and MDPE, but mention, for example, that MDPE is considered together with LDPE (RIVM, 2019). This makes it difficult to comprise these PE types separately and find information specifically for the Netherlands about these plastics. Therefore, when information about LDPE is found in a report about different plastic types, and LLDPE and MDPE are not mentioned separately, it is for the remainder of this report assumed that these types fall under LDPE.

2.2.2. PP films

Although PE is the most common type of flexible film, PP also makes up a relative proportion of flexible films in the Netherlands (RIVM, 2019). PP film is a seen as a very versatile packaging material, which is widely used in the food packaging industry due of its low cost, good mechanical and thermal properties and chemical stability (Ebnesajjad, 2013; Abudonia et al., 2018). PP is of high clarity, high gloss and good tensile strength. It has a higher melting point than PE, making the material suitable for applications that require sterilization at high temperatures. Nonetheless, the heat-sealing properties, tear strength and low temperature impact resistance of PP are not as good as those of LDPE (Polymer Properties Database, n.d.). Moreover, during the recycling of PE films, attempts are made to filter out PP, but a small percentage of PP still ends up in the recyclate (Interview WREC, 2021).

2.2.3.Plastic packaging waste

The European Union proposes increasing targets for encouraging the recycling of plastic packaging (Van Eygen, Laner & Fellner, 2018). The European Strategy for Plastics states that 55% of the annual plastic packaging wastes should be recycled by 2030. This means that ten megatons of extra recyclates must find a market application in Europe, compared to 2017. In the Netherlands, agreements about the collection and reuse of plastic packaging waste from households have already been made with the packaging industry (Krebbekx, Duivenvoorde & Haffman, 2018; De Afvalmanager, 2019). The aim is to further increase plastic recycling and for collected and sorted plastic to actually find application in new packaging and products (Kawecki, Scheeder & Nowack, 2018). According to NRK (The Federation of the Dutch Rubber and Plastic Industry) and Plastics Europe, this means that an increase in recycling from around 250 kilotons to 750 kilotons is desirable before 2030 (Rijksoverheid, 2018).

2.3. Circular economy and the circular supply chain

To be able to achieve the set targets by the different governmental organs and solve the problems associated with plastic waste, the development of a circular supply chain might provide a solution. In order to elaborate on the circular supply chain, the economic paradigm of the circular economy (CE) is explained first. CE is defined as a philosophy on the economic system that represents a change of paradigm in the way that human society is interrelated with nature, with the aim to prevent the depletion of resources and close energy and materials loops (Dey et al., 2020). The economic paradigm is conceptually rooted in industrial ecology and aims for an economy where the maximum value is extracted from resources and they are kept in use as long as possible (Nasir et al., 2017). To attain such a circular economy, cyclical and regenerative environmental innovations are required for the way society legislates, produces and consumes (Dey et al., 2020).

Subsequently, the concept of a circular supply chain is closely linked to CE. Several definitions of supply chains and its management can be found in literature. Kenton (2019, in Hrdá, Juríčková & Filová, 2020) explains the concept of a supply chain as a network between a company and its suppliers for producing and distributing a specific product or service from its original state to the eventual customer. This network involves different activities, people, entities, information, and resources. (Kenton, 2019, in Hrdá et al., 2020). This definition, however, seems the neglect the inclusion of the downstream processes of a product after its use within the supply chain. This seems to align with the concept of a linear supply chain, which abstractly comprises the supply chain links as *take-make-distribute* (Dey et al., 2020) or *take-make-dispose* (Nasir et al., 2017).

The definition of supply chain management (SCM) as given by Martín-Gamboa, Dias, Arroja and Iribarren (2020), on the other hand, seems to include the downstream processes of a product within the supply chain. Their definition of this concept refers to the effective and responsible planning, implementation and control of all upstream and downstream processes involved in an organized network for producing value in the terms of products and services (Martín-Gamboa et al., 2020). This definition, in comparison to Keton's (2019, in Hrdá et al., 2020) definition, considers the disposal or recovery processes of the product after its use within the concept of a supply chain. Therefore, this description seems more beneficial in trying to achieve a circular supply chain. In contrast to a linear supply chain, a circular supply chain is abstractly described as *take-make-distribute-use-recover*, enabling products at the end of their life cycle to be reapplied as an input through re-use, remanufacturing and recycling (Dey et al., 2020; Nasir et al., 2017). In this way, practicable relationships between ecological systems and economic growth could be achieved (Nasir et al., 2017). Figure 2.1 displays the basic concept of a linear supply chain in comparison to a circular supply chain. For this study, the supply chain of flexible films considers both upstream and downstream processes.

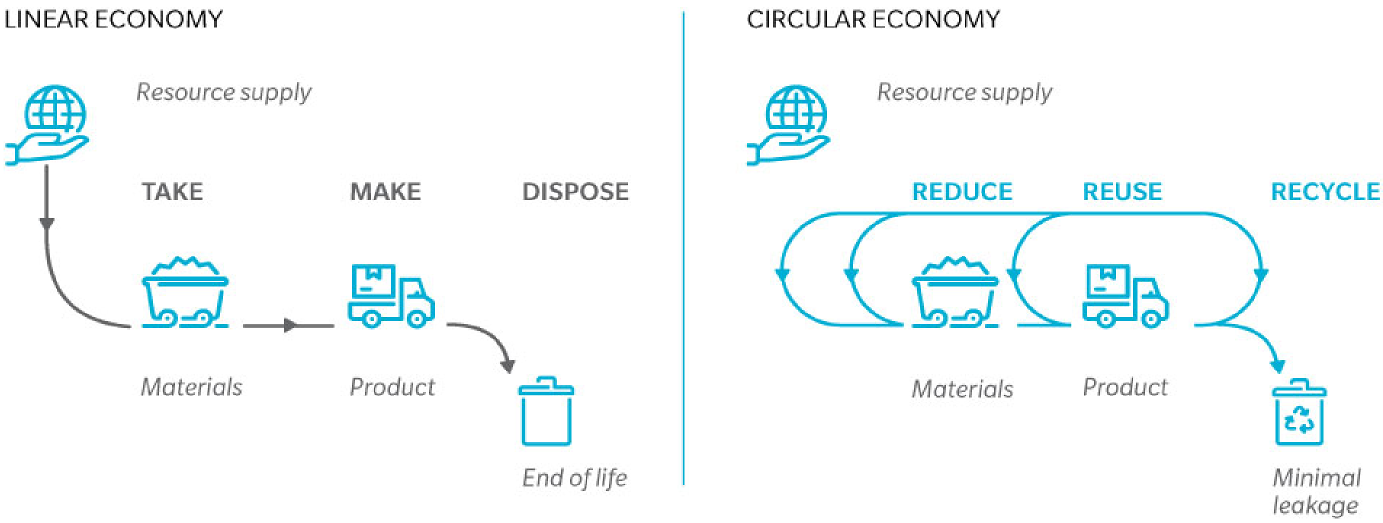

Figure 2.1.
Representation of the basic concept of a linear supply chain (left) and a circular supply chain (right).
Note: reprinted from "Supporting the circular economy transition", from Bark, Achimescuw, Neumann & van Wijk, 2017, p. 11.

As mentioned before, for a supply chain to become circular, it is important to reuse or recycle materials so they can be applied again. In the case of flexible films, recycling is the most feasible. Therefore, the next section goes into the recycling of plastics.

2.4. Recycling of plastic waste

2.4.1. Different methods for plastic recycling

Several methods are proposed for recycling of waste polymers like flexible films. First, *primary recycling* represents the recycling of in-plant scrap material (Achilias et al., 2007). Secondly, *mechanical recycling* refers to the approach of separation of the polymer from its associated contaminants and the reprocessing of the material by melt extrusion (Achilias et al., 2007; Gu et al., 2017). Thirdly, *chemical recycling*, means the recycling of plastics through depolymerization and dissolution. With this type of recycling, the waste polymers can be turned into original monomers or other valuable chemicals (Achillias et al., 2007). In this way, polymers can be separated from additives like flame retardants (TNO, n.d.-a; Ragaert, Delva & van Geem, 2017). This makes for chemical recycling to be a more robust and suitable process for mixed and contaminated plastic flows (TNO, n.d.-b). On the one hand, the process requires a high temperature, more expensive units and more energy than mechanical recycling (TNO, n.d.-b). Therefore, it should be noted that, in terms of sustainability, a waste management and recycling company should initially opt for mechanical recycling. If this is not possible, chemical recycling can be looked at (TNO, n.d.-a). Lastly, *energy recovery through incineration* is sometimes referred to as recycling (Achilias et al., 2007; Bergsma, Bijleveld, Otten, & Krutwagen, 2011). Nonetheless, within this study we refer to recycling as the material being reapplied in new products. Moreover, the study focuses more on mechanical recycling, as chemical recycling is still underdeveloped and will not yet operate on a large scale in the coming years (Ministerie van Infrastructuur en Waterstaat, 2021).

2.4.2. Recycling hierarchy for application of recycled plastics

Building on the notion of plastic recycling, there is an order of preferred uses for plastics after their useful life. Brouwer, Thoden van Velzen, Ragaert and Ten Klooster (2020) represented this order through *the hierarchical classification of recycled plastics in relation to their applicability*. This hierarchical classification is, for this study, transformed into a simplified value pyramid applicable to flexible films is stated in Figure 2.2. The application types in hierarchical order are taken from Brouwer et al. (2020). Nonetheless, the titles of the application types are altered. Moreover, a new

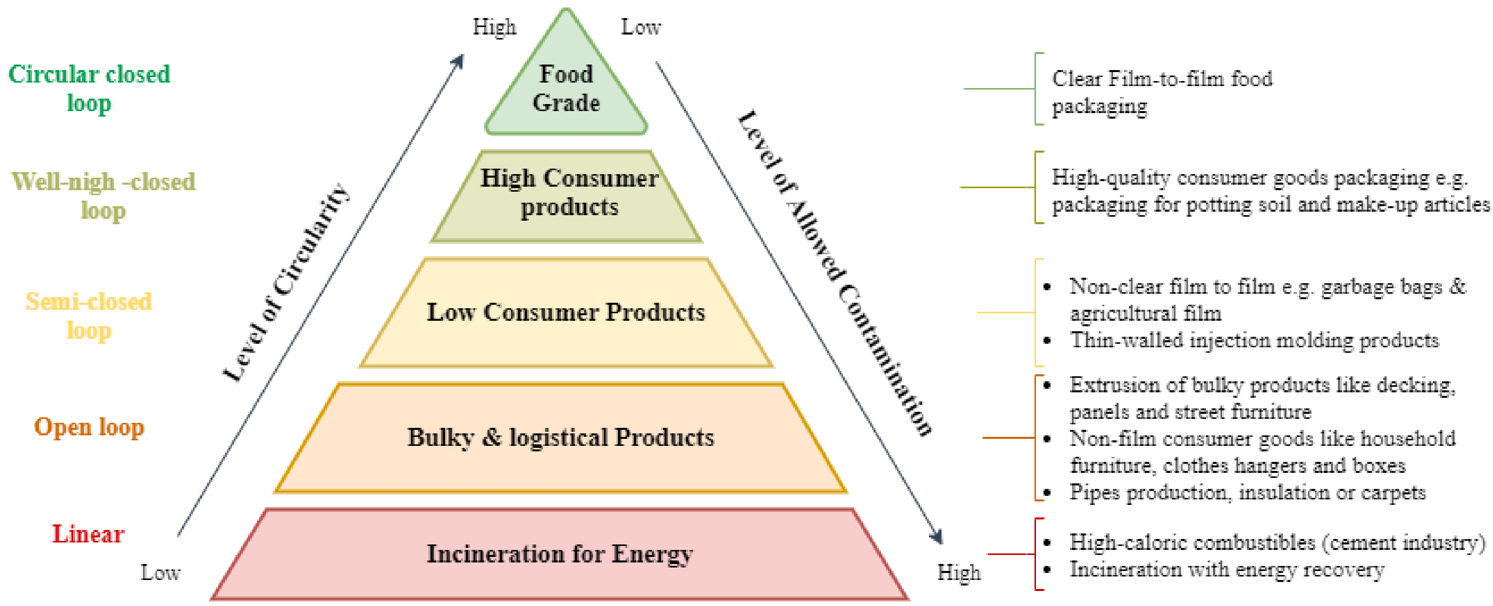

Figure 2.2
Value pyramid for recycled plastics, based on the hierarchical classification of recycling plastics in relation to their applicability from Brouwer, Thoden van Velzen, Ragaert and Ten Klooster (2020). The pyramid shows the different levels of circularity based on the application of the films after one life cycle. In addition, it is shown that the allowed contamination of the films actually decreases as the level of circularity increases. On the right side of the pyramid are examples for each application type after a lifetime.

category is added in comparison to the classification of Brouwer et al. (2020), in between food grade and low consumer products. This is done because the hierarchy by Brouwer at al. (2020) showed to have a large gap between the food grade category and the low consumer products category. Therefore, the high consumer products market segment is added, which represents a more high-quality application of films, in contrast to garbage bags and agricultural film in the low consumer products category. This category includes consumer goods or packaging which is not in direct contact with food, for example packaging for potting soil or for make-up articles in stores and supermarkets.

Moreover, two products types are added to the bulky logistical products category in comparison to the hierarchy of Brouwer et al. (2020). These are construction applications like pipes production, insulation or carpets and non-film consumer goods like household furniture, clothes hangers and boxes. Those product types are added, because they were mentioned by several authors as application types (Bergsma & Bijleveld, 2017; Partners for Innovation & Rebel, 2018; Deloitte Sustainability, 2017) and seemed to fit best in this category.

2.4.3. Plastic recycling versus incineration for energy recovery

Lately, there has been some debate in the public sphere and scientific literature about the recycling of plastic. It is said that the environmental benefits of recycling are nil in relation to the costs and that a large part of the collected plastic is currently not recycled (Meindertsma & Wiessing, 2017; BNNVARA, 2018). Gradus (2019) even states that oceans benefit more from plastic incineration than recycling. Nonetheless, this statement was built on the fact that, until recently, a large part of the plastic waste was exported to countries outside the EU, which is currently put to a stop by the European Commission (Simon, 2021; CE Delft, 2019). Furthermore, Gradus (2019) claims that the profit of plastic recycling compared to the incineration of plastic is very modest, namely 0.1% to 0.15% of the total CO_2 emissions in the Netherlands. This statement is based on a study by CPB (2017) for an indication of the size of a specific policy measure. This study, however, performed a rough calculation of the CO_2 reduction of only the amount of plastic waste collected separately from households, neglecting industrial and commercial plastic waste streams.

Moreover, a study by Hillman et al. (2018) in Denmark, Norway and Sweden shows that CO_2-equivalent emissions from secondary production (recycling) are 37% lower than those from virgin material production. In addition, a report in the Netherlands showed that the recycling of plastic saved more than three times as much CO_2 in comparison to the incineration of plastic waste (Corsten et al., 2010). Environmental performance is, however, multifaceted and not only measured by emission reduction. Merrild, Larsen and Christensen (2012) compared the overall environmental benefit of recycling and incinerating from household waste in Denmark. Results showed that the environmental impact of recycling plastic over incineration for energy recovery was unclear and differentiated between scenarios. The research concluded, however, that this was influenced by the limited content of collected plastic from Danish household waste (Merrild et al., 2012).

Nonetheless, a life cycle assessment (LCA) study compared the environmental benefits of the initiatives in the Netherlands for the collection, separation, sorting, processing and recycling of plastic packaging waste from households, compared to incineration for energy recovery (Bergsma et al., 2011). The results showed that source separation and post-separation of plastic packaging waste both provide a significant environmental benefit compared to incineration, for all types of plastic waste. However, the amount of recyclate that is produced after recycling that can be used in new products is, again, decisive for the environmental score (Bergsma et al., 2011). Based on the above, it can be inferred that the recycling of plastics can provide environmental benefits over incineration. This is, however, influenced by the efficiency of collection, separation, sorting and recycling.

Another critical point made by Gradus et al. (2016), is that the recycling of plastic is not yet cost-effective. The authors state that the implicit CO_2 abatement price of recycling is currently higher than alternatives to reduce CO_2 emissions. Nevertheless, the authors suggest that industrial scale post-separation of plastic waste, as shown in the north of the Netherlands, could lead to larger volumes and higher qualities of collected plastic, possibly increasing the cost-effectiveness of plastic recycling (Gradus et al., 2016).

The discussion of incineration versus recycling does not seem to include the long-term goals and requirements. Currently, incineration for energy recovery currently offers a relatively sustainable alternative to energy from fossil fuels. Nevertheless, plastic is made from an exhaustive fossil fuel: Oil (KIVO, n.d.a). The Dutch government has ambitions for nature and society to move towards a zero-emission circular economy towards 2050 (Ministerie van Infrastructuur and Waterstaat, 2019). When this development starts to slowly manifest, waste incineration for energy recovery will become less applicable. This is why, in any case, a movement towards more circularity must be made. The question therefore remains why more than half of the plastic waste is still incinerated in the Netherlands. This might be explained by the notion of *techno-institutional lock-in*, which is elaborated on in the next section.

2.5. Techno-institutional lock-in as a barrier for sustainable innovation

If plastic recycling provides can provide environmental benefits over incineration for energy, then what is holding back the further development of plastic recycling and the circular flexible film supply chain? A concept that might explain this is *techno-institutional lock-in*, which describes a persistent state constituting systemic market and policy barriers to environmentally superior technological alternatives (Könnölä, Unruh & Carrillo-Hermosilla, 2006).

Foxon (2002) describes this interlinkage between technological and institutional lock-in and how it forms a barrier for sustainable innovation. Institutions comprise formal constraints - such as legislation, economic rules and contracts - and informal constraints - such as social conventions and codes of behaviour. Development of (technological) innovation influences and is influenced by the social, economic and cultural context, which are all components of the institutional structure. Successful innovation relies on *path dependency*; the path of its development, which includes the characteristics of initial markets, regulatory components and consumers' expectations (Foxon, 2002).

Decisive is the extent to which the aforementioned factors favour incumbent technologies against innovative ones. For the development of innovations, the role of institutions in fostering or hindering the process of change is important. Lock-in occurs when an innovation or technical change is locked in by the dominant technical and institutional regime (Foxon, 2002). A regime, in this sense, is best described by the concept *socio-technical regime*: a shared set of rules and routines to ensure the provision of a relevant function (Cherp et al., 2018). The concept of a socio-technical regime in definition describes the interlinkage of the social and the technical within a regime. Foxon (2018) describes that modern technological systems are deeply embedded in institutional structures, which displays how institutional and technical regimes are intertwined. Regimes are stable and resilient. To survive or expand, they can foster but also hinder innovations that threaten their stability (Cherp et al., 2018).

The above summarizes techno-institutional lock-in as phenomenon where beneficial innovations are hindered because they are incompatible with the dominant regime. Economies of scale or influence over the political system are examples of reinforcing structures for the dominant regime (Foxon, 2002; Cecere et al., 2014). Another notion that seems similar to techno-institutional lock-in is *Techno-Institutional Complex*. This captures the idea that lock-in occurs through combined interactions among technological systems and governing institutions (Unruh, 2000). In this study, the term used for the dominant structures in the context of an innovation is *techno-institutional regime*.

A visible representation of techno-institutional interlinkage, in context of mobility innovations, is given in Figure 2.3 (Unruh, 2000, p. 826). This figure displays how reinforcing technological, social and institutional structures are interlinked, which could make use and progress of conventional mobilization more favourable over new developments. These reinforcing structures can therefore hinder the development of new and more sustainable mobilization technologies. This rigidness of the dominant techno-institutional system might result in a techno-institutional lock-in for mobility innovations. The next section dives into possible reinforcing technological, social and institutional structures, hindering the development of the circular flexible film supply chain.

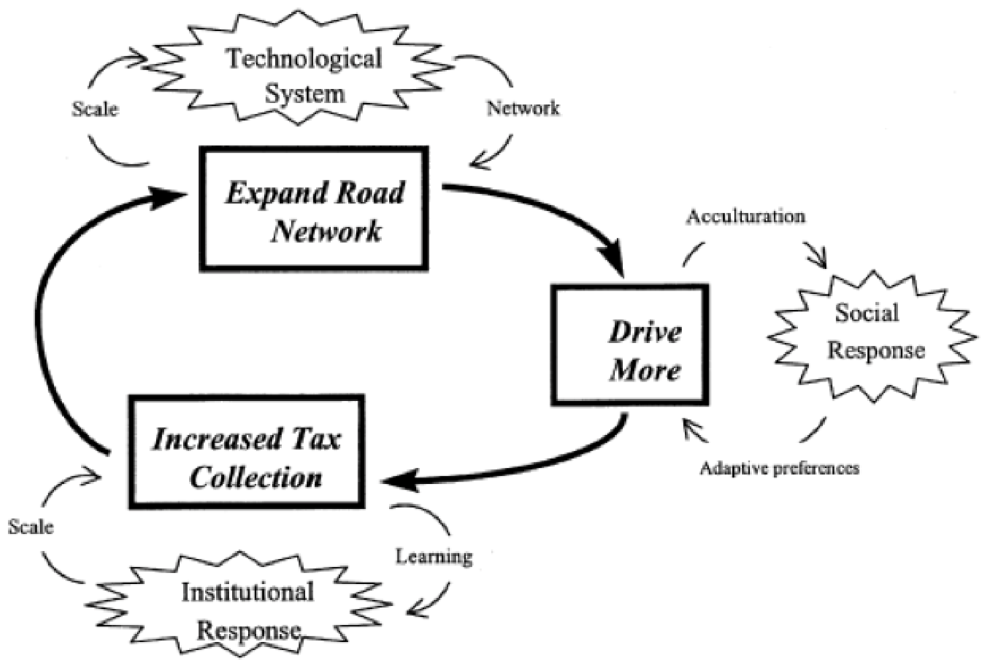

Figure 2.3.
Visual representation of techno-institutional reinforcement of dominant structures in the context of mobility. The figure displays how reinforcing technological, social and institutional structures are interlinked, which could make use of conventional mobilization more favourable over new developments. These reinforcing structures hinder the development of new and more sustainable mobilization technologies, which might result in a techno-institutional lock-in for mobility innovations.
Note: Reprinted from "Understanding carbon lock-in" by Unruh, G., 2000, Energy Policy, 28, p. 826.

2.6. Techno-institutional barriers for circularity in the flexible film supply chain

Building on the notion of techno-institutional complex, explained in the previous section, several barriers can already be identified that might lead to techno-institutional lock-in for the development of the circular flexible film supply chain. In this section, various techno-institutional barriers are discussed.

2.6.1. Ambiguity about the Dutch recycling values and actual recycled content

First of all, to be able to innovate the flexible film supply chain and make it into a circular process, it is important to have precise insights into the current material flows of flexible films in the Netherlands. There is, however, a discrepancy between the plastic material offered for recycling in the given national reports and the actual recycled production content. Chapter 1 already introduced how there is a gap between the incinerated amount of plastic compared to the annual production, which is estimated at 60%, and the recycled plastic content in relation to the total mass of plastics, estimated at 18% (Geurtsen, 2019; RIVM, 2019). The remaining 22% seems to be underexposed and raises questions about the course of this still large amount of plastic waste. Research showed that the quantity of collected PMD (he co-collection of Plastic, Metals and Drinking / beverage cartons) from Dutch households increased with 37% between 2014 and 2017, from 75 to 103 kilotons, based on the national figures (Brouwer et al., 2017). The increase in collected PMD was, however, accompanied by an increase in residual waste. When PMD arrives at the sorter, it is separated into different flows, such as PET, films and residual flows. In 2014, there was 19 kilotons of sorting residue in comparison to 55 kilotons in 2017 (Geurtsen, 2019; Brouwer et al., 2017).

After sorting, it is determined how much material is offered for recycling, which constitutes the national recycling values. This moment is based on the official measuring method that has been determined at European level (Geurtsen, 2019). The recyclers turn the content into recyclate; flakes or granulates of, for example, flexible film that can be used again to make new products. But also, at the recyclers, another residual flow is rejected. This can sometimes be up to a third of the flow, which is still classified as recycled content in the national figures (Geurtsen, 2019). Moreover, part of the separately collected plastic was exported to China until recently (CE Delft, 2019), which adds to the complexity of the national values of recycled content.

Moreover, part of the confusion in plastic waste recycling statistics, may be caused by the ambiguity surrounding the terminology of post-consumer recycled plastic (PCR) and post-industrial recycled plastic (PIR). More specifically, there is ambiguity around post-commercial plastic waste, which seems to fall between two stools. When post-commercial plastic waste is recycled, it falls under the term 'post-consumer recycled' (PCR), just like post-consumer (household) plastic waste (DEISS, n.d.). Nevertheless, Brouwer, Thoden van velzen, Ragaert and Ten Klooster (2020) delineate post-commercial plastic to the category Post-Industrial Plastic Packaging Waste (PIPPW) and not PCPPW. Another commonly used terminology is commercial and industrial (C&I) waste, where commercial and industrial waste are merged (Kleinhans, Demets, Dewulf, Ragaert & De Meester, 2021). This term can be confusing, as there is a distinction between industry that produces, and industry that "consumes". This unclear and ambiguous use of terminology for this commercial waste streams causes commercial plastic waste to often remain underexposed. Kleinhans et al. (2021) even developed the term "forgotten plastics" for non-household end-use plastic. Their research concludes that industrial actors and some policy makers are well aware that these waste streams exist, yet these potentially highly recyclable plastic waste streams often disappear in the overall waste statistics. Consequently, policies and scientific research do not address it separately, also caused by the lack of data (Kleinhans et al., 2021).

For this reason, it was difficult to gather data for this waste flow during this study. Nonetheless, a separate category is made for this waste flow, based on the literature that was found and assumptions that had to be made. In this study, PCR determines only recycled household plastic waste. PIR, on the other hand is described in this study as the recycled content from the losses that occur during production and manufacturing processes. Post-commercial waste defines the waste flows from businesses. It should, however, be noted that both post-commercial and post-consumer products are considered as PCR products after recycling when they are sold on the market. This indicates that post-commercial recycled waste is a sub-category under PCR.

Based on the above mentioned multi-faceted confusion surrounding the recycled plastic content in the Netherlands, it is important to investigate the actual material flows of flexible films in the Netherlands from a systems perspective.

2.6.2. Plastic market characteristics and consumer expectations

Secondly, a barrier is formed by the current plastic market characteristics and consumer expectations. As stated by Gradus et al. (2016), the recycling of plastic is not yet cost-effective. This is, however, dependent on the efficiency of the incumbent technological recycle system (Bergsma et al., 2011; Gradus et al., 2016). As a consequence, recycling flexible films is not profitable (Verrips et al., 2017). Part of the Dutch foil fraction is processed in the Netherlands and the remainder is processed abroad. Partly due to export restrictions of unsorted plastic waste, first to China and now also to non-OECD countries, supply is currently exceeding demand. Subsequently, low and sometimes negative prices apply for this waste stream (Kawecki, Scheeder & Nowack, 2018; Verrips et al, 2017; Simon, 2021; CE Delft, 2019).

Furthermore, virgin plastic is currently cheaper than recycled plastic, due to the historically low oil prices (Gimbrère & van de Keuken, 2020). Because of the continuous competition with cheap newly produced plastic, recycled plastic has become unsaleable for recyclers, now more than ever considering the circumstances surrounding covid-19 (Gimbrère & van de Keuken, 2020). Furthermore, the expectations of the consumer and the plastic product producers, are said to not be met by recycled plastic. Not only is virgin plastic cheaper, but some critical notes have also been made about the colour, smell and quality of recycled plastic, compared to its virgin competitor (Gimbrère & van de Keuken, 2020). This already touches upon some technical obstacles, which shows the interlinkage of these structures.

2.6.3. Regulatory and technical components

Regulatory and technical components form the third techno-institutional barrier. The aforementioned export restrictions display a barrier of its own from a regulatory perspective. Until recently, separately collected plastic was exported to China (CE Delft, 2019). This plastic was counted as recycled in the waste statistics. It is, however, unclear whether these plastics have actually been recycled and under what circumstances. In 2016, approximately 11 kilotons of packaging from companies were exported in this way. The exporting of plastic waste was legal due to European legislation, but is currently prohibited (Simon, 2021; CE Delft, 2019). This export might have been to countries where the social and environmental impact of the processing of this packaging is not (or cannot) be controlled as well as in Europe.

Furthermore, a bottleneck is formed by the current strict regulations for the quality of plastic packaging in combination with some technical obstacles. The quality of materials decreases during reprocessing, for example due to heating (Bergsma & Bijleveld, 2017). Nonetheless, a research about polyethylene during reprocessing showed that primary recycling of polyethylene under well controlled conditions only leads to minor material property losses. LDPE specifically is less sensitive to thermal-degradation phenomena than other types of polyethylene (Mendes, Cunha & Bernardo, 2011). The quality of plastics, however, also decreases whilst in use, due to the influence of ultraviolet radiation (Bergsma & Bijleveld, 2017). This indicates that the quality of the recyclate is dependent on the quality of flexible film when thrown away.

A similar barrier arises with multilayer films, consisting of several material types. These films cannot yet be properly recycled (Bergsma & Bijleveld, 2017; RVO, 2016; Verrips et al, 2017; Thiounn & Smith, 2020). Nevertheless, research by TNO (2020) concluded that two methods of recycling multi-layered plastics were successful at laboratory level. One of these methods was to separate the polymers. However, not all polymers can yet be separated from each other and the technology still needs to be scaled up (TNO, 2020; RVO, 2016). The second method is focused on changing the composition of multi-layered films. Chemical company Dow experimented for two years with packaging films consisting of several layers, with different properties, but all made of the same type of polymer. These types of multi-layered packaging showed to be easier to recycle. The procedure of making these newly composed multi-layered films, however, allows a little more oxygen through than conventional methods, which makes the materials less applicable for packaging of products with stricter food safety requirements (TNO, 2020). Although stakeholders agree that food safety is of the highest importance, current strict regulations for quality of packaging prevent the use of recycled plastic for them (Kawecki, Scheeder & Nowack, 2018).

2.7. Scientific knowledge gap: circular supply chain development from a systems perspective

The abovementioned techno-institutional barriers already give insight into the complexity involving innovation and development towards circularity for the flexible film supply chain. Even though the term techno-institutional seems to only refer to technical and institutional structures, the socio-economic level is also considered under this term. Current literature mentioned the persistent interlinkage of techno-institutional structures as a possible obstacle for innovation (Könnölä, Unruh & Carrillo-Hermosilla, 2006; Foxon, 2002). Nevertheless, current literature still falls short in performing multidisciplinary analyses, including these interlinking structures, on development towards circularity from a supply chain perspective. More specifically, no research has been done on achieving circularity within the flexible film supply chain from a systems perspective. Analysing the development towards circularity of the flexible film supply chain from a systems perspective, makes for this study to provide a unique angle compared to current literature. Whereas previous studies mainly focus on either the technical, institutional or socio-economic level considering flexible films (Brouwer et al., 2020; CE Delft, 2019; Partners for Innovation & Rebel 2018; Boragno et al., 2012), this research aims for combining these three levels and providing a helicopter perspective on the flexible film supply chain. Moreover, the ambiguity about the distribution of recycled and incinerated plastic contents in national figures asks for an analysis of the actual material flows in the Netherlands. Based on the above, the following research question is proposed:

How can circularity in the Dutch flexible film supply chain be identified in the current techno-institutional regime, and how can it be fostered in the future?

This question is multi-faceted as it focuses on defining the current status of circularity development and factors influencing it within the supply chain as well as discovering how this development can be stimulated. Through mapping institutional, technical and socio-economic factors associated with the flexible film supply chain and visualizing their interactions and influence on each other, this study can provide a contribution to the current scientific knowledge on flexible films. Therefore, this research offers an example in the field of Industrial Ecology, as it considers the importance of interdisciplinarity in the context of sustainability issues. This multi-faceted systems focus asks for a mixed method approach. In the next chapter, the research approach, methods and the sub-questions for this study are discussed.

3. Research Approach and Methods

This chapter elaborates on the research approach for the study. Subsequently, the sub-questions, which together should provide an elaborate answer to the research question, are given. Hereafter, the applied research methods are described on the basis of the given sub-questions. Lastly, the data requirements are defined and elaborated on.

3.1. Mixed methods approach

The main research question is answered by use of a mixed method approach. The mixed methods framework involves assumptions and guidelines for practice (Creamer, 2018). The first assumption is that qualitative and quantitative data and methods are not incompatible, but the combination of qualitative and quantitative methods could rather produce more robust findings. Secondly, it is assumed that the use of multiple data types enhances validity and that the use of more than one approach can compensate for the weaknesses inherent in just one method (Creamer, 2018). Therefore, mixed methods indicate a systematic and coherent collection of practices and procedures for conducting research. This implies that a mixed method research contains both qualitative and quantitative approaches, which are integrated at some point in the study (Creamer, 2018).

For this study, a mixed method approach can offer a broader perspective than a single-sided method would have done. The different qualitative and quantitative methods complement each other and thus contribute to a deeper understanding of the topic under study. The different methods applied, which are separately explained in section 3.3, each provide a view of the flexible film supply chain from a different angle. The methods each provide information that is useful for the following methods and provide insight from different viewpoints, contributing to the supply chain view from a systems perspective. In this way, this approach can also better map the interdisciplinary nature of the problem. Moreover, the combination and quantity of methods applied in this study is exceptional and, to the author's knowledge, not yet performed in current scientific literature. For this reason, the approach of this study serves as an example for follow-up studies on other materials and their supply chain or, for example, in other regions. In section 3.3, the different methods, their successive use and their utility for each other are elaborately explained.

Some limitations to the mixed method approach are mentioned by Driscoll et al. (2007). First, they state that reducing rich qualitative data to dichotomous variables makes it single dimensional and unchangeable. In this study, this limitation has been taken into account when interpreting the results of the different methods, but it remains a complex obstacle in the quantification of qualitative data. Nevertheless, efforts have been made to reduce the consequences of this limit by providing extensive substantiation and argumentation for the quantification of qualitative data. By noting this in detail, either in the main report or in the appendices, this can be verified by the reader. In addition, this argumentation can be examined in follow-up studies and, if newer or more accurate knowledge for argumentation is available, the quantification can be adjusted accordingly.

Moreover, since qualitative methods go into more depth and are therefore more time-consuming per respondent, it can force researchers to reduce sample size. This can, however, limit the types of statistical procedures that could be used, since significant results in quantitative analysis are partly dependent on bigger sample sizes (Driscoll et al., 2007). This limitation is, however, not an obstacle for the quantitative methods applied in this study.

3.2. Sub-questions

In order to adequately answer the main research question, the following sub-questions are developed:

1. a. What does the current flexible film supply chain look like?
   b. What actors are associated with the different links in the supply chain?

2. a. What are the actual material flexible film flows in the Netherlands?
   b. What is the distribution between the share of incinerated and recycled flexible films?

3. a. What do the supply chain actors perceive as the most relevant factors for developing circularity in the flexible film supply chain?
   b. Are there areas of conflict or disagreement between the main supply chain actors? If so, what are they?
   c. How do the supply chain actors perceive their interdependency throughout the supply chain in achieving circularity?
   d. What does the current techno-institutional regime involving the flexible film supply chain look like from a systems perspective?

4. a. What are the estimated developments for and relationships between the relevant factors, associated with the flexible film supply chain, up until 2025?
   b. How will these developments influence the circularity of the flexible film supply chain?

3.3. Research methods

As mentioned at the beginning of this chapter, a mixed methods approach is applied, where qualitative and quantitative methods are integrated. The different sub-questions require different methods and each answer to a sub-question provides input for the next sub-question. The different research methods are elaborated in the following sections.

3.3.1. Supply chain analysis and desk research

First of all, it is important to get a better picture of the flexible film supply chain in the Netherlands, which is what answering sub-question 1.a entails. Sürie and Wagner (2005) state that, before improvement of processes can take place, one has to have a clear picture of the structure of the existing supply chain and the way it works . Therefore, a desk research approach is used to assess what the supply chain of flexible films in the Netherlands looks like. Based on the information found, a visual representation of the Dutch flexible film supply chain is constructed, including the key actors at each link of the chain. In this way, the results are used to uncover the main supply chain actors involved in the overall Dutch flexible film supply chain, answering sub-question 1.b. Moreover, the economic value and the technical status of the material is determined throughout the entire supply chain. The results provide a representation of the structure of the supply chain, which serves as the basis for the MFA model.

3.3.2. Material flow analysis and desk research

For answering sub-question 2.a and 2.b, the flexible film material flows in the Netherlands need to be analysed and visualized. The method applied for this is material flow analysis (MFA). MFA takes a systems approach of looking at a specific material, flexible film in this case. It results in the identification of material flows and a visual representation of these flows inside a defined boundary. The MFA method provides information about the behaviour of systems and, when combined with other disciplines, facilitates the control of an anthropogenic (human controlled) system. Therefore, it reduces the complexity of the system and provides a basis for sound decision-making (Brunner & Rechberger, 2016). The data analysis tool used is for this method is STAN (short for substance flow analysis), which is a freeware program for performing MFA (Stan2Web, 2012).

MFA is described as the systematic assessment of flows and stocks of materials within an arbitrarily complex system, defined in space and time. In this context, the word material serves as an umbrella term for both substances and goods (Cencic & Rechberger, 2008). Conduction of an MFA follows a specific structure, existing of the following three steps (Mudacumura, Mebratu, & Haque, 2017):

1. Goal and system definition
2. Inventory and modelling
3. Interpretation of results

These steps are followed during conduction of the MFA. The first step, goal and system definition, is concerned with clearly formulating the goal(s) and definition of the system. This includes defining the system boundaries. Secondly, the inventory and modelling step concerns the computation for the flows and stocks for a given year (Mudacumura, Mebratu, & Haque, 2017). Various data sources and calculations are involved in this step, which explains why desk research is also a part of this analysis. Based on the data from databases and literature, and the lacking thereof for more recent years, the base year chosen for this analysis is 2017. To display a more relevant representation of the material flows of flexible films, the MFA 2017 model is nowcasted into a 2020 MFA. Nowcasting is defined as the prediction of the present, the very near future or the very recent past (Banbura, Giannone & Reichlin, 2010). The computation in this step can apply several types of modelling. In this study, *static modelling* is applied, which describes a static condition apart from possible changes in the immobile stocks and from changes outside the given system. The main aim with static modelling is to develop one consistent mathematical structure, which enables to specify relations among the different flows and stocks within the system (Mudacumura, Mebratu, & Haque, 2017). As stated before, the model is created in STAN. This programs also performs some automatic calculations, if the right amount of data is inserted.

Lastly, the interpretation step involves the expression of the results in terms of mass of flows and accumulations of the material under study (Mudacumura, Mebratu, & Haque, 2017). This provides an answer to sub-question 2.a, about the actual material flows of flexible film in the Netherlands. Moreover, the final models and values are examined, results are described, and explanations are sought on how to interpret these results. When the flows of flexible films in the Netherlands are mapped and understood properly, the supply chain and the main supply chain actors can be more accurately understood and identified. Moreover, the distribution between the share of incinerated and recycled flexible films can be uncovered during this phase, providing an answer for sub-question 2.b.

3.3.3. Semi-structured interviews

After identifying the main supply chain actors, they are approached for interviewing. Since part of the study is conducted in collaboration with a company that has connections with the relevant stakeholders, these could easily be approached via e-mail. For conduction of these interviews, a semi-structured interview method is applied. Semi-structured interviews focus on specific themes, covering them in a conversational style. This is often the best method to find out an actor's motivations for choices and behaviour and their attitudes in context of these specific themes (Raworth et al., 2012). In total, six stakeholders were interviewed. Due to the sensitivity of the subject, the interviewees have been kept anonymous. The summaries and notes of the interviews cannot be attached to this study for reasons of anonymity and confidentiality but are in the possession of the author.

3.3.4. Comparative cognitive mapping

After interviewing the main supply chain actors, the interviews are analysed by means of Comparative Cognitive Mapping (CCM). This method is applicable for exploring the ideas of individuals, institutions and groups on any subject (van Esch & Joosen, 2015). Cognitive maps are a common tool in the analysis of complex problems and represent how actors think about it in a structured way (Hermans et al., 2018). The program used for this method is the Dynamic Actor Network Analysis (DANA) tool, developed by Pieter Bots, an associate professor at Delft University of Technology (DANA, n.d.). The third sub-questions entail the defining of techno-institutional structures, including relevant factors, associated with the flexible film supply chain. CCM provides the right method for structurally displaying the actor’s perceptions of perceived techno-institutional barriers in achieving a circular flexible film supply chain, by creating cognitive maps for each stakeholder.

Subsequently, the cognitive maps are analysed. CCM can be used for qualitative data analysis. The DANA tool for CCM can analyse cognitive maps and define what the respondents perceive as relevant factors in the context of achieving circularity in the supply chain (sub-question 3.a). Furthermore, the results can provide information about conflicting actions and goals between the supply chain actors (sub-question 3.b). This can help to uncover possible unnoticed underlying barriers, but also spaces of opportunity. Lastly, the tool can provide insights into the perceived interdependency between the supply chain actors (sub-question 3.c). With this information, the results contribute to the construction of the current dominant techno-institutional regime in the context of the flexible film supply chain (sub-question 3.d).

3.3.5. Dynamic modelling and desk research

In order to determine how the supply chain and the associated factors develop over time, these are simulated towards 2025 by means of dynamic modelling. Dynamic modelling follows the same structure as static modelling of the MFA, which is as follows:

1. Goal and system definition

2. Inventory and modelling
3. Interpretation of results

The first and third phase entail the same as for MFA static modelling. The inventory and modelling phase, however, is a little different. This is because, in dynamic modelling, the process equations include time as a variable, in contrast to static modelling (Mudacumura, Mebratu, & Haque, 2017).

When the influential factors that are relevant from a multi-actor supply chain perspective are discovered through CCM, desk research is done to determine future developments for and relationships between these factors. Based on the data found, equations are performed, and estimations are made to quantify these trends and relationships towards 2025. This means that the causal links between relevant factors and their expected developments over the coming years are estimated (sub-question 4.a). Trends are represented in annual growth rates or compound growth rates. These are estimated in by means of the following equation:

$$1. Compound\ growth\ rate = \left(\frac{Future}{Present}\right) - 1$$

$$2.\ Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$

After the trends and relationships are estimated, the model is made in Vensim PLE software. Vensim PLE is fully functional system dynamics software (Vensim, n.d.). The year 2025 is chosen on the basis of relevant targets set by the government up until 2025 (European Plastics Pact, 2020; Kerstens & Blanksma, 2019) and because longer-term estimations can be made less accurate and credible. On the basis of the MFA results, the supply chain, including the proportional division between flows, is reconstructed into a model in Vensim PLE. If not indicated otherwise, the division between flows is kept the same as in the MFA 2020 model when simulating towards 2025. Furthermore, the relevant and influential factors given by the supply chain actors are incorporated.

It should be noted, however, that the future is uncertain, and these estimated trends and relationships are prone to unpredictability and error, weakening the credibility of the analysis. Therefore, both two low and two high scenarios are simulated, which gives a more likely bandwidth for future predictions. The analysis results in values for key factors, flows and stocks associated to the flexible film supply chain within the two scenarios up until 2025 (sub-question 4.a). In this way, it can be examined whether certain expected technical, socio-economic and institutional developments lead to a more circular supply chain. Furthermore, it can be discovered which factors and links in the supply chain require even more management and development in the coming years.

3.4. Data requirements

For the different methods, various types of data are required. The data requirements and sources for the sub-questions and methods are given in Table 3.1. In this table, a distinction is made between primary and secondary data. Primary data considers information is gathered at first hand by the researcher, while secondary data includes information from secondary sources, like published articles (Hox & Boeije, 2005). Furthermore, when secondary data was required, several data sources are mentioned, as extensive information was often required. The data sources in each row are listed in preferred order of use, based on the hierarchy of sources for research, given by Eaton (2018).

Table 3.1
Data requirements for conduction of this research and associated data sources for the different sub-questions and methods.

Sub-question	Research Method	Data requirements	Data Source In preferred order of use*
1.a.b	Supply Chain analysis & Desk Research	Qualitative secondary data about the flexible film supply chain and the involved supply chain actors	➢ Recycle and waste reports and documentations from acknowledged research institutes (e.g. In De Keten) ➢ Webpages from entities knowledgeable in their area of supply chain
2.a.b	Material Flow Analysis (MFA) & Desk Research	Qualitative secondary data about the flexible film system and flows in the Netherlands.	➢ Peer-reviewed studies and reports; scientific journal articles ➢ White papers and reports from credible research institutes or think thanks
		Quantitative secondary data behind the flexible film flows like export and import values, recycle rate values and production values of flexible films.	➢ Official governmental and university reports and statistics ➢ Documentation from highly credible non-governmental organizations ➢ Recycle and waste reports and documentations from acknowledged research institutes (e.g. TNO, KIDV) ➢ Recycle and waste reports from credible commercial entities (e.g. Deloitte)
3.a.b.c.d.	Interviews	Primary data results from the supply chain analysis and MFA to grasp what stakeholders to interview.	➢ Supply chain analysis and MFA results
	Comparative Cognitive Mapping (CCS)	Primary data from the interviews to insert in DANA software	➢ Conducted interviews
		Primary data from the MFA results for reconstructing the supply chain of flexible films in Vensim PLE.	➢ MFA results
		Primary data from the CCS results for defining perceived influential factors, conflicting terrains, interdependency throughout the supply chain and the current dominant techno-institutional regime	➢ CCS results
4.a.b	Model Simulation & Desk Research	Primary data from the CCS results for inserting relevant influential factors and their causal relations in Vensim PLE. Qualitative and quantitative secondary data to estimate trends and developments for the flexible film chain and associated influential factors.	➢ CCS results ➢ Peer-reviewed studies and reports; scientific journal articles ➢ White papers and reports from credible research institutes or think thanks ➢ Official governmental and university reports and statistics ➢ Documentation from highly credible non-governmental organizations ➢ Recycle and waste reports and documentations from acknowledged research institutes (e.g. TNO, KIDV) ➢ Recycle and waste reports from credible commercial entities (e.g. Deloitte)
5		Primary data from supply chain analysis, MFA, CCS and Model Simulation results to define crucial reinforcing loops and influential factors re-enforcing techno-institutional lock-in	➢ Supply chain analysis, MFA, CCS and Model Simulation results

*Preferred order of data use is based on Eaton's (2018) hierarchy of sources.

4. Supply Chain Analysis

This section discusses the results of the supply chain analysis. First, the specific flexible film supply chain in the Netherlands and the actors associated with it are elaborated on. Each of the main stages is zoomed in on, so that the flexible film supply chain can be clearly understood by the end of this chapter. Subsequently, a visual representation is developed and analysed, to better grasp the notion of the flexible film supply chain. In this way, the two folded first sub-question is focused on, about what the flexible film supply chain looks like (1.a) and what the associated stakeholders are (1.b).

4.1. Analysis of the Dutch flexible film supply chain

In order to get a better picture of the flexible film supply chain, the different phases are discussed on the basis of desk research. These phases include (1) production and manufacturing, (2) wholesale and retail, (3) use, (4) waste collection and sorting and (5) waste processing.

4.1.1. Production and manufacturing

4.1.1.1. Refinery

The production and manufacturing phase involves several processes and actors. Plastic granules, which are used for making foils, are made from the raw material oil (KIVO, n.d.a). Oil is not mined in the Netherlands, so it is imported to the Netherlands through a supplier. The imported oil is processed in a refinery. This refinery ensures the purification of raw materials such as natural gas or oil. For plastic production, the processed crude oil needs to be converted into a fraction of hydrocarbons called crude gasoline or naphtha (KIVO, n.d.a). After this, naptha cracking takes place. This is done in so-called naphtha crackers by means of steam cracking. This is a process in which molecules are, under extremely high temperatures, chopped up into pieces into monomers such as ethylene, propylene and many other compounds (KIVO, n.d.a).

There are a number of refineries in the Netherlands, which are mainly located around the port of Rotterdam. The greatest representative in this field Shell in Pernis. This is one of the largest refineries in the world. In addition, BP in Europoort is a major representative in the refinery. This company processes around 400,000 barrels of oil every day (Chemische-Industrie, n.d.).

Moreover, the price of oil is currently set at 62 dollars per barrel. Converted to euros, the price is slightly above €52 per barrel. Moreover, one barrel of oil weights around 136 kilograms (Donev et al., 2018). Based on this, the price of the material in this life phase is set at €0.38 per kilogram.

4.1.1.2. Petrochemical industry

Monomers are the basic raw materials for the petrochemical industry and are the building blocks for plastic (KIVO, n.d.a). They cannot be seen with the naked eye and are gaseous. That makes it a challenge to transport. Therefore, the transport is done with large pipelines from the crackers to the petrochemical plants. The production of the plastic takes place in the petrochemical plants. This process can best be described as stringing the monomers together into a large chain. The chain of monomers is called a polymer, or the plastic (KIVO, n.d.a).

There are quite some petrochemical companies in the Netherlands. In total, there are six petrochemical clusters present, in and around Rotterdam, Amsterdam, Delfzijl, Sittard (Chemelot), Emmen and Terneuzen (Chemical Parks in Europe, n.d.). A large number of chemical companies, currently 45, are also located in the Port of Rotterdam (Port of Rotterdam, n.d.). This means that an impressive petrochemical cluster is active within the boundaries of the Rotterdam port area. As a result, not only cooperation and exchange of end products takes place, but also in the field of tank storage, industrial gases, heat, steam, wastewater treatment and electricity. This can be called synergy, which contributes to a higher efficiency. Some petrochemischial companies are, among others, Lyondell Chemical, Aluchemie, Cabot and, again, BP (Port of Rotterdam, n.d.). An international important actor in this field is Dow. Dow has eight locations in the Netherlands, including three big ones in Terneuzen, Delfzijl en Dordrecht (Dow, n.d.)

Furthermore, the price of the virgin material differentiates between the different types of plastic in flexible film. These prices go from €1820 (HDPE) to €2170 (LDPE) per ton (Nederlands Verpakkingscentrum, n.d.). For this study, the rounded average of the different prices of €2000 per ton is assumed. This subsequently is converted to a price of €2.00 per kilogram.

4.1.1.3. Plastic manufacturer

When the granules have arrived from a petrochemical plant at a plastic manufacturer, they are stored in large silos, after which they are passed on to the extruders (KIVO, n.d.-a). During the extrusion, granules are heated and melted. Film is subsequently blown from this molten emulsion. Ultimately, the foil needs to be processed into the final procces. To do this, the film roll has to go to the clothing department. Here the plastic roll is cut and sealed to serve as the final product, for example consumer packaging (KIVO, n.d.-a). In the case of this study, the final product is flexible film, applied in several different use categories. Moreover, there are various big plastic film manufacturers in the Netherlands are KIVO, CEDO, Oerlemans, Plasthill and Plastopil (KIVO, n.d.a; CEDO, n.d.; Oerlemans Plastics BV, n.d.; Plasthill BV, n.d.; Plastopil, n.d.). Since the manufacturer is often also the wholesaler, the price of the product after manufacturing and wholesale is taken together, and elaborated on in the next section.

Moreover, it is important to note that manufacturing is decisive for the technical characteristics of the end product. Later on, this study shows that it can be determining, wether a material is manufactured into a mixed material blend or a mono-material film for the recyclability. This determines, subsequently, the efficiency of recycling to some extent.

4.1.2. Wholesale and retail

After the plastic is manufactured into its intended purpose, it is transported to wholesale and retail. The main aggregated use categories are considered as the different categorical sectors in which flexible film is sold through wholesale and retail as well. These categories, taken from Kawecki et al. (2018), are: Packaging, Electrical and Electronic Equipment (EEE), construction, agriculture, automotive and other (remaining categories).

Wholesalers buy their product in bulk and sell it in bigger quantities to the retailers (Bullock, Jennings & Timbrell, n.d.). Because of that, they are able to often offer a low price. A retailer, on the other hand, is a business that sells goods in smaller quantities through a shop, online or through another retail outlet directly to the costumer for their own use (Bullock, Jennings & Timbrell, n.d.). When the plastic films are produced and manufactured, they are distributed to the wholesalers. There are retailers and wholesalers for the different aggregated use categories, that sell the product to different types of costumers for different types of uses. For flexible film, manufacturing, wholesale and retail are often intertwined and done by one actor. For example, manufacturers sell agricultural, construction and customized packaging themselves through wholesale and retail (KIVO, n.d.a; Oerlemans Plastics BV, n.d.; Plasthill BV, n.d.; Plastopil, n.d.). Retail, however, is also involved with selling quantities of flexible film in, for example, supermarkets, clothing stores, garden centres and furniture shops. In this case, the flexible film is often, but not always, not the main product that is being bought. Rather, it is incorporated in the product, or surrounds it by means of packaging.

Moreover, the price of a product after manufacturing, involving flexible film, is difficult to decide, as the plastic is often not the main purpose of the purchase. Therefore, as an example, the wholesale price of flat packaging film is taken from a packaging industry (Verpakkingsindustrie Veenendaal, n.d.). The price is taken from their website and rounded to an average of €91 per 25 kilograms. This, subsequently, indicates a price of €3.64 per kilogram.

4.1.3. Use

After (products involving) flexible film are bought through wholesale and retail, it is used by the consumer/costumer. Since flexible films are manufactured and sold for different sectors, it is also consumed within these sectors by the costumer. The use phase can be very short, which is the case for packaging. Often packaging is discarded right after the costumer buys the product. In other cases, the plastic has a longer lifespan. Plastic incorporated in construction, cars and EEE products, for example, tempt to have a longer lifespan (CE Delft, 2019). When flexible film is discarded, it becomes waste, which should be collected. From the 2020 MFA model, it became clear that some flexible film content is littered when applied in packaging. The actual amount of plastic in litter that ends up in the plastic soup is unknown (CE Delft, 2019). Even though it is a small amount of flexible film that is being littered, it is vulnerable for eventually ending up in the plastic soup. Therefore, further research should discover how to minimize this amount.

After being used, the plastic price decreases towards a negative price. This is indicated by the notion of Extended Producer Responsibility (EPR) and is reflected in the waste management contribution (Afvalfonds Verpakkingen, n.d.). Producers have to comply with the legal requirements for collection and recycling. Rates are given for different types of material by Afvalfonds Verpakkingen (n.d.). For plastic, the price is currently set between €0.41 per kilogram as a lower tariff[2] and €0.67 per kilogram as regular tariff. For this analysis, the regular tariff is assumed.

4.1.4. Waste collection and sorting

The responsibility for the collection of household waste in the Netherlands lies with the municipalities (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, n.d.). That is stipulated by law. Each municipality can decide for itself how it collects household waste. For example, municipalities can pick up door-to-door. Or via a central assembly point in the street. The municipality therefore also makes the choice between source or post-separation. In addition,

[2] As of January 1, 2019, it is possible to use a differentiated rate for plastic. A lower rate applies for packaging that can be properly sorted and recycled with a positive market value (Afvalfonds Verpakking, n.d.).

municipalities should have a larger collection point where people can bring their waste. These are the waste disposal stations or environmental stations (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, n.d.). The municipalities can then also engage private companies to actually collect the household waste. One such company is Suez (Suez, n.d.).

Businesses are themselves responsible for the collection of commercial waste (Ministerie van Algemene Zaken, n.d.).They must have the waste be collected themselves, by private companies, such as Milieu Service Nederland, Renewi and Remondis Nederland (Milieu Service Nederland, n.d.; Renewi, n.d.; Remondis Nederland, n.d.). Suez also collects waste from companies, beside the household waste it collects. Businesses can let commercial waste that resembles household waste be collected by the municipality. They can also take waste to the waste disposal station or the recycling centre. Companies pay a cleaning fee for this service (Ministerie van Algemene Zaken, n.d.).

After collection, the waste streams are sorted into different waste streams determined by material type. In the Netherlands, plastic packaging waste is sorted according to the DKR standards, with different standard per plastic type (In De Keten, 2015). For example, after the sorting step, films must be empty, with surfaces in accordance with DKR standard 310, larger than A4 size, such as bags, wrappers and pouches (In De Keten, 2015). The sorting is done by the entities that collect the waste as well. In regions where source separation is not applied, post-separation and sorting are kind of combined.

Moreover, the price of wasted plastic does not yet change in this phase, as compared to its price after use elaborated on in the previous section. Nonetheless, a change in price occurs during waste processing. This is discussed in the next section.

4.1.5. Waste processing

In this study, waste processing is concerned with the recycling, landfilling or incineration for energy recovery of plastic waste.

4.1.5.1. Recycling

Of the three processing options mentioned above, an attempt is always made to first recycle the plastic waste (if it cannot be reused). The steps in the mechanical recycling process of flexible packaging usually consist of grinding and/or shredding, washing, separating, drying, melting, granulating, cooling and drying again (KIVO, n.d.a). Often, collection and sorting are described as part of the recycling process as well, but for greater clarity and simplification during the MFA (chapter 5) , these steps are discussed separately for this study.

Often, the recycling process is executed by the same parties that collect the plastic waste as well. These parties include Suez, Milieu Service Nederland, Renewi, Remondis Nederland (Suez, n.d.; Milieu Service Nederland, n.d.; Renewi, n.d.; Remondis Nederland, n.d.). After this, the recycled granules are transported to the plastic manufacturers. Moreover, beside the waste collectors, some plastic manufacturing companies also provide recycling processes, like KIVO and CEDO (KIVO, n.d.a; CEDO, n.d.). Some other companies that provide recycling services are KRAS Recycling and Attero (KIVO, n.d.-a; Attero, n.d.).

The price of recycled plastic is twofold. After the first drying session, the material is called regrind. After melting, granulating, cooling and drying again, it is called regranulate. Nonetheless, the recycler can also offer the regrind to a certain costumer. Regrind of films currently has a market price of around €850 per ton (Nederlands Verpakkingscentrum, n.d.). This converts to €0.85 per kilogram. Regranulate, on the other hand, has a market price around €1150 per ton (Nederlands Verpakkingscentrum, n.d.), indicating a price per kilogram of €1.15.

Plastic waste that is sorted out and lost during the recycling process, is transported to AVI's for incineration for energy recovery. Some of the plastic waste losses that occur during recycling are, as a last option, landfilled (CE Delft, 2019).

4.1.5.2. Incineration for energy recovery

Besides losses that occur during the recycling processes, some residual waste streams are directly brought to waste incineration plants (WIPs) (CE Delft, 2019). There are currently twelve WIPs in the Netherlands (Ministerie van Infrastructuur en Waterstaat, n.d.-d). These WIPs process the combustible waste that cannot be recycled. This waste consists for the most part of household residual waste and residual waste from companies and offices. The expansion of WIPs has resulted in additional capacity for processing combustible waste. This has contributed to the fact that almost no combustible waste is landfilled in the Netherlands. Preventing the landfilling of combustible waste is an objective of the national government (Ministerie van Infrastructuur en Waterstaat, n.d.-d).

Moreover, all Dutch WIPs produce energy (Ministerie van Infrastructuur en Waterstaat, n.d.-d). This can be electrical energy or heat supply. The energy production is divided into renewable and non-renewable energy. Renewable energy comes from organic waste such as organic waste and wood. Non-renewable energy come, for example, from plastic. The share of renewable energy in the total energy produced at the WIPs was 52% in 2018 (Ministerie van Infrastructuur en Waterstaat, n.d.-d).

One of the bigger players in waste incineration is HVC (HVC, n.d.). This entity is active for 44 municipalities and six water boards. Moreover, ARN represents a big player in this field (ARN BV, n.d.). Beside HVC and ARN, some beforementioned parties that also have WIPs present at their installations are Suez and Attero (Suez, n.d.; Attero, n.d.).

Furthermore, the rate for landfilling and incinerating waste within the Netherlands is €33.15 per 1,000 kilograms, which translates to €0.03 per kilogram (Belastingdienst, 2021). This indicates a negative value, which is mostly paid through the waste levy for households Ministerie van Infrastructuur en Waterstaat, n.d.-b). Nonetheless,waste that is subsequently turned into energy, becomes valueable again. Plastics have a lower heating value, which is the amount of heat released by combusting, of approximately 40 megajoule per kilogram (Wasilewski & Siudyga, 2013). This translates to around 11 kWh of electricity. The price per kWh in the Netherlands is, on average, €0.22 (NLE, n.d.). Subsequently, 11 kWh has a price of €2.42, meaning that the value per kilogram incinerated plastic now has turned into €2.42.

4.1.5.3. Landfill

Landfilling is the least desirable way to dispose waste in the Netherlands. A dumping ban therefore applies to waste materials that are reusable or combustible (Ministerie van Infrastructuur en Waterstaat, n.d.-c). Nonetheless, a small part of the plastic waste seems to still end up in landfill (CE Delft, 2019). The 'Overview of Landfills' from a collaboration of WAR (workgroup waste registration) and several ministries indicates per province which landfills are present, in which location they are located and in what status the landfill is in (Ministerie van Infrastructuur en

Waterstaat, n.d.-b). The majority of the landfill sites included in the overview are in operation. In addition, landfills have been included that have (recently) closed and are currently in the finishing phase. Moreover, the overview includes landfills that have yet to be put into operation (Ministerie van Infrastructuur en Waterstaat, n.d.-b).

Several players can be identified in the field of landfilling. Delta Milieu en Afvalzorg Deponie both have landfill in two different provinces in the Netherlands (Ministerie van Infrastructuur en Waterstaat, n.d.-b). Moreover, ARN offers, besides waste incineration services, also several landfills (ARN BV, n.d.; Ministerie van Infrastructuur en Waterstaat, n.d.-b). Attero, however, seems to be the biggest representative in this field, with landfill locations in four different provinces of the Netherlands.

As stated before, the rate for landfilling and incinerating waste within the Netherlands is €33.15 per 1,000 kilograms, which translates to €0.03 per kilogram (Belastingdienst, 2021). When being landfilled, the wasted plastic is not transformed into another product, so the value remains negative with a price of €0.03 per kilogram.

4.2. Visualization of the flexible film supply chain in the Netherlands

With the supply chain analysis, the focus was on the first two folded sub-question:

1. *a. What does the current flexible film supply chain look like?*
   b. What actors are associated with the different links in the supply chain?

On the basis of the desk research results of the flexible film supply chain described in the previous sections, a visual representation is developed and presented in Figure 4.1. The figure aims to incorporate a institutional, technical and socio-economic level to a certain degree. First, the institutional layer is presented, on a basic level, by the stakeholders and institutions connected to the different processes throughout the supply chain. It becomes clear from the results that some actors are connected to different processes within the supply chain. Due to their multi-connected role, it can be said that these actors have more say and influence within the supply chain and they, therefore, could play an important role in the process towards a more circular supply chain.

Secondly, the technical layer is displayed by the white phrases withing the large arrows. These phrases represent the different technical phases the material goes through, throughout the supply chain from oil to flexible films wasted, used for energy recovery, lost through landfill or recycled into regrind and eventually regranulate. Moreover, some technical details are given about the different processes involved in the different stages of the supply chain. An example is the different processes involved in recycling that are laid out in steps. The technical status of the material, to a certain extent, determines the economic value it has. This already shows the interconnection with the socio-economic level.

Lastly, the socio-economic level is represented by the economic values throughout the supply chain, which displays how the value of the material changes throughout its life cycle. It must be noted that this economic value is determined by institutional structures - like laws and regulations- , social norms and trends - like consumption behaviour - and technical characteristics – like the quality of the material. The interrelations between these three levels determine the obstacles and opportunities for development of the circular flexible film supply chain. An observation can be made about the value of regranulates in comparison to the value of incinerated plastic turned into energy. It seems like one kilogram of recycled plastic has a lower economic value (€1.15) than one kilogram of incinerated plastic that is turned into energy (€2.42). In order to make a valid estimate of the profitability of the different processes, a cost-benefit analysis should be executed. Nevertheless, these different values seem to indicate that incinerating energy is more valuable than recycling under current circumstances. This might explain why a large amount of flexible film waste still ends up at WIPs instead of the material being recycled. At an economic level, this does not encourage companies to invest in the recycling of flexible films and thus does not steer in the direction of circularity. In the coming chapters it will become clearer how this economic climate is related to the institutional and technical structures. First of all, the next chapter will deal with the material flows of flexible films in the Netherlands, providing an even better picture of the size of the various flows and the current ratio between the incinerated and recycled flexible films in the Netherlands.

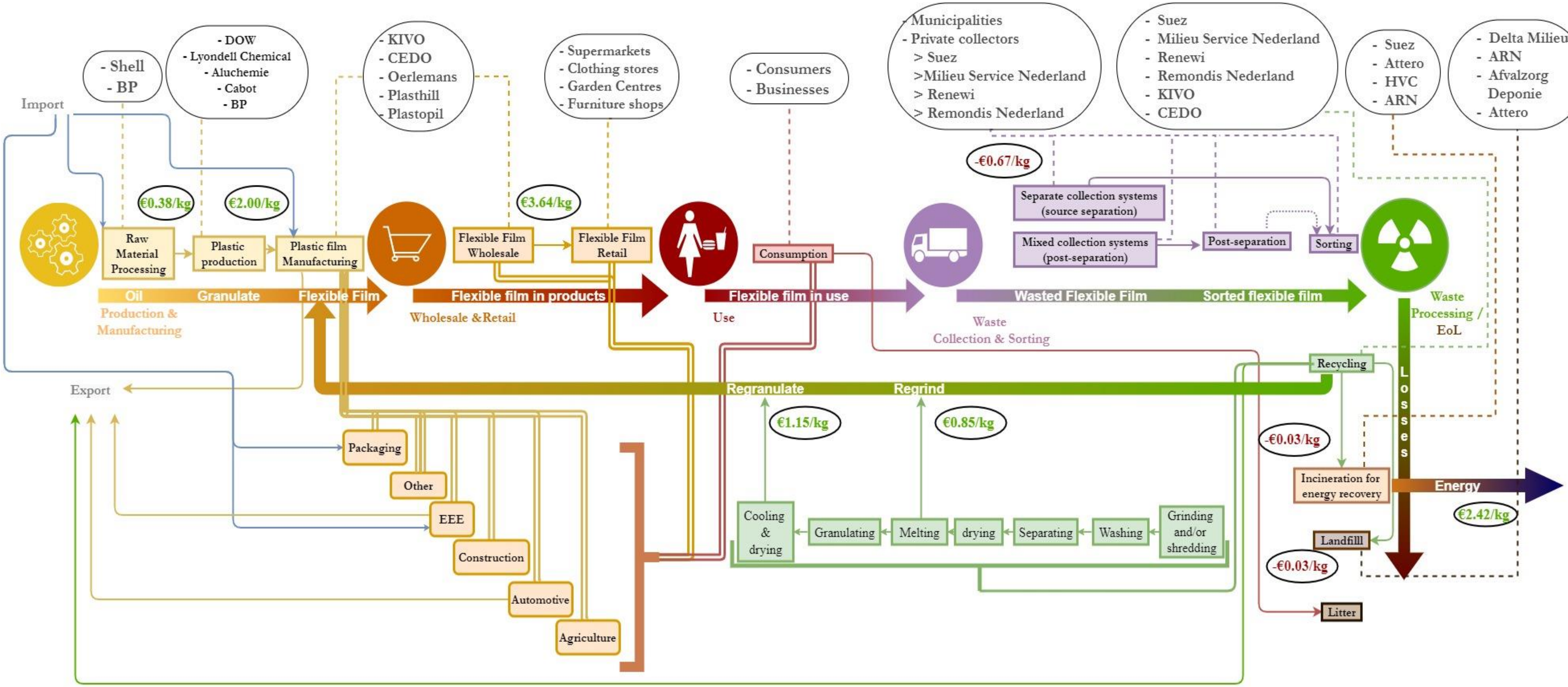

Figure 4.1
Visual representation of the flexible film supply chain in the Netherlands. The supply chain represents the circular and the linear flows of flexible film in the Netherlands. The economic value throughout the supply chain is represented in the black circles in €/kg. Green prices represent a positive value, whereas red prices determine negative values. The circles on top of the figure display the key stakeholders associated with the processes its connected to with a dashed line. The white phrases within the large arrows display the technical status the material is in throughout the supply chain.

5. Material Flow Analysis

5.1. Goal and system definition

The first step of the MFA methodology is to clarify the goal(s) and definition of the system, which includes defining the system boundaries. The basic goal of MFA is to define and analyse a real system as simple as possible. However, it should contain enough detail to make the right decisions based on the final model (Cencic & Rechberger, 2008). The goal of modelling this MFA system for flexible films, is to get answers to sub-questions 2.a and 2.b. Sub-question 2.a focuses on discovering the actual material flexible film flows in the Netherlands. By performing an MFA, a visual overview of the complex material flows in the Netherlands can be made. Moreover, sub-question 2.b is concerned with the distribution between the share of incinerated and recycled flexible films. When the MFA model is finalized, this distribution can be displayed and compared to the national given values for recycling and incineration. Due to the ambiguity of the national value for recycled content and the absence of an MFA specifically for flexible films in the Netherlands, this MFA is an important step to conduct when analysing the Dutch flexible film value chain. With this MFA, it is possible to visualize the flexible film material flows and discover where a lot of flexible film content may be lost, where more efficiency is required and where bottlenecks are present. This forms a good basis for further research into the (circular) plastic flexible films value chain and the associated actors.

This analysis is focussed on flexible films, which comprises flexible PE and PP films. Nevertheless, due to lack of information about flexible film material flows, it is necessary for this analysis to sometimes assume the LDPE distribution of flows, as this is the most applied plastic type in flexible packaging (RIVM, 2019). A source used for this is the proportional material distribution of plastic types given by Kawecki et al. (2018). This paper provides material flows of different types of plastics within Europe. Even though the material flows of HDPE and PP are also described by Kawecki et al. (2018), assuming an average of both these types and LDPE would be further from reality than basing it off of the LDPE distributions. This is the case because the known material flows of HDPE and PP describe their flows in flexible and rigid form, but do not make a distinction between these two forms. Since both PP and HDPE are also commonly used in rigid form, their proportional division of material flows and, for example, aggregated use categories are not representative for flexible films in general. LDPE, on the other hand, is the biggest representation in flexible films and is not often applied in rigid form. Therefore, in case data is lacking for flexible films in general, the proportional distribution of material flows of LDPE is considered.

Lastly, the *system* comprises a set of material flows, stocks and processes within a defined boundary (Brunner & Rechberger, 2016). The system for the MFA is bounded by the national Dutch borders. For the modelling, it is attempted to visualize all material flows within the Dutch borders. The system boundaries are, thus, defined by the national Dutch boundaries. Only imports and exports of flexible films exceed this border.

5.2. Inventory and modelling

The second step of the MFA methodology is concerned with identifying, quantifying and modelling the material flows of the material under study. Various data sources and calculations are involved here. Therefore, desk research is also a part of this analysis. For this step, all the links in the supply chain, where a change in material flow, losses or accumulation is occurring, are described and assessed separately. Since no changes in material flow, losses or accumulation is assumed to take place during retail, this link in the supply chain is not included in the MFA. The base year for this study is 2017, since this is the year with the most recent and available data about flexible films. However, if data was not available, estimations and assumptions had to be made. All of these assumptions are clearly explained in, but some assumptions come back more often and are therefore stated already in Table 5.1. When the MFA model for 2017 is built, the MFA model for 2020 is nowcasted from the results, based on the two assumptions given in the table below.

Table 5.1
Assumed growth rates for specific concepts used when data is missing for a specific year, material and/or sector. The substantiation for these assumptions is described in the right column. Moreover, these growth rates are used for the nowcasting of the MFA 2017 model into the 2020 model.

Topic	Assumption	Explanation
Overall annual growth rate	4%	There are various estimates for the growth of plastics production. The Ellen MacArthur Foundation (2016, in Verrips et al., 2017) assumes a business as usual scenario, with global growth of approximately 3.5% per year. In North America and Europe, growth is expected to be 3% per year (Verrips et al., 2017). Plastics Europe (2016, in Verrips et al., 2017), on the other hand, assumes a growth of 1.5% per year in Europe. A way higher estimation is made by the Dutch Foundation of Life Sciences and Society, stating the annual growth of plastic production is 8%. For this study, the assumption is kept between the estimates, with an annual growth rate of 4%. This is taken as the annual growth rate of the flexible film plastic overall, and is assumed to grow steadily across the entire supply chain.
Plastic packaging annual growth rate	2.6%	The amount of post-consumer plastic packaging waste (PCPPW), has increased by 8% from 2014 up until 2017 (CE Delft, 2019). For this study, it is assumed that the flexible film packaging market has increased the same rate. In order to make this value easier to calculate with, it is transformed into an annual growth rate in the following way: $$Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$ $Growthrate\ plastic\ packaging\ market\ (three\ years) = 8\%$ $Growthrate\ plastic\ packaging\ market\ (three\ years) = 0.08$ $Annual\ growthrate\ of\ plastic\ packaging\ market = (1.08)^{\frac{1}{3}} - 1$ $Annual\ growthrate\ of\ plastic\ packaging\ market \approx 0.026$ $Annual\ growthrate\ of\ plastic\ packaging\ market = 2.6\%$ This growth rate is taken as the annual growth rate of the flexible film plastic packaging.

2.7.1. Inventory

First, it is important to collect all the necessary data and perform the relevant calculations based on the found data. Table 5.2 provides the relevant values, based on desk research. The extensive elaboration on the desk research done, assumptions made and equations performed, is given in Appendix A.

Table 5.2
Summary of relevant values for MFA inventory data and values, based on desk research. Elaboration and equations for achieving these values is described in Appendix A.

Variable	Value
Plastic on the Dutch market	1,900
Flexible Film percentage of total on the Dutch market	32%
Production efficiency	99.41%
Manufacturing Efficiency	93.32%
Distribution of plastics in packaging	35% LDPE 15.5% HDPE 16.5% PP 33% other plastics
Distribution of plastics in construction	5.1% LDPE 12.8% HDPE 7.4% PP 74.7% other plastics
Distribution of plastics in Automotive	44% PP 7% PE 49% other plastics
Plastic content in EEE products	12.70%
Plastic mix in WEEE	16% other materials and 84% plastic composition
Flexible film content of plastics in agriculture	77.1%
PCPPW amount	350 kilotons
Plastic packaging waste collected in municipalities through source separation	80%
Plastic packaging waste collected in municipalities through post separation	20%
Source separation collection efficiency	65%
Percentage of flexible films correctly sorted to films (DKR 310) from separate collection	48.66%
The average proportion of the different types of plastic films incinerated	11%
Flexible film percentage of sorted DKR 350 flow arriving at recyclers	30%
Commercial collection efficiency	57%
Flexible film content in composite packaging	20%
Source separate collection efficiency Beverage cartons	52%
Post-separate collection efficiency beverage cartons	20%
Sorting efficiency of source collected beverage cartons	73%
Sorting efficiency of post-separate collected beverage cartons	75%
Amount of plastic litter	9 kilotons
EEE distribution of flows after use	8% exported

	9% to residual waste
Amount of plastic waste from construction	68 kilotons
Agricultural sorting efficiency	58.89%
Plastic waste from agriculture	44 kilotons
Sorting efficiency of agricultural plastic waste	55.89%
Automotive export percentage per plastic type after use	PP 18.61% HDPE 17.39% LDPE 18.18%
Plastic in automotive waste	27 kilotons
Percentage of other category going to residual waste	100%
Recycling efficiency household plastic waste	61%
Recycling efficiency beverage cartons	85%
Recycling efficiency WEEE waste	71% (reuse) 27% is incinerated 2% is landfilled
Recycling efficiency of automotive waste	40% 52% incinerated 8% landfilled
Recycling efficiency industrial waste	90%
Recycling efficiency construction waste	25% 65% incinerated 10% was landfilled
Recycling efficiency commercial waste	85%
Remanufacturing Efficiency	93.32%
Distribution between PCR and PIR content of recycled Flexible films	93% PCR 7% PIR
Distribution recycled PCR content	23% to packaging (trash bags) 27% to construction 25% to agriculture 25% to other

2.7.2. Modelling

Based on the inventory data found and the estimations and calculations that are done, an MFA model of flexible films in 2017 is made in STAN. The model is built on the basis of the given and calculated weight values, efficiencies, production numbers, proportional divisions and by means of calculations for unfilled values by STAN. The representation of the 2017 MFA model is given in Appendix A.2. Subsequently, on the basis of this 2017 model, an MFA model for 2020 is nowcasted. This is done by applying the overall annual growth rate of 4% and the packaging market annual growth rate of 2.6%, as given in Table 5.1 at the beginning of this chapter. Furthermore, the distribution of flows is kept the same.

An exception is made in nowcasting the exported amount of manufactured flexible film, for which data was found for 2019. The exported amount of flexible film from The Netherlands to other countries in the world was 49.71 kilotons in 2019 (World Integrated Trade Solution, n.d.). This is assumed to only be the manufactured amount of flexible films and not flexible film content incorporated in products. Considering the annual growth rate of 4% for just one year, the estimated amount of exported flexible films from manufacturing is around 51.7 kilotons[3].

5.3. Interpretation: results of the material flow analysis

In order to interpretate the results of the MFA, it is important to acknowledge the sub-questions focused on for this analysis. Those were as follows:

2. *a. What are the actual material flexible film flows in the Netherlands?*
   b. What is the distribution between the share of incinerated and recycled flexible films?

First, sub-question 2.a is dived into. As stated earlier, the final MFA model of a particular system consists of processes, flows and stocks. A *process* is described as a form of transport, transformation or storage of materials. *Stocks* are material reservoirs within the determined system, with tons as the physical unit. A stock is a part of a process, containing the mass that is stored in that process. Processes are, subsequently, linked by *flows* of materials in mass per time (Brunner & Rechberger, 2016; Cencic & Rechberger, 2008).

Figure 5.1 displays the finalized schematic representation of the material flows of flexible film in the Netherlands in 2017. Subsequently, Figure 5.2 displays the 2020 flexible film MFA model, which is nowcasted from the 2017 MFA results. The representation in figure 5.2 provides an answer to sub-question 2.a, as it represents the actual material flexible film flows in the Netherlands in 2020. The processes are presented as boxes and the arrows represent the material flows, where thickness displays the relative mass of the flow in comparison to the other flows. The dotted line squaring the flows and processes defines the system boundary of flexible films in the Netherlands in 2020. As the model displays, the packaging category comprises the largest part of flexible films on the Dutch market.

Moreover, the colours of the boxes represent the different phases the material flows through: *Import and export* (grey), *Production and manufacturing* (light red), *use* (orange), *sorting and collection* (yellow), *recycling* (light green), *remanufacturing* (moss green), *PCR* and *PIR supply of rPE* (turquoise), *reuse* (fluorescent green), *linear waste processes* (purple) and *disposal* (bright red).[4] In the model, several processes are holding flexible film content, which is displays a net addition to stock by a squared value within a process. For 'incineration for energy' and 'fuel for cement kilns', these values determine the amount of flexible films incinerated and used for fuel respectively. For litter and landfill, these values represent the amount of flexible films net additions

[3] $49.71 \times 1.04 = 51.70\ kilotons\ of\ exported\ manufactured\ flexible\ film$

[4] The orange boxes 'composite plastic', 'consumer use' and 'commercial use' are the packaging use process, but then unfolded in three categories. These are therefore not processes within themselves. Moreover, the turquoise boxes do not so much represent a process but have been added in this way to show a split between PCR and PIR supply of rPE films. These boxes display final supply of rPE, both from PCR and PIR flexible films for clarity. These are therefore also not processes of their own.

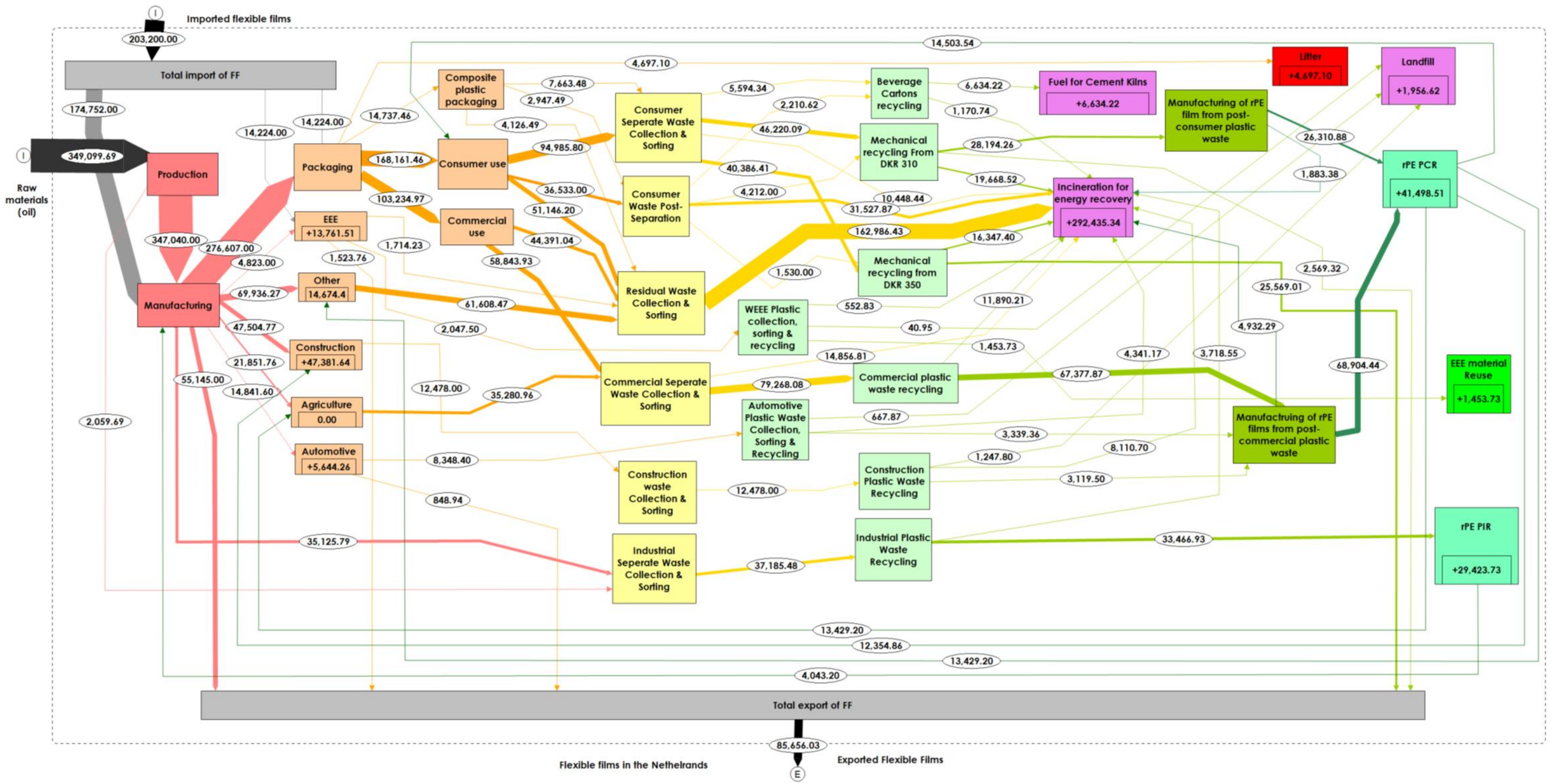

Figure 5.1

Schematic representation of the nowcasted material flexible film stocks and flows in the Netherlands in 2017. It represents the actual material flexible film flows in the Netherlands. The processes are presented as boxes and the arrows represent the material flows, where thickness displays the relative mass of the flow in comparison to the other flows. The dotted line squaring the flows and processes defines the system boundary of flexible films in the Netherlands in 2020.

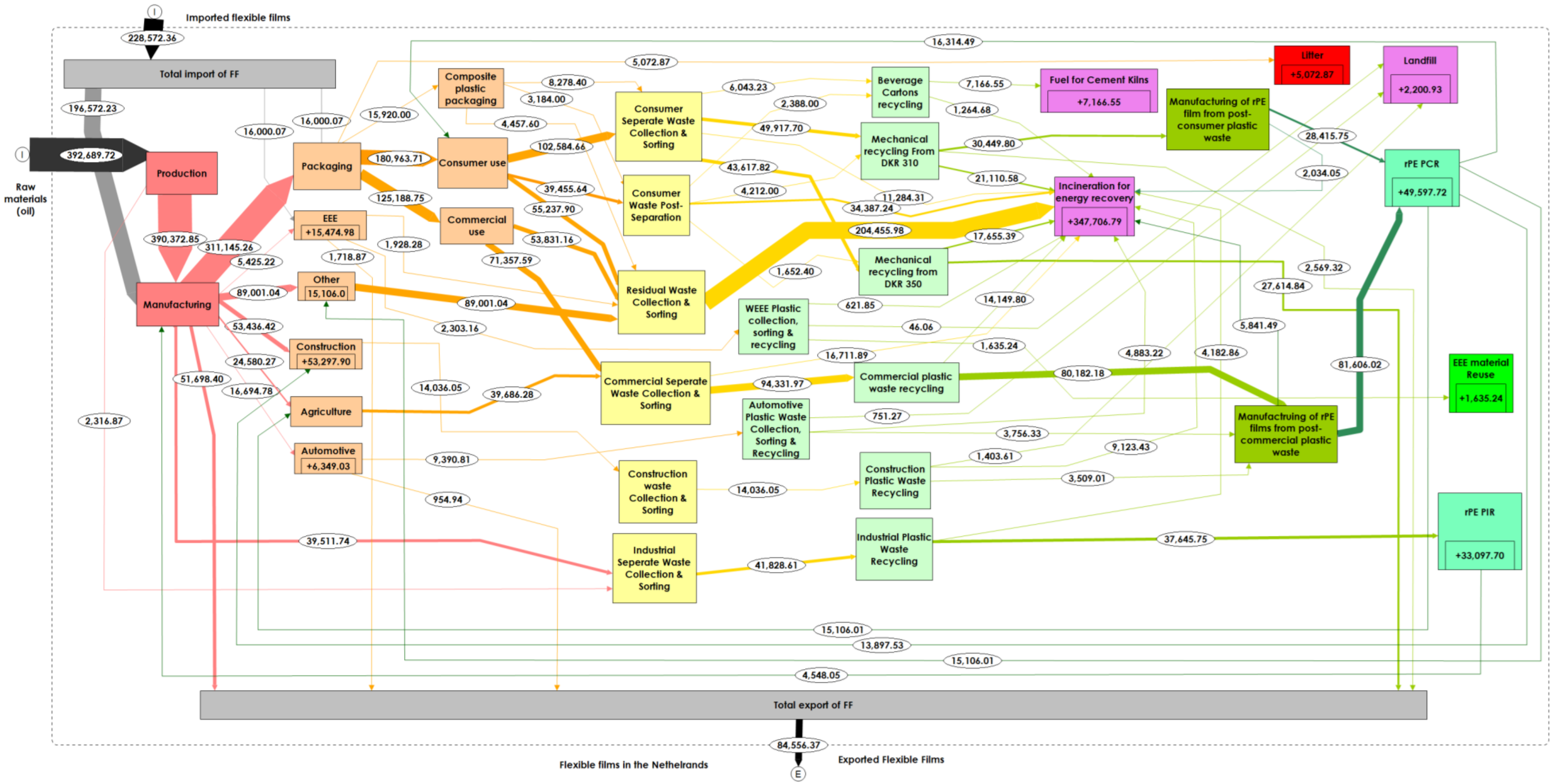

Figure 5.2

Schematic representation of the nowcasted material flexible film stocks and flows in the Netherlands in 2020. This model is nowcasted from the 2017 MFA model in Figure 5a. The model represents the actual material flexible film flows in the Netherlands in 2020. The processes are presented as boxes and the arrows represent the material flows, where thickness displays the relative mass of the flow in comparison to the other flows. The dotted line squaring the flows and processes defines the system boundary of flexible films in the Netherlands in 2020.

to the stocks of flexible film litter and landfill. The squared value in 'EEE material reuse' represents the amount of reused flexible films in electronical products. Furthermore, all of the net additions to stocks in the use phase represent products that are kept in use for longer than a year. The values shown within the processes 'rPE PCR' and 'rPE PIR' represent the amount of rPE left-over supply as a net addition to the stock, which is kept unused.

A first observation that can be made from the representation in Figure 5.2, is that there are quite some losses occurring during collection of flexible film waste. This can either be explained

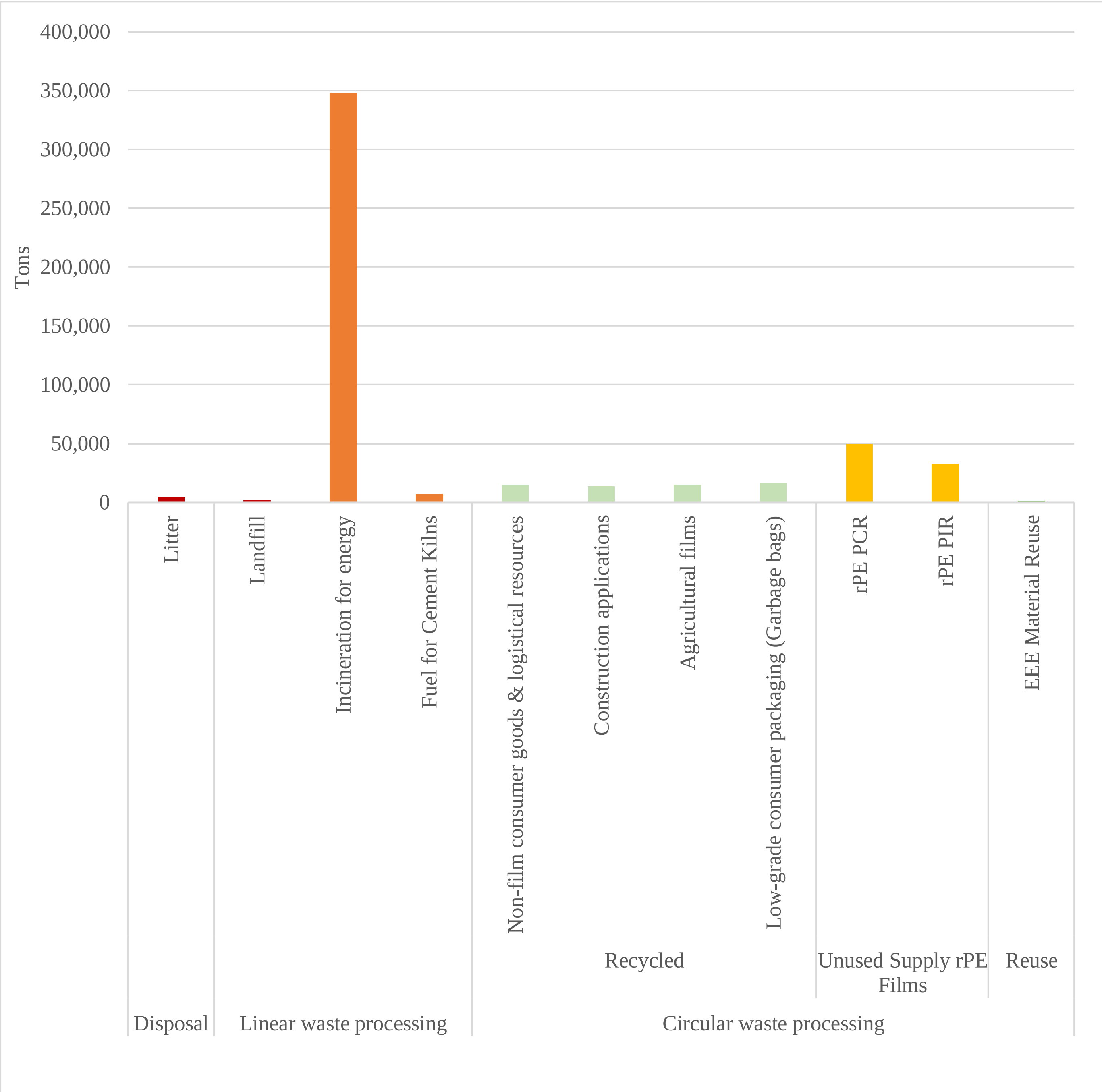

Figure 5.3

Bar chart representing the amount of flexible films processed linearly (incineration for energy, fuel for cement kilns and landfill) and circularly (reused, recycled and unused rPE supply), as well as the amount disposed through litter. Based on the MFA results of the 2020 MFA model.

by poor separation by consumers on the one hand, and underperforming collection systems on the other. Either way, innovation in terms of collection of flexible film waste seems required.

Secondly, the distribution between the share of incinerated and recycled flexible films is focused on (sub-question 2.b). The bar chart displayed in Figure 5.3 visualizes the relative amount of

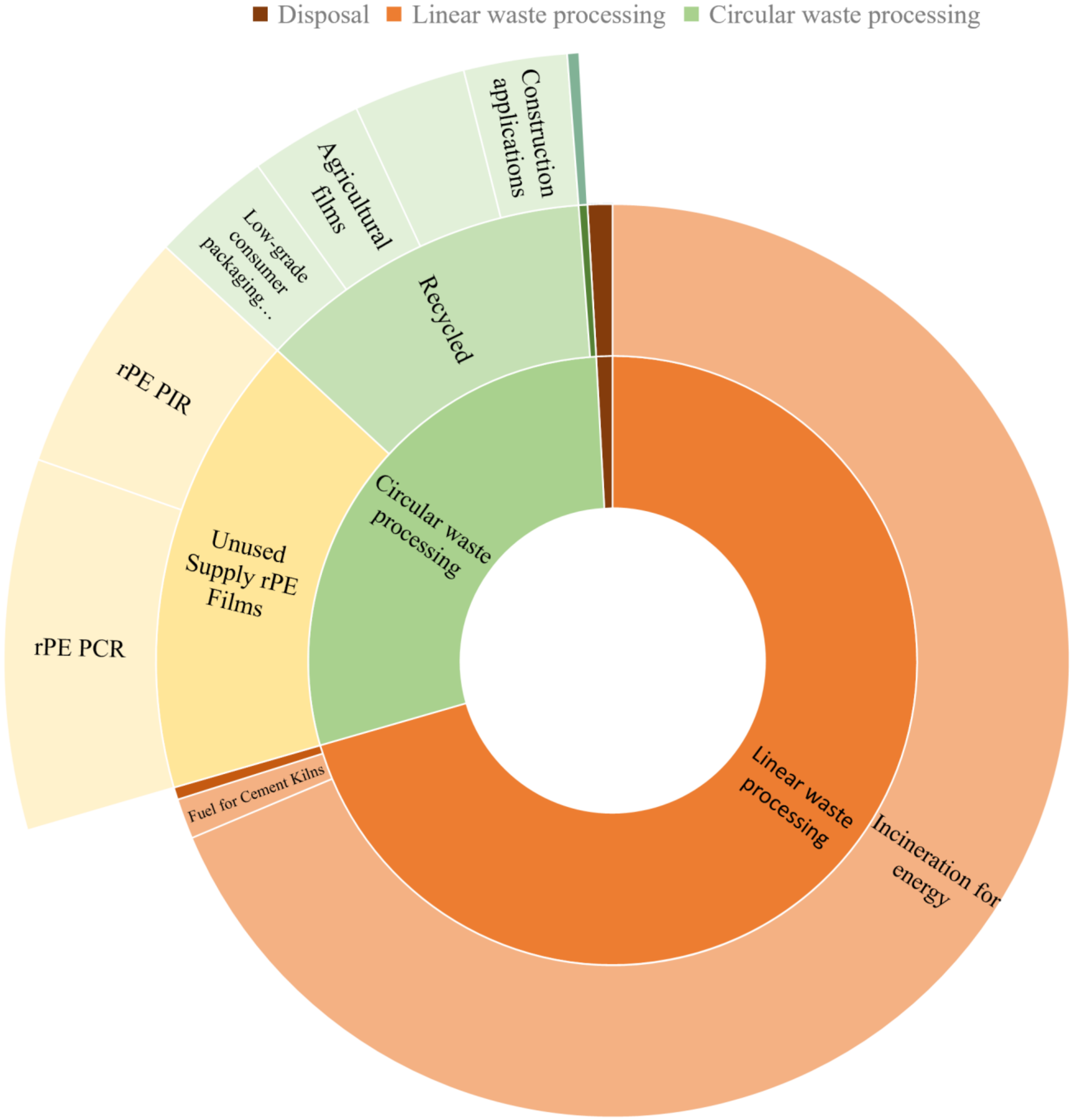

Figure 5.4
Sunburst chart representing hierarchial data of the different destinations of flexible films after one life cycle as concentric rings in a circle.The inner circle describes the way of processing categories films after one life cycle, whereas the middle circle displays the different destinations within these categories. The outer (part of a) circle represents divisions within the broader destinations. The category 'Disposal' and destination 'Litter' are too small to be presented with titles in this sunburst chart, but their proportion can be seen from the associated color in the legenda. Moreover, the darker green proportion under the category 'Circular waste processing' represents the amount being reused in electronic products, but is also too small to be presented with titles.

linearly processed flexible films in relation to disposed and circularly processed plastic waste. As the graph shows, the amount of flexible film that is incinerated exceeds all the amounts of flexible film in other categories altogether. The amount demand of rPE (both PCR and PIR) is approximately 58 kilotons. Figure 5.4 represents the data from figure 5.3 hierarchially as concentric rings in a circle. The categories represent the final destination of flexible films after (first) use.
This sunburst chart visualizes a very small amount of flexible film that is being littered is relatively low, it has a high chance of eventually ending up in waters and the North Sea. The North Sea is already one of the most heavily exploited seas in the world (Wurpel, Van den Akker, Pors & Ten Wolde, 2011). Further research should focus finding out how this amount, ending up in litter in the consumption phase, can be minimized.

More evidently, it becomes clear from the sunburst chart in Figure 5.4, that almost three times as much flexible films are incinerated as is currently reused and reapplied. Nevertheless, more than 80 kilotons rPE could be used under current conditions, but are currently not applied. With innovation and developments in mind, it becomes clear that there are still quite some opportunities for unused, already recycled flexible film content. As stated before the current rPE demand is about 58 kilotons, whereas the total supply (used and unused) is currently around 148 kilotons. This indicates that there currently is a supply-driven market, causing for a higher supply than demand. This manifests itself as a negative business case for rPE recycling, due to a mismatch between the output prices and the actual chain costs to obtain recyclate (Partners for Innovation & Rebel, 2018). Since rPE films from industrial and commercial waste is preferred over postconsumer waste, due to its better quality, the business case for post-consumer rPE films appears to currently be even worse. These analyses thus confirm the surplus in supply relative to demand already mentioned by other sources (Kawecki, Scheeder & Nowack, 2018; Verrips et al, 2017; Simon, 2021; CE Delft, 2019). The net addition to stock of unused recycled flexible film also confirms the images of mountains of unused recycled content, displayed by Gimbrère and van de Keuken (2020). Subsequently, the stock of unused recycled flexible films will only increase if the demand does not increase, which can also cause logistical storage problems in the Netherlands.

Moreover, if the amount of unused supply of rPE films would be applied, the portion that is currently incinerated would still exceed the reapplied content. The table in Appendix A.2 displays proportional division between linearly and circularly processed flexible film content and, subsequently, the proportion incinerated for energy recovery and recycled content being reapplied. These proportions are first expressed relative to the amount of flexible films produced in the Netherlands, as the Court of Audit estimates the incinerated content also against the total annual plastic production (Geurtsen, 2019). This gives proportions of approximately 91% linearly processed content and 38% is circularly processed content. Together, this is more than 100%, as the amount of flexible films imported is not accounted for in the amount produced in the Netherlands, but does end up in the waste processing activities. Therefore, it is assumed that the Court of Audit actually estimates against the total amount of plastic being brought on the Dutch market annually (including import). This calculation provides a distribution of 52% of flexible films being linearly processed and 22% circularly processed. Nonetheless, the percentages for incinerated and actually reapplied and reused content are 51% and 10% respectively. The value for the incinerated proportion is lower than the 60% that the Court of Audit estimated (Geurtsen, 2019), which seems positive. Nonetheless, the actual reapplied flexible film content is also almost twice as low as the estimated 18% for plastic in general by RIVM (2019). It is also lower than the given reapplied rLDPE - a wrongfully used term for rPE films relative to the total LDPE market

(Appendix A.1, section 'Production and manufacturing') - value, which was set at 19% (RIVM, 2019).

Nevertheless, estimating these values relative to the total amount of flexible film brought on the Dutch market can also give a distorted picture, as the amount of flexible films kept in use and littered are included, whilst these flows do not arrive at waste processing activities. Therefore, the linear-circular ratio and incinerated, reused and recycled content is also estimated relative to the total amount of processed flexible film waste. This seems like the fairest manner for calculating these values, as the waste processors cannot process flexible films that do not arrive at their facilities. This proportional division is represented in Figure 5.5.

The stacked bar chart in Figure 5.5 shows that the circularly processed plastic waste currently represents approximately 29%, compared to 71% linearly processed. If the actual reapplied and reused content is focussed on, this is only slightly more than 13%. The share of incinerated plastic waste is approximately 69%. This also reflects a slightly different image than the national reports claim for the incinerated and reapplied and reused content, which were estimated to be 60% and 18% respectively (Geurtsen, 2019; RIVM, 2019). These results show that it matters against what reference the incinerated and reapplied content are relatively estimated for the final results that are obtained.

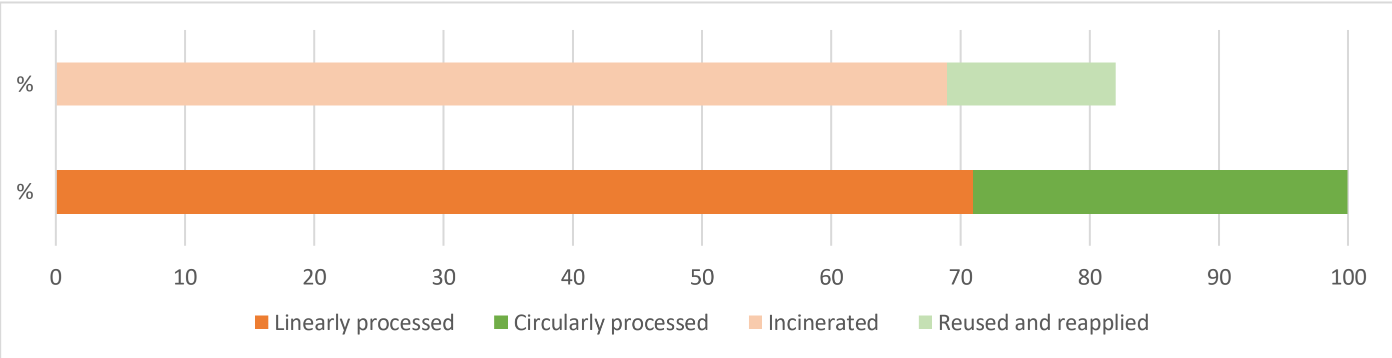

Figure 5.5

Stacked bars displaying the proportional distribution between processing categories for wasted flexible film. The percentages given in the table relate to the share of flexible films that ends up in waste. The values indicate the share that is processed circularly, in proportion to the share that is processed linearly. Furthermore, it is indicated what proportion of the full amount of linearly flexible film is ultimately incinerated and what proportion of circularly processed flexible film is actually reapplied. The shares of incinerated and recycled and reapplied content together do not count up to 100%, in comparison to circularly and linearly processed flexible film waste. This is because linear processing incorporates flexible film that ends up as fuel for cement kilns and, especially, because a significant share of the circularly processed flexible film waste is not actually reapplied in the economy.

In sum, the results indicate that there should be improvements for the recycling industry, especially collection processes. By improving recycling processes, the amount of lost and incinerated flexible films could be reduced. It should, however, be measured what the alternative environmental impact would be of generating energy in another way than from these waste flows when renewable energy generation is not yet the status quo. Moreover, the linear-circular ratio and the incinerated and reapplied quantities as proportions should be estimated relative to the quantities that eventually arrive at the collectors, as this gives the fairest values. Furthermore, it is important to display the actual reapplied content beside the recycled content, since a large part of the recycled content is currently not reapplied in new products.

Even though innovation within the flexible film supply chain is expected, a number of obstacles must also be taken into account. The next chapter dives into the relevant factors influencing the supply chain from a supply chain perspective.

6. Comparative Cognitive Mapping

Based on results from the supply chain analysis, supply chain actors were approached and interviewed. Due to the sensitivity of the subject, the interviewees have been kept anonymous. The intention is for each respondent to represent a (direct or indirect) link in the flexible film supply chain. For the interviewed respondents, abbreviated terms as indicated in Table 6.1 are applied, both for the sake simplicity. These terms are only used in the appendix, with a few exceptions in, for example, figures displayed in the report. Table 6.1 also shows the link in the supply chain represented by each actor and a short description of the entity they represent. Besides the more evident supply chain actors, two respondents represent a knowledge link. These respondents are closely related to the actors in the supply chain, in providing scientific information about the recycling of rPE films.

Table 6.1
Interviewed stakeholders (respondents), their given abbreviation, the links they represent in the flexible film supply chain and a short description of each stakeholder.

Respondent	Representation in the flexible film value chain	Abbreviated term	Description
Waste processor / recycler	Waste processing & Recycling	WREC	This respondent represents two links in the chain and is both the waste processor and the recycler of flexible films. Several waste streams are processed by this entity, but the waste stream mainly discussed is the DKR 310 stream. The product that this actor offers at the end of its processes is PCR rPE films.
Plastic producer	Flexible film producing (Petrochemical industry)	PLPRO	This respondent represents an international virgin plastic producer and therefore the petrochemical industry in the flexible film value chain. They also aim to incorporate 100,000 tons of recycled plastic in the products they commercialize.
Researcher	Research institute (knowledge link)	RES	This respondent is a researcher at one of the technical universities in the Netherlands.
Recycle Researcher	Recycle research institute (knowledge link)	RERES	This respondent is working at a research institute with a focus on improving recycling for other entities.
Packaging producer	Flexible film manufacturing & Wholesale	PAPRO	This respondent is working at an entity in the flexible plastic packaging production industry, which it sells to retailers.
Retailer	Retail	RET	This respondent represents the customer of packaging from the packaging producer. It is the retailer of products, where the flexible packaging is used for, to the end-user.

These constructed cognitive maps of the supply chain actors are analysed to define what the supply chain actors perceive as relevant factors for developing circularity in the supply chain (sub-question 3.a). Furthermore, the analysis can provide insights about conflicting actions and goals between the supply chain actors (sub-question 3.b). This can help to uncover possible unnoticed underlying barriers, but also spaces of opportunity. Lastly, the tool can provide insights into the perceived interdependency between the supply chain actors (sub-question 3.c). With this information, the results contribute to the construction of the current dominant techno-institutional regime in the context of the development of the circular flexible film supply chain (sub-question 3.d).

6.1. Explanation of concepts and figures

6.1.1. Case and arena

The cognitive maps, also called perception graphs, are made and analysed with the DANA tool. In DANA, a problem is modelled as a *case*, which is the highest-level entity. Within a case, each issue is modelled as an arena (DANA, n.d.). Within this study, the case is called ‘Circular Flexible Films’ and there is only one arena: The Dutch flexible film value chain.

6.1.2. Actors, stakeholders and agents

The actors that are defined for a case represent individuals, organizations or other groups. As the name implies, actors can take action. Actors are added to an arena when they are *stakeholders* in the issue addressed in that arena (DANA, n.d.). An actor is a stakeholder when his interests are affected when certain changes occur in the arena, regardless whether these changes occur due to either his own actions, the actions of other actors, or external developments. Not all actors need to be stakeholders: some actors may have the capability to cause changes in an arena but have no stake in the issue. If actors can take action in an arena but are *not* stakeholders, they are called *agents* (DANA, n.d.).

In this study, the respondents represent links in the flexible film supply chain, which aligns with the organisation they work for. All of the interviewed respondents represent actors and stakeholders, in terms of the explanation above. Furthermore, three actors are added that are not interviewed but are mentioned by the respondents. Those actors are the consumer (CON), the central government (GOV) and the municipalities (MUN). In the cognitive maps for each stakeholder, these three added actors can take action that influences the interest of our respondents. Nonetheless, the central government and the municipalities themself do not have an interest that can be affected in this case, which makes them agents for now. This is only the case because these actors could not be interviewed during the timespan of this study, which means their interests considering this subject could not be represented. For further research, interviewing those actors and representing their perspective and interests could be added or combined with the results of this study.

6.1.3. Factors, attributes and actions

In DANA, there are three types of factors: system attributes, actor attributes and actions (DANA, n.d.). The word *system* refers to ‘everything that the analyst considers to be relevant for the case’.

This means that the system actually encompasses arenas, actors and factors. By default, a factor is a *system attribute*, meaning it is a property of the entire system, rather than a property of a specific actor. Factors are represented as oval-shaped boxes in the cognitive diagrams (DANA, n.d.).

An *actor attribute*, on the other hand, describes a factor specifically attributed to a certain stakeholder or actor. For example, the business profit of the packaging producer can increase by certain actions represented in a causal cognitive diagram, which does not mean that the business profit of the entire system or a specific other actor or stakeholder is increasing by these actions. Actor attributes are represented by the (purple coloured) abbreviation of the actor to which the factor is attributed within the oval-shaped box (DANA, n.d.).

The same argument as mentioned for actor attributes also holds for *actions*. Actions are taken by, and therefore attributed to, specific actors. Actions are represented by squared boxes, with the abbreviation of the actor the action is attributed to, stated in purple inside the box (DANA, n.d.).

6.1.4. Actor goals

In perception graphs, a goal associates a utility value with possible changes in a factor. These utility values are defined on a semi-qualitative scale that ranges from a “strong disapproval” via "neutral" to a “strong appreciation” (DANA, n.d.). For this study, only disapproval and appreciation are selected for goals. This is done to avoid misinterpretation of the degree of appreciation or disapproval by the author.

Figure 6.1
Three examples of how goals are displayed in the cognitive maps of the supply chain actors. The goals represent a desired increase (left), an undesired decrease (middle) and a desired decrease (right) of the associated factor (business sustainability of the packaging producer, costumer satisfaction of the packaging producer and environmental impact of products of the retailer, respectively).

The goal on the left in Figure 6.1 represents a goal defined for a factor that should, according to an actor, preferably increase. In this case, the goal is represented in the perception graph of the packaging producer, which wants the business sustainability of the packaging producer to increase. The goal in the middle defines a factor that should not increase, according to the actor. This goal is again, from the perception graph of the packaging producer, which wants the customer satisfaction attributed to the packaging producer to *not* decrease. Lastly, the goal on the right represents that, according to the actor in which the perception diagram is visible, a factor should preferably decrease. In this example, the retailer wants the environmental impact of their own products to decrease.

6.1.5. Causal links

Links in the perception diagrams are represented as arrows between factors. The links are assumed to be causal, meaning that a change in factor A is believed to cause a change in factor B (DANA, n.d.). The type of relationship can be positive, displayed with a + sign, or negative, displayed with a - sign. a Positive relationship described that an increase in factor A causes an increase in factor

B and vice versa. A negative relationship, on the other hand, indicates that an increase in factor A causes a decrease in factor B and vice versa (DANA, n.d.). A *path*, subsequently, represents one or multiple links between factors, leading to a certain factor.

6.1.6. Aggregating and clustering

Many of the analyses that DANA can perform produce interesting results when applied to groups of concepts. DANA therefore allows the analyst to define groups for arenas, factors and actors. This grouping is achieved by defining tags to label concepts. Factor or actor can be labelled with one or several tags. Subsequently, concepts having the same tag(s) constitute a group (DANA, n.d.).

For this analysis, only actor and factor groups are made. The actor groups consist of two groups: (1) the stakeholder group, including the interviewed respondents; and (2) the agent group, involving the influential actors mentioned by the stakeholders. Moreover, several factor groups were made, differentiating the factors under different categories. The first three factor groups include socio-economic, institutional and technical factors. The factors are divided into these three categories on the basis of the author's knowledge of these three interlinked subjects following the desk research done in chapter 2. It should be noted that this can be prone to inaccuracy and, subsequently, reduction of validity. Nevertheless, it was often self-evident under which factor group(s) a factor fell, so any sensitivity to a reduction in validity turned out to be manageable. Furthermore, some factors fall are multifaceted and fall under more than one factor groups. During performing the analysis, two factor groups were added: rPE demand and rPE quality. These factor groups only included their eponymous factors, but were added for doing separate analyses with these factors specifically.

6.2. Results of the comparative cognitive mapping and DANA analyses

The cognitive maps for each of the interviewed stakeholders are given in Appendix B.1. The results are elaborated on, on the basis of the different sub-questions in the following sections. After conducting the interviews, a cognitive map was constructed for each of the respondents. These maps are analysed to define what the supply chain actors perceive as influential factors in the context of recycling flexible films (sub-question 3.a). Furthermore, the analysis can provide insights about conflicting actions and goals between the supply chain actors (sub-question 3.b). This can help to uncover possible unnoticed underlying barriers, but also spaces of opportunity. Lastly, the tool can provide insights into the perceived interdependency between the supply chain actors (sub-question 3.c). With this information, the results contribute to the construction of the current dominant techno-institutional regime in the context of the development of the circular flexible film supply chain (sub-question 3.d).

6.2.1. Relevant factors for circularity in the flexible film supply chain

First, sub-question 3.a is dived into. This sub-question states the following:

What do the supply chain actors perceive as the most relevant factors in achieving circularity within the flexible film supply chain?

This means the focus is on discovering the relevant factors in the context of recycling flexible films, as perceived by the supply chain actors. The relevance is discovered on the basis of relevance and centrality and connectivity analysis. Subsequently, the influence of different factors on each other is elaborated on.

6.2.1.1. Relevance, connectivity and centrality

Relevance is measured by the number of occurrences of a factor within the different cognitive map and, subsequently, by dividing the occurrence by the total amount of actors. A table mentioning all the mentioned factors and their relevance is given in Appendix B.2. From this analysis, it becomes clear that ‘rPE demand’ is the most relevant factor, occurring six times, which means it was mentioned in every cognitive map. This means it has a relevance of 100%. Other relevant factors, with five occurrences and a relevance of 83%, are (1) the quality of rPE, (2) the bad smell of rPE and (3) the efficiency of PCR mechanical recycling. Moreover, two relevant actions, which are also considered as factors, are (1) ‘the investing in improvements for quality of rPE by the waste processor / recycler’ and (2) ‘the transferring of the EU plastic tax on to the packaging producers by the government’, both with five occurrences and a relevance of 83% as well.

Furthermore, factor connectivity is measured as the number of causal links that connect to a factor divided by the number of actors. Factor centrality, on the other hand, is measured as the number of paths on which a factor occurs, divided by the number of actors. The table in Appendix B.2. represents the results of the connectivity and centrality analysis. The results show that ‘Quality of rPE, again shows to be a relevant factor, by being the most central and connected factor of all. In the second place comes rPE demand, which again, shows to be a relevant factor. As stated before, the factors are categorized under socio-economic, institutional and technical. The relevance of these aggregated factor groups is given in Table 6.2. From this table, it becomes clear that socio-economic and technical factors occur almost three times as much as institutional factors. This makes for these categories to display a higher centrality and connectivity than institutional factors.

Table 6.2
Relevance table, displaying the relevance, connectivity and centrality of the aggregated socio-economic, institutional and technical factors mentioned by the supply chain actors. The higher the value displayed, the more relevant, connected or central the aggregated factor group is.

Factors	Relevance	Connectivity	Centrality
	# Occurrences	μ Links / actor	μ Paths / actor
socio-Economic	60	23	160
Institutional	21	5.2	25
Technical	62	24	154

6.2.1.2. Influence between different factors

Next, it is interesting to focus on the perceived causal relationships between factors, according to the supply chain actors. Figure 6.2 displays the similarity of perceived causality. The graph in this figure indicates how much of the perception of the actor where an arrow starts, is shared by the perception of the actor where the arrow points to, in terms of path similarity. The thicker the arrow, the higher the path similarity between actors. Even though some arrows involving the plastic producer are represented very thin or even dashed, this does not necessarily mean that the similarity between the plastic producer and another actor in perceived causal relationships is low. Rather, this indicates that the shared factors between the plastic producer and other actors is low. The table in Appendix B.3. represents this more elaborately. It shows that, quite often, the percentage of shared factors between actors is low and never higher than 53%. Nonetheless, the percentage perceived path similarity is never lower than 73%. This indicates that the actors most often agree about the relationships between factors.

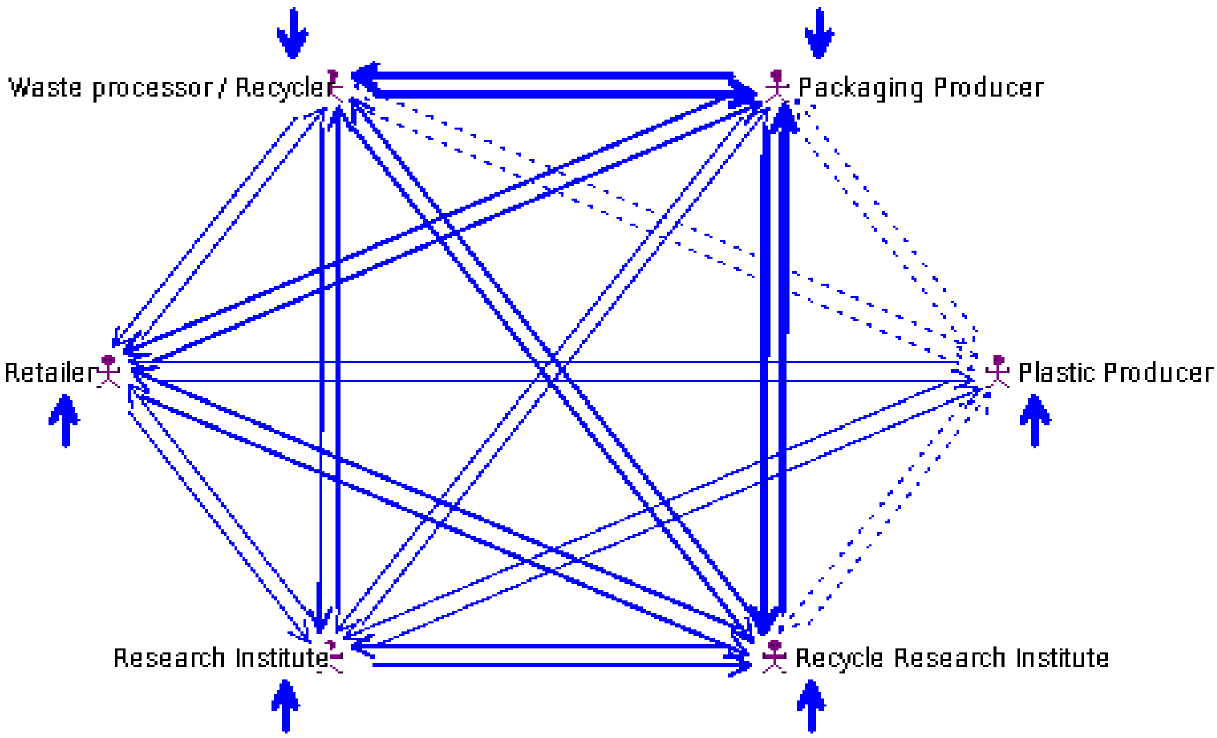

Figure 6.2
Graph displaying the similarity of perceived causality between the different actors.
The arrows display the percentage of path similarity, where the thickness of the line relatively present how much of A's (actor where the arrow starts) perception is shared by B (actor where the arrow points to).

On the basis of the displayed relevance, connectivity and centrality of the factors 'rPE demand' and 'rPE quality', the influence of the socio-economic, institutional and technical factor groups on these factors is analysed. Results are shown in Figure 6.3. The figure displays the causal influence that can be inferred from the links in the perception graphs. The causal influences are the averaged influence perceived by the different stakeholders. It becomes clear that institutional factors are perceived to have the highest influence on the two most relevant factors. In contrast to what the relevance table for the different factor groups (Table 6.2) displays, this analysis displays that the indirect influence of institutional factors is the highest, compared to socio-economic and technical

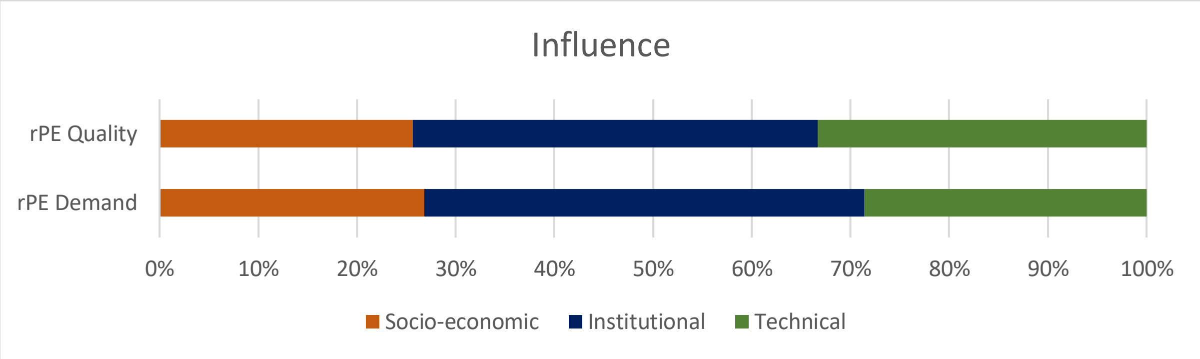

Figure 6.3
Stacked bars displaying the perceived proportional causal influence of the socio-economic, institutional and technical factor groups on the two most relevant factors: rPE demand and rPE quality.

factors. This means that, even though the occurrence of institutional factors is lower than the occurrence of socio-economic and technical factors, institutional factors still have a higher influence on the two most crucial factors: rPE demand and rPE quality.

It is striking to see that in the first instance the discussion is mainly about technical and socio-economic factors, based on the occurrence of these factors, but institutional factors subsequently have a large indirect influence. This provides food for thought for public and scientific debate, as technical and socio-economic factors are also often presented as relevant here. The discussion may be taking place in the socio-economic and technical fields, because the institutional factors could seem intangible. An explanation for this may be that the average consumer, producer, waste processor and recycler may feel that they have no real influence on governmental institutions and policies, and for this reason do not mention them prominently in the discussion.

6.2.2. Conflicting actions and goals between supply chain actors

Secondly, sub-question 3.b is focused on, which states:

Are there areas of conflict or disagreement between the main supply chain actors? If so, what are they?

This sub-question is focused on conflicting goals and actions between the supply chain actors. The conflict table in Appendix B.4. displays that there are no goal conflicts between the actors. This indicates that there are no opposite desired goals between the different actors. Nonetheless, some action conflicts occur, which is visualized in Figure 6.4. An action conflict displays the difference in expected utility, summed over a full action range, between two actors.
As can be seen from the graph in Figure 6.4, most action conflicts occur between the plastic producer and other actors. Mostly, this has to do with the difference in perceived causal influence of the possible action of the government to transfer the EU plastic tax on to the packaging producers. Mostly, they perceive this action to have a likewise effect, only the path towards this effect is a perceived a little different between the actors. For example, the plastic producer expects

this plastic tax to cause a higher rPE demand, but simultaneously encourage companies to use other materials than plastic. Such differences for the most part explain the action conflict displayed.

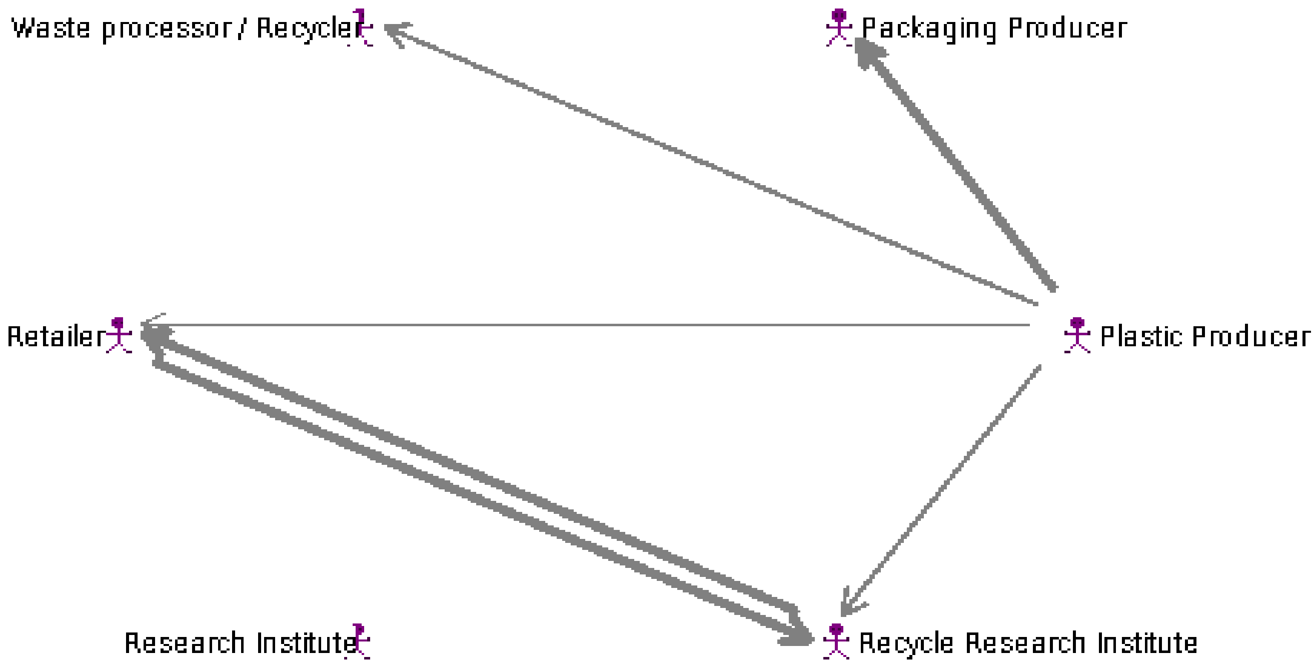

Figure 6.4
Conflict graph displaying the action conflicts in expected utility between the supply chain actors.
The arrows display the percentage of conflict, where the thickness of the line relatively present how much of B's (actor where the arrow points to) ideas oppose A's (actor where the arrow starts) ideas.

Furthermore, an action conflict occurs between the recycling research institute representative and the retailer. This conflict is about the difference in perceived influence of the action of the government to enter a differentiated rate for properly recyclable flexible films. The retailer sees this action as a stimulus for the recycling chain, subsequently resulting in more efficiency, more supply and more use of rPE films. The representative from the research institute, on the other hand, thinks this action invites to use more virgin plastic, because it is more recyclable and therefore making companies eligible for this differentiated rate. Other than the beforementioned conflicts, no conflicts occur between the different actors. Moreover, the action conflicts that occur are not very weighty and often do not reflect an opposing view of causality. Therefore, it seems like no relevant conflicting views or actions are displayed by the supply chain actors, which makes collaboration in developing circularity a more achievable task.

6.2.3. Perceived interdependency between supply chain actors and of relevant agents

Thirdly, the focus is on the sub-question 3.c.:

How do the supply chain actors perceive their interdependency throughout the supply chain in achieving circularity?

A resource dependency analysis is conducted to answer this question. Resource dependency is, in this case, measured by relevant actions from one actor for another. In this analysis, beside the stakeholder group, the agent group (GOV, CON and MUN) is involved as well. The resource dependency table is stated in Appendix B.5. The graph in figure 6.5 displays the resource dependency between the different actors, on the basis of relevant actions. The graph shows that the supply chain actors state, in the context of achieving circularity within the supply chain, to be most dependent on actions taken by the government. This aligns with the perceived influence of institutional factors from the influence analysis. Moreover, the consumer seems to have a relative amount of relevant actions in achieving circularity. Nonetheless, this graph does not display the relevant actions of the actors for themselves, as this would not indicate resource dependency.

Beside the agents' relevant actions, two supply chain actors seem to be able to perform relevant actions in the context of achieving circularity, according to the other actors. The waste processor / recycler could invest in improvements for the quality of rPE, according to most other supply chain actors. In contrast, the retailer could perform some relevant actions in this context, according to the waste processor / recycler . processor and the respondent from the recycling research institute by lowering the quality standards required for their products involving flexible film. These are two actions that would be recommended to be taken by both the waste processor and the retailer, as it could set development towards more circularity in the supply chain motion, according to the supply chain actors.

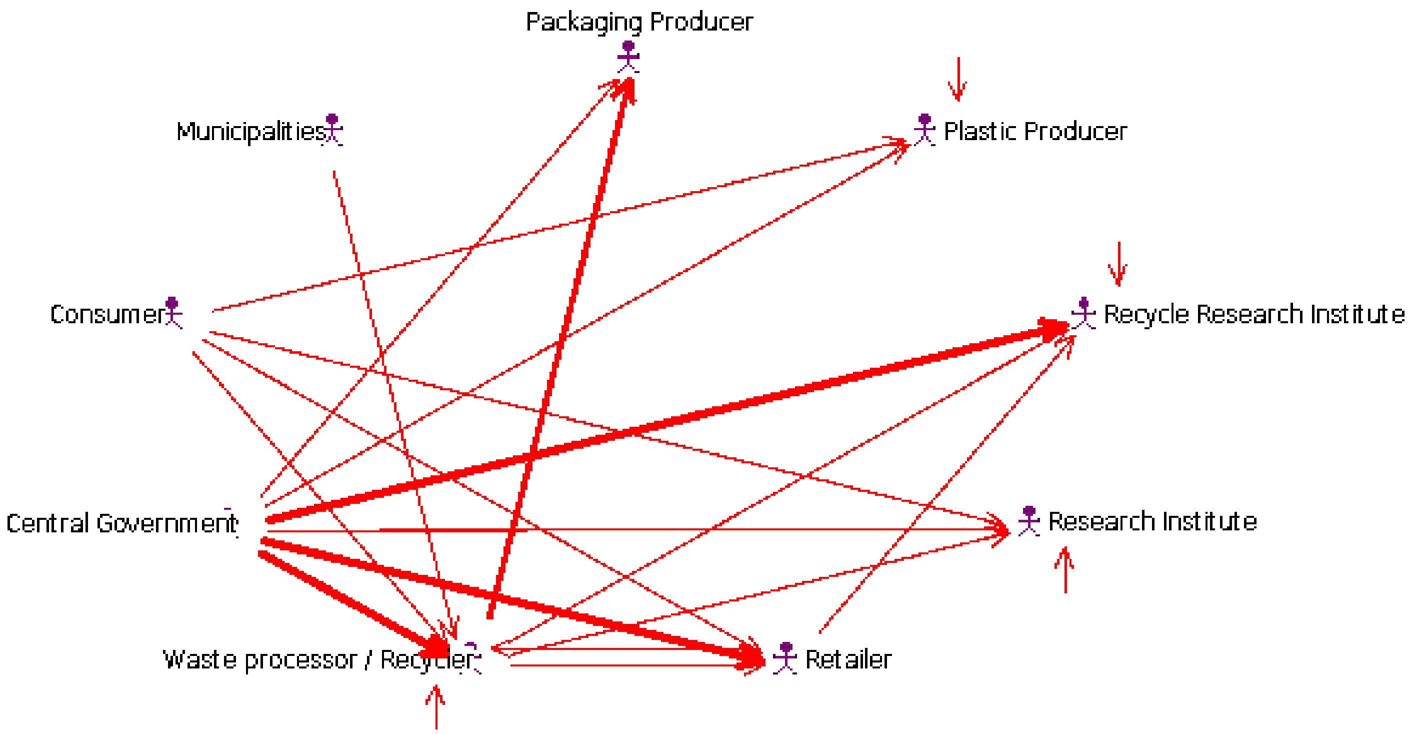

Figure 6.5
Resource dependency graph displaying the relevant action between the supply chain actors.
The arrows display the relevant action, where the thickness of the line relatively present how strongly A's (actor where the arrow starts) actions can effect B's (actor where the arrow points) ideas on achieving circularity within the supply chain.

6.2.4. Techno-institutional regime of the Dutch flexible film supply chain

Lastly, sub-question 3.d is focused on. This question entails:

What does the current techno-institutional regime involving the flexible film supply chain look like from a systems perspective?

The answer to this question summarizes the CCS results and the previous desk research done for defining the research problem in chapter 2, and combines it with the theory about techno-institutional lock-in (Könnölä, Unruh & Carrillo-Hermosilla, 2006; Foxon, 2003). A visual representation of the constructed current techno-institutional regime is presented in Figure 6.6. There is no definite start in this visual, since it involves some reinforcing loops. Nevertheless, the image is explained through starting from the socio-economic system (on the right side of the image).

The inconvenient socio-economic factors result in a low demand for PCR rPE films, subsequently reinforcing the socio-economic status quo through a relative increased virgin film demand and supply. One of the main reasons for this low demand for PCR rPE films is the low quality of the product, compared to its virgin competitor. Nevertheless, the current market conditions provide an unprofitable business case for making investments for increasing the quality of PCR rPE films. This subsequently leads to further scaling up of the technological infrastructure surrounding virgin plastics within the current technological system. As a result, no further investment is made in design-for-recycling and other quality improvement, which in itself also worsens the demand for recycled films. This creates a reinforcing loop between the technological and socio-economic system, as well as reinforcing loops within both of these systems.

Moreover, the current results seem to indicate that the strict regulations surrounding the recycling of rPE films and the marketing of this product, enforce the continuation of the reinforcing loops between the technological and socio-economic system. Because there are currently little financial policy incentives for improving the quality and market position of PCR rPE films, this loop between the technological and the socio-economic system continues to exist. However, the reason for some of these strict regulations is found in the low quality of rPE films, which is precisely caused by the lack of policy incentives for improvement. As a result, the crux of the problem seems to mainly take place in the institutional system, which is also the only system without a self-reinforcing loop. This means that the first changes will have to take place in the institutional system to prevent the flexible film supply chain from entering a techno-institutional lock. This should, subsequently, lead to the breaking down of reinforcing loops in the technological and socio-economic system. In this way, the rigid structures of the current techno-institutional regime can be interrupted, stimulating development of a circular supply chain can be stimulated.

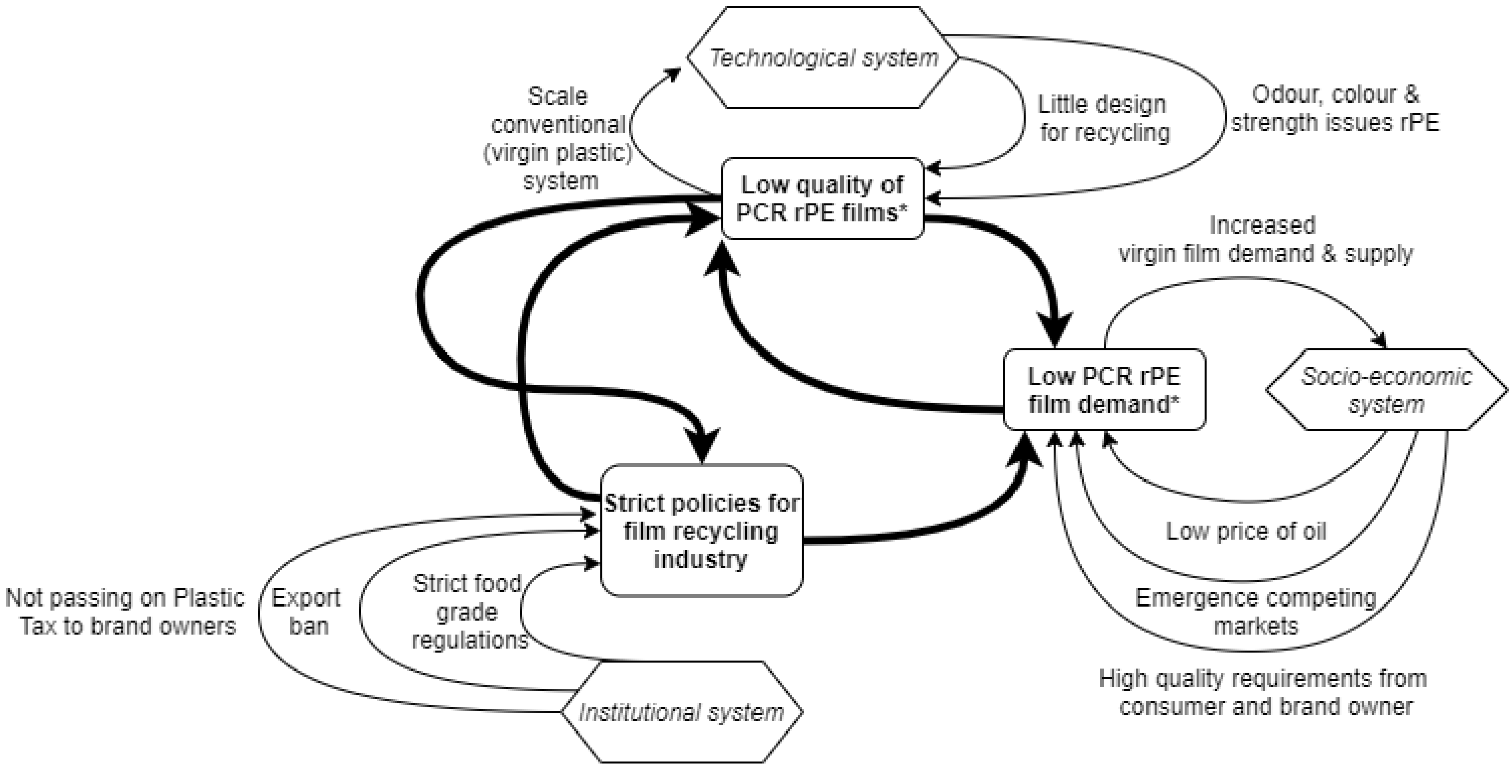

Figure 6.6
Visual representation of the current techno-institutional regime involving the flexible film supply chain. The figure displays the technological, socio-economic and institutional structures influencing the flexible film supply chain. Some reinforcing loops are present within the technological and socio-economic system.. Furthermore, there are some reinforcing loops present between the different systems. These reinforcing structures consolidate current practices and might hinder development towards circularity.

The schematic visualization in Figure 6.6 displays a very abstract explanation of the current institutional, technological and socio-economic structures in the context of the flexible film supply chain. In order to get a more practical insight into the development of these structures and their underlying factors, a dynamic model is constructed in the following chapter. In this way, a more practical view can be formed and it is possible to estimate how the different factors associated to the underlying structures develop over coming years. This can give insight to where improvement is required in the future.

7. Dynamic Modelling

7.1. Goal and system definition

The goal of this analysis is to discover the development of circularity within the flexible film supply chain towards 2025 (sub-question 4.b). To do this, the trends in development and influence of relevant factors, associated to the flexible film supply chain, until 2025 (sub-question 4.a) need to be explored first. Therefore, the first step is to define trends for the relevant factors that resulted from the CCM analysis. Subsequently, a model is simulated, estimating the development of the flexible film supply chain towards 2025. The MFA results showed that the surplus of supply relative to rPE demand seemed crucially disadvantageous for the development of more circularity. Moreover, the CCM results also indicated rPE demand to be one of the most relevant factors. Therefore, this dynamic modelling analysis is mainly focused on the influence of the relevant factors on rPE demand and supply, to determine if the business case for rPE mechanical recycling within this supply chain is remunerative in the coming years. Moreover, the main focus is on PCR rPE in this context, as many companies already recycle their own stream of post-industrial waste (PIR), which means that this material is not available on the free market (KIVO, n.d.a).

In order to determine the development of the different factors influencing the supply chain, several themes are set out. These themes are (1) Trend waste production, (2) Trend rPE market, (3) Competing and complement markets, (4) Policy development and legislation and (5) Technical components. The themes and included factors are given and displayed in Table 7.1. The first theme is involved with internal factors (within the supply chain) and the second till fifth theme focuses on external factors. Two main scenarios are developed: a low and a high scenario. One internal factor showed to be significantly influential: the Plastic Pact. This target describes a relative decrease in relation to the total volume of products on the market (less plastic packaging per volume of product). It applies to the volume of plastic that is placed on the market by the signatories of the Plastic Pact, which is 20% of the market in the Netherlands. This factor will be applied in the same way as done by Kerstens and Blanksma (2019), by annually decreasing the total volume of flexible films on the Dutch market towards a decrease of 20% in 2025. Quite some factors are related to the total amount of flexible films on the Dutch market. For example, the factor concerned with the recycled content target is compared to the total amount of plastic on the market per type of plastic. Due to the high influence of the Plastic Pact as a factor, a separate high and low scenario are created. Therefore, the results are presented for a high scenario, a low scenario, a high scenario including plastic pact and low scenario including plastic pact scenario. This seems like the best way to incorporate this factor, since the plastic pact is not an enforceable agreement and might as well not be complied with (Kerstens & Blanksma, 2019).

The *system* of the dynamic model comprises a set of flows, stocks and processes within a defined boundary, just as for the static model (Brunner & Rechberger, 2016). The system for the dynamic model is defined the same as for the static MFA model, which means the system boundaries are again defined by the national Dutch boundaries. The same processes as for the static MFA model are included within the system boundaries. Only imports and exports of flexible films exceed this border.

Table 7.1
Themes applied for the dynamic modelling, with their associated factors influencing the flexible film supply chain.

	Themes	Factors
1	Trend waste production	Volume flexible film market
		Volume and efficiency collection via source separation and deposit
		Volume and efficiency post-separation
		Volume and efficiency sorting
		Volume and efficiency of recycling
2	Trend rPE Market	Price of oil
		Retailer and Consumer Behaviour
3	Competing & Complement Markets	Chemical recycling
		Biobased
4	Policy development and legislation	Recycled content targets
		Differentiated rate of waste fund packaging
		Single-use plastic ban
		EU plastic tax
		Food grade
5	Technical components	Grain quality Improvements
		Design-for-recycling

7.2. Inventory and Modelling

7.2.1. Inventory

First, desk research is done to uncover trends for and relationships between relevant factors for the flexible film supply chain. Therefore, this section already provides an answer for sub-question 4.a, as it represents the estimated trends for the development of the relevant factors, associated to the flexible film supply chain, up until 2025.

7.2.1.1. Internal Factors

For the internal factors, involving the trend of waste production, some calculated factors are applied, given by a research carried out by Rebel, on behalf of the Ministry of Infrastructure and Water Management (Kerstens & Blanksma, 2019). This considers the volumes of plastic waste per collection route (source separation, or post-separation) in the various steps of the chain (collection, subsequent separation, sorting, recycling). If a range was given, the average value was taken for that factor. For example, the given efficiency of source separation of household waste for the low scenario is 71% to 75% (Kerstens & Blanksma, 2019). For this study, 73% is then taken for this factor.

The factors from Kerstens and Blanksma (2019) are applied on the flexible film supply chain for this analysis. There are five factors that influence the supply side of rPE. These are given in Table 7.2, including their expected value or efficiency for the low and high scenario in 2025. Sometimes, an (annual) increase is given. If this is not the case and a rigid value is given only for the expectation for 2025, the growth rate is calculated on the basis of the annual growth rate formula (section 3.3.5.).

Table 7.2
Theme 1: Expected trend for each factor associated to the trend of waste production. An arrow pointing upwards indicates an increase and an arrow pointing downwards indicates a decrease. When no arrow is given, this indicates a fixed number in 2025 which is assumed to develop exponentially over the years.

Theme	**Factor**	**Trend Expectation (↑ = increase, ↓ = decrease)**		**Explanation**
Theme 1: Trend Waste production		**Low scenario**	**High scenario**	
Volume flexible film Market	Autonomous growth PE market	1.8% ↑ annually	↑ 1.8% annually	Based on the monitoring of the Packaging Waste Fund, a growth in the volume of plastic packaging between 2013 and 2017 on the Dutch market of 1.8% on average is visible.
Efficiency collection via source separation	Efficiency of source separation of household waste	73% in 2025	76% in 2025	The increase in efficiency is assumed because a number of large municipalities with many high-rise buildings and a relatively low source separation efficiency will opt for post separation in the future.
	Increase of separate source collection efficiency of commercial waste	3% ↑ towards 2025	6% ↑ towards 2025	The given values are increases compared to 2017, where the efficiency was 57%. This is assumed to be commercial, since losses from industrial processes are assumed to be collected and sorted with 100% efficiency, as in the MFA.
Volume and efficiency post-separation	Increase of commercial waste going to post-separation	25 kilotons in 2025	31.5 in 2025	As of 2023, the producer responsibility will be extended to industrial waste. The assumption is that, as a result of this measure, some of the plastic packaging waste in industrial waste (which is now incinerated) will be collected through post-separation of residual industrial/commercial waste in 2025.
	Optimization return post-separation	45% post-separation efficiency in 2025	55% post-separation efficiency in 2025	Certain partial flows, including foils, are released directly in some post-separation installations during post-separation and in other installations after the sorting step. For that reason, a combined return of post-separation and sorting is applied here.
Volume and efficiency sorting	Sorting efficiency of source separated consumer waste	72.5% in 2025	77.5% in 2025	This assumption is based on new agreements in 2020, describing more central control over sorting, whereby the DKR specifications are not by definition the starting point.[5] Because the combined post-separation and sorting efficiency is already mentioned above, this sorting efficiency is assumed for source separated plastic waste to be correctly sorted (to DKR310). This increase in sorting efficiency is not considered for beverage cartons in the low scenario, as the sorting efficiency for these is already higher than 72.%, namely 73%. For the high scenario, an increase in sorting efficiency for beverage cartons is considered.

[5] From 2020, new agreements have been made between the packaging industry and municipalities about the direction of collection, sorting and marketing in the Framework Agreement on Packaging 2013-2022. These agreements imply more central control over sorting, whereby the DKR specifications are not by definition the starting point. This central control of sorting, in combination with the increase in more recyclable and sortable packaging, is expected to lead to an increased sorting efficiency of plastic packaging waste in 2025 (Kerstens & Blanksma, 2019).

Volume and Efficiency of recycling	Recycling efficiency of household waste and of the post-separated commercial waste	62.5% in 2025	67.5% in 2025	For the low scenario, the assumption is that the recycling yield remains within the bandwidth of the WUR (57-65%), but that bandwidth becomes slightly smaller in a positive direction. In addition, the expectation is that more recyclable packaging will increase towards 2025. Partly for this reason, a slightly higher bandwidth has been assumed in the high scenario. For the recycling efficiency of post-separated commercial waste, the starting efficiency in 2020 is assumed to be the same as for household waste (61%), since post-separated commercial waste was not yet accounted for in the MFA 2020 model for commercial waste.

7.2.1.2. External Factors

For the external factors, extensive desk research is done. Table 7.3 displays the expected trend for the different scenarios and the effect in has on the supply chain. An extensive elaboration, estimations and calculations done for achieving the given values for trends and effects, is given in Appendix C.1.

Table 7.3
The expected trend for each factor and their relationship with the flexible film supply chain.

Theme	**Factor**	**Trend Expectation (↑ = increase, ↓ = decrease)**		**Relationship in supply chain**	**Explanation**
		Low scenario	**High scenario**	**+ = positive - = negative**	
Theme 2: Market trends rPE	Price of oil	↓ 2.02% annually	↑ 1.87% annually	+0.18% rPE demand per % price increase oil	Due to the increasing demand for renewables, the oil price is expected to decrease in the low scenario. Therefore, the price of virgin plastic is also expected to decrease, negatively influencing rPE demand. Nevertheless, geopolitical tensions could also rise, ultimately leading to a high price of oil and, thus, plastic from oil. Therefore, rPE demand is affected positively in the high scenario. Furthermore, the relationship between rPE demand and oil prices is based on the relationship between WTI and PPI.
	Retailer and Consumer behaviour	↑ 4.40% annually	↑ 4.40% annually	+ directly to rPE demand	There is more societal pressure visible influencing retailer and costumer requirements, according to the respondents. More sustainable consumer behaviour is, for example, visible in the food sector. The same positive trend is assumed for both the high and low scenario.
Theme 3: Competing and comple-	Bioplastic Biobased Market	16.2% ↑ annually	20% ↑ annually	-0.06% rPE demand per % increase of biobased market	Bioplastic demand is expected to increase in the coming years, negatively influencing rPE demand.

menting markets		Biodegra-dable	11.82% ↑ annually	20% ↑ annually	-0.43% rPE demand per % increase of biodegradable market	Biodegradable plastic is currently disruptive for the recycling chain and the demand is expected to increase in the coming years, negatively influencing rPE demand.
	Chemical recycling		↑ 1.0% annually (of production chemically recycled)	↑ 0.4% annually	- (direct) of off PCR rPE demand	This industry is currently in development, and it will not represent a big competitor on the market for rPE in 2025. In 2030, it might result to be a big competitor. Nonetheless, for experimenting, chemical recycling will provide a competitor to mechanical recycling. More specifically, it will compete with post-consumer and post-commercial waste streams, as the post-industrial waste streams are too clean.
Theme 4: Policy develop-ment and legislation	Differentiated rate of waste		-	-	No direct effect*	Since most stakeholders agree that this rather affects the design of products and packaging, it is accounted for with the factor 'Design for recycling'.
	Single-use plastic ban		-	-	No effect	This directive is on the planning, but apparently does not influence flexible films in general.
	EU plastic tax		-	↑ 8.21% annually	+0.2% rPE demand per % price increase	This regulation is already present, but is currently taken care of by the central government. This is kept the same in the low scenario. In the high scenario, it is expected to be transferred to the producer, according to the polluter pays principle.
	Recycled content target		↑ The percentage recycled content increases by 10.2% annually	↑ The percentage recycled content increases by 16.73% annually	+ directly added to recycled content percentage increase	In both scenarios, this regulation is assumed to be implemented and reenforced, with a gradual effect. In the high scenario 16.73% is annually added to the 9.5% recycled content on the total flexible films market. In the low scenario, only 8.997% is annually added to the 13% recycled content target.
	Extension food grade regulation		-	↑ + 3.1% annually of demand for PCR rPE in high consumer product market segment	+ directly to rPE high consumer product demand	Roughly two-thirds of the packaging comes into direct contact with food. For the high scenario, it is therefore assumed that 33% of the consumer packaging market becomes available for PCR rPE films, linearly over the coming 5 years. It is assumed that only 50% of this market will adapt PCR rPE in their packaging.
Theme 5: Technical compo-nents	Grain quality improvements	Odour Colours Strength	-	rPE sufficient for application in high consumer products market segment in 2021.	indirect effect* through 'Extension food grade regulation'	From the interviews and desk research it seems that, with the right choice and amounts of additives, these quality factors should be improved well enough for application in the high consumer product market segment. Nonetheless, in the low scenario, we do not expect the food regulation to be extended. Therefore, in the low scenario, no effect on is assumed, as an improvement in

				quality is not required for the lower segment markets.
Design-for-recycling	↑ 26% annually	↑ 44% annually	+0.07% overall recycling efficiency per % increase designed for recycling	The trend of using less unsustainable multi-material packaging is visible from the collected waste. This affects the net recycling rate of flexible film waste. Efficiency of sorting and recycling processes is increased by 0.07% per increase in flexible film products designed for recycling.

*Combined effect with 'Design-for-recycling'
**Combined effect with 'Extension food grade regulation'

7.2.2. Modelling

The basic structure of the dynamic model is built on the basis of the 2020 MFA static model. If not indicated otherwise in the previous section, distributions of flows are assumed to continue in the same as in the 2020 MFA model. Moreover, equations are inserted behind each factor within the model in order to make it run. As it is an extensive model, only the relevant equations that differ from the balances and distributions of the MFA 2020 model, are given in Appendix C.2.

7.3. Interpretation: results of dynamic modelling

The dynamic modelling, in combination with desk research, is performed for providing answers to sub-question 4.a and 4.b.:

a. What are the estimated developments for and relationships between the relevant factors, associated with the flexible film supply chain, up until 2025?
b. How will these developments influence the circularity of the flexible film supply chain?

The first question of those sub-questions is already answered by means of desk research in the inventory analysis. This mainly provides a setup for answering sub-question 4.a, about the development of circularity within the flexible film supply chain. The MFA and CCM results showed that rPE demand seemed crucial for the development of circularity within the flexible film supply chain. Therefore, the focus is mainly on the development of rPE demand and supply in the this analysis. Figure 7.1 displays the results for the PCR rPE demand factor, involving both post-consumer and post-commercial rPE, in the dynamic model. The graph shows that, for each scenario, rPE demand increases towards 2025. This growth seems significant for the high scenarios, but also the low scenarios show some relevant growth. Nonetheless, whether this increase has a positive influence on circularity within the supply chain, depends on the supply side of rPE film recycling as well. Figure 7.2 therefore displays PCR rPE supply over the coming years and compares this to PCR rPE demand. The actual values behind this graph are displayed in the result table in Appendix C.3.The graph shows demand and supply next to each other for each scenario on

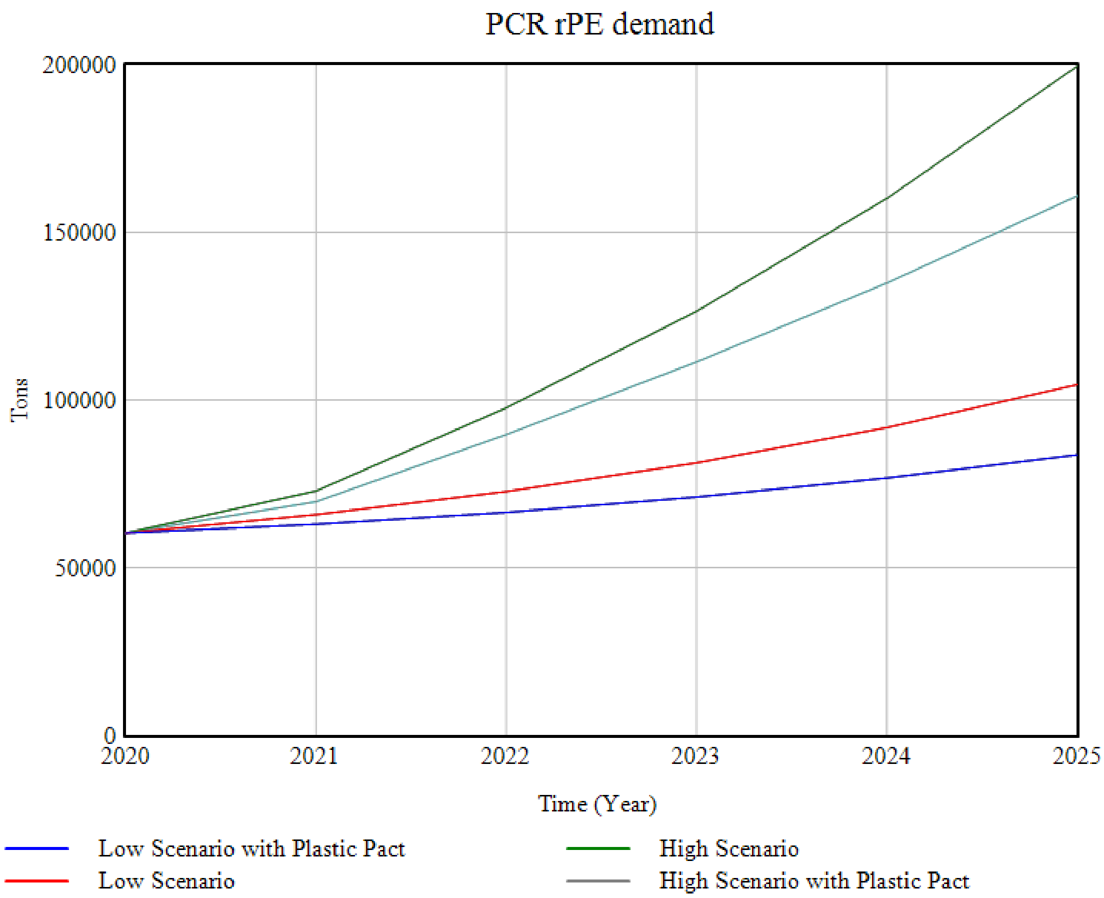

Figure 7.1
Line graph displaying dynamic modelling results for the simulated recycled flexible film demand (PCR). The graph displays the development of post-consumer and post-commercial recycled flexible film demand for the different scenarios from 2020 up until 2025.

X-axis and the values for supply and demand in tons on the Y-axis. The year is presented by the colours of the bars and on the Z-axis on the chart. The bars on the chart visualize if supply is still greater than demand, as is the case in the 2020 MFA model, or whether demand exceeds supply in the coming years. The results in the graph show that only in the high scenarios, demand exceeds supply eventually in 2024 and 2025, which might result in a positive business case for the PCR rPE recycle chain. A positive business case can be crucial for the necessary developments towards a circular supply chain for flexible films, as it stimulates waste processors and recyclers to invest in this. The low scenarios, on the other hand, do not seem to indicate a positive business case for the recycle chain, because rPE demand does not exceed supply in these scenarios in the coming years.

In addition, an eventual decrease in the left-over rPE supply stockpile is only visible within the high scenarios. This is displayed by the graph in Figure 7.3. The decrease in the stockpile in the high scenarios, starting around 2024, can be explained by the fact demand exceeds supply in these scenarios. This cause supply to be taken from the left-over stocks to meet demand. This accumulating stockpile could have logistical storage complications as a consequence. Subsequently, the table in Appendix C.4 displays the linearly processed, circularly processed, incinerated and reapplied and reused proportion relative to 3 references. The proportions are shown are relative to (1) the flexible films produced in the Netherlands, (2) the total amount of flexible films on the Dutch market and (3) the total amount of processed flexible film

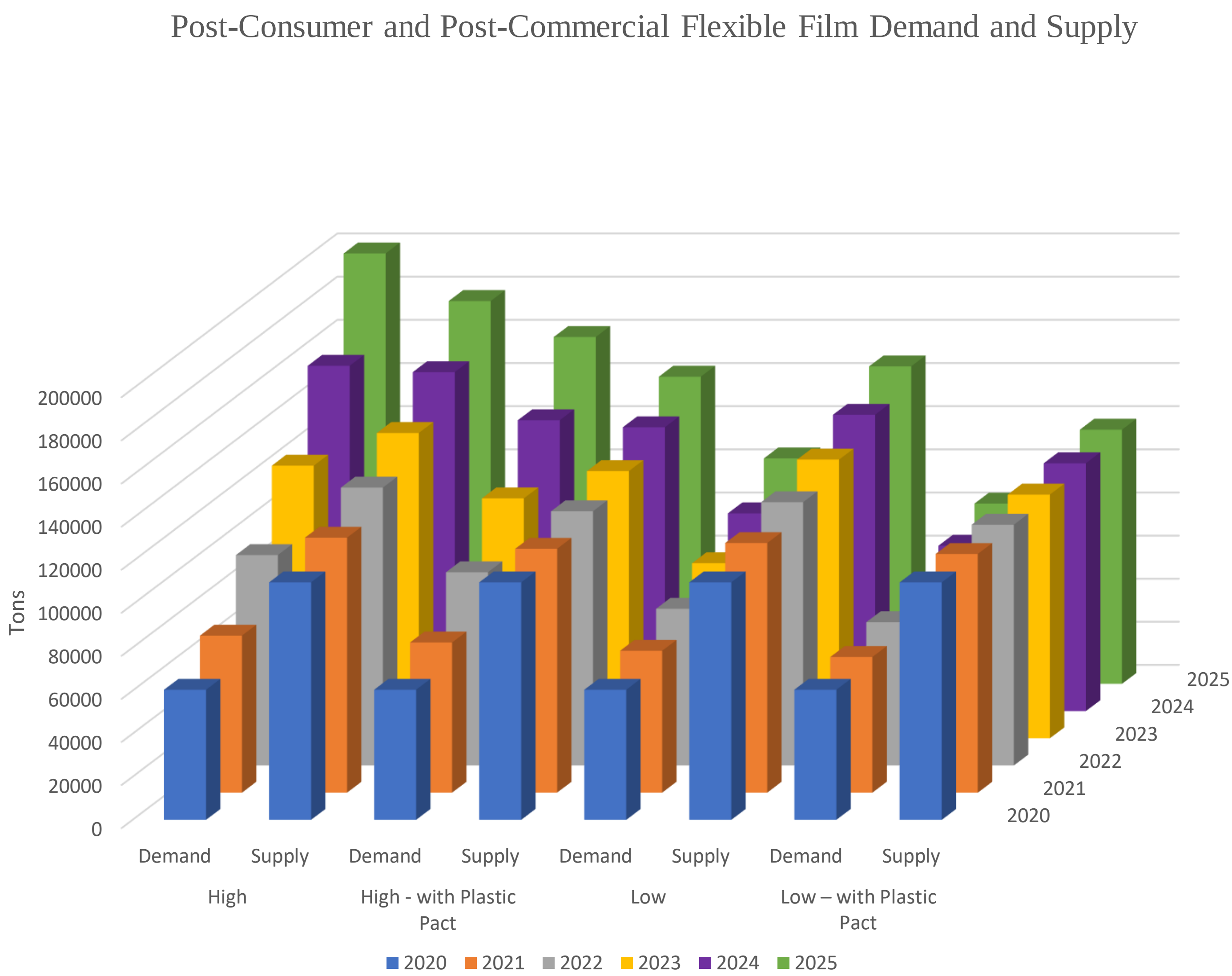

Figure 7.2
Estimated demand and supply for post-consumer (including commercial) recycled flexible films from 2020 up until 2025. The difference in value between those variables determines whether there is a positive or a negative business case for flexible film recycling. As the chart displays, demand only exceeds supply in 2024 and 2025 of both the high scenarios. In the low scenarios, supply keeps exceeding demand.

waste that actually arrives at the waste processors. Based on the same argumentation as given while interpretating the MFA results (section 5.3), the recycled-incinerated ratio seems most relevant if it is expressed relative to the total amount of processed flexible film. Therefore, Figure 7.4 shows how the balance between linearly and circularly processed flexible film towards 2025 relative to the total amount of processed flexible films, for the different scenarios.

The results show that the circular-linear ratio does not differ very much within the different scenarios. For all scenarios, the circularity percentage absolutely increases with about 8-10%. Nevertheless, it is striking that the development of actual reapplied recycled content only produces such a significant result, between 37% and 39%, in the high scenarios, relative to 23-25% in the low scenarios. This actually confirms the crucial effect that the balance between demand and supply

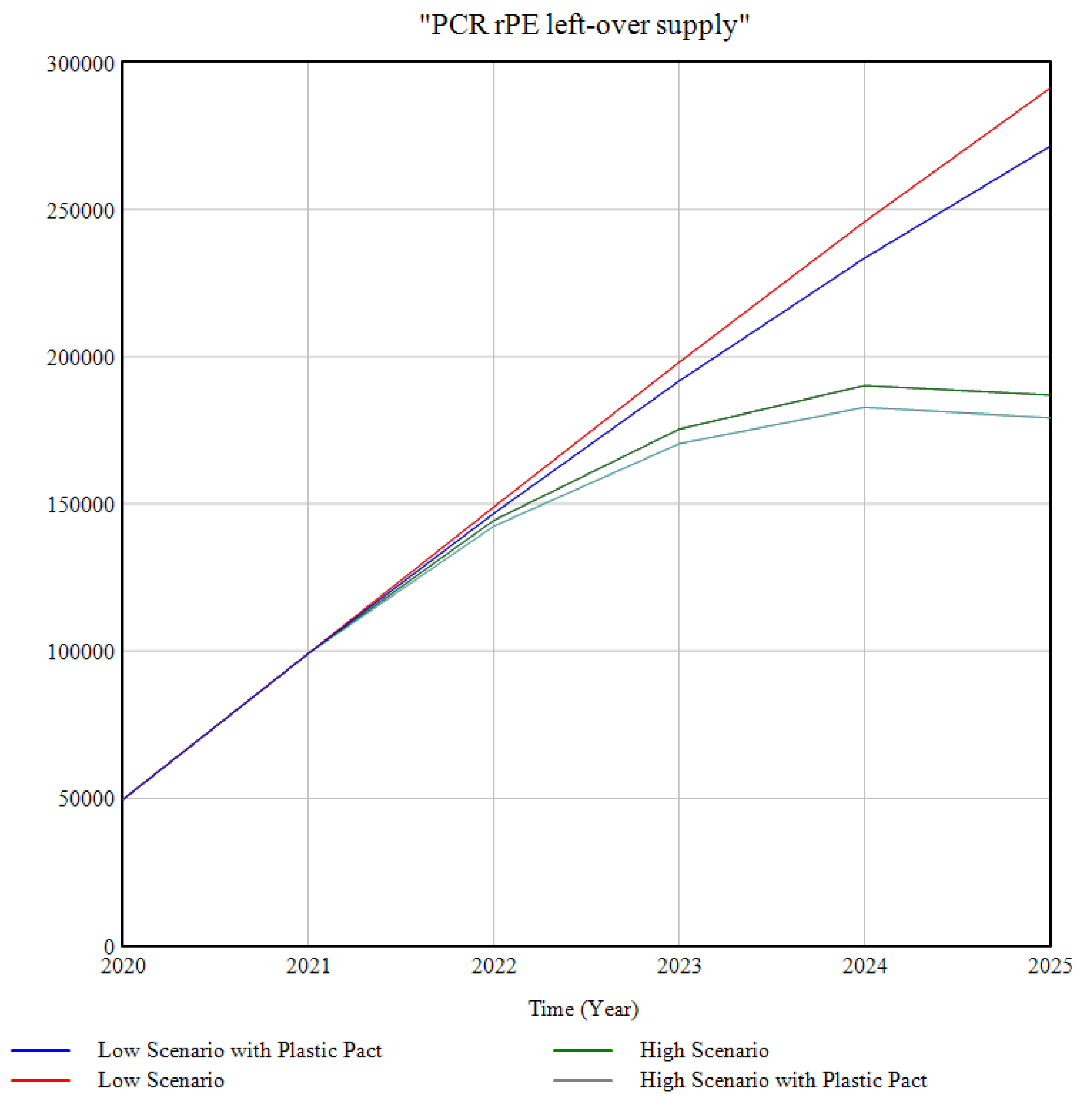

Figure 7.3
Line graph displaying dynamic modelling results for the simulated recycled flexible film left-over supply (PCR). The graph displays the development of the stockpile of post-consumer and post-commercial recycled flexible film supply for the different scenarios from 2020 up until 2025.

has here, as it determines the actual application of the recyclate in the market. The possibilities for application of rPE films that is so important as an incentive for this recycling industry.

It should be noted that both supply and demand are connected to a variety of variables, which are the relevant factors as discussed in the inventory of this analysis (Appendix C.1). The analysis shows that it is important to focus on steering the development of relevant factors towards the circumstances in the high scenario. Due to the crucial importance of mainly institutional factors, government action is important for this. Not only is institutional steering beneficial for nature and society by reducing emissions and reusing materials, it is also in the government's own interest to take action. Not only to solve the logistical problem of the increasing stockpiles, but also because the own targets will not be achieved with moderate development (as in the low scenarios). Technical and socio-economic factors are important, but institutional factors appear to be determining. Government actions that according to the analyzes have a lot of influence are the transfer of the EU Plastic tax on to the producer and the reconsideration and dissemination of the foos grade regulation. The latter could potentially open a new market for rPE films and provide a good incentive to the relevant actors in the market.

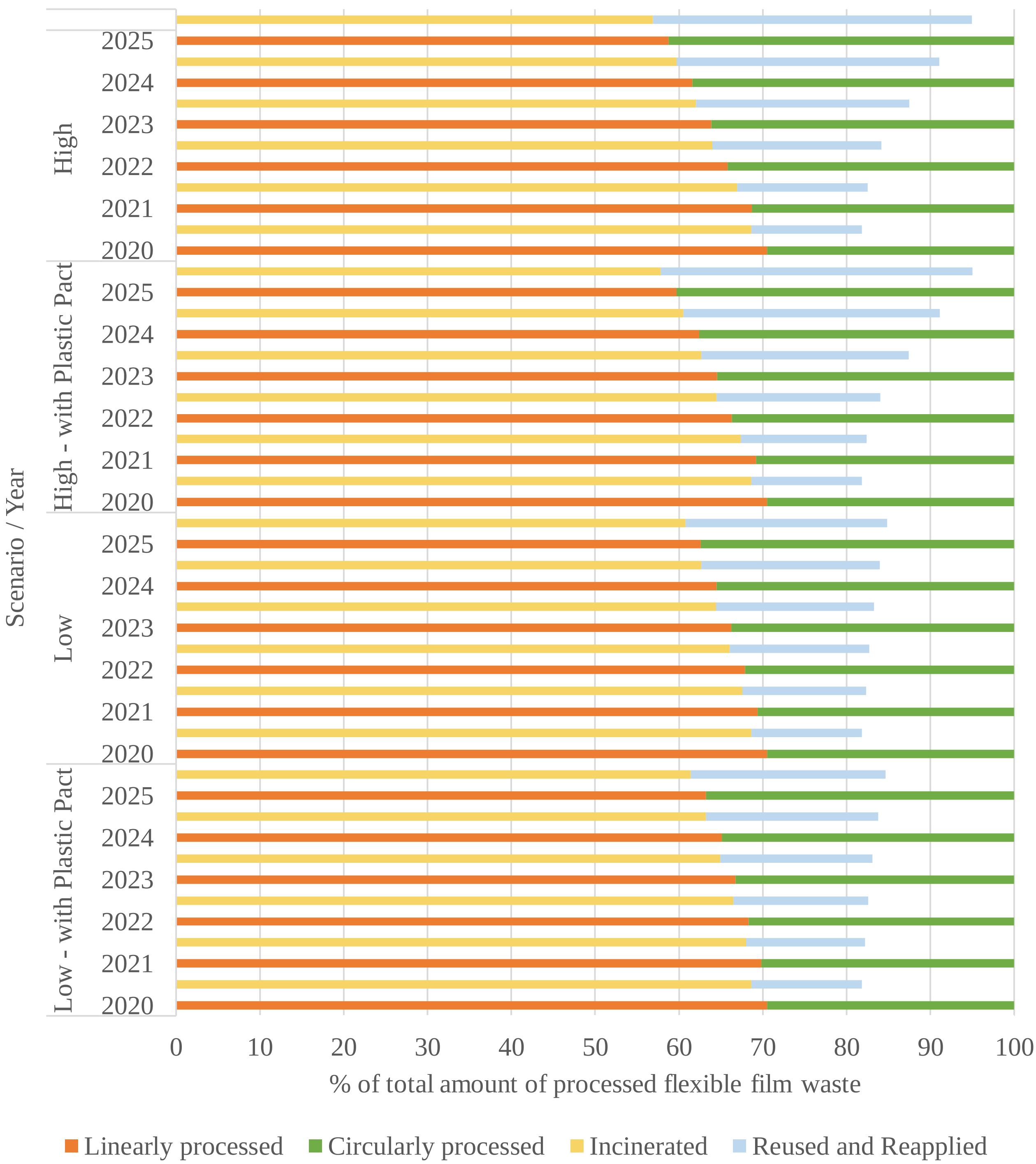

Figure 7.4
Stacked bar chart displaying the ratio between circularly and linearly processed flexible films and incinerated and actual p reapplied recycled content from 2020 to 2025. The proportions are displayed relative to the total amount of processed flexible film waste.

8. Conclusion

This study is conducted for achieving insights into the flexible film supply chain in the Netherlands and for discovering the development of circularity over the coming years. The main research question reads as follows:

How can circularity in the Dutch flexible film supply chain be identified in the current techno-institutional regime, and how can it be fostered in the future?

To answer this question, a mixed method approach is applied. Several sub-questions are formed, that together conduct to an extensive answer to the main research question. For answering the main question, it is first of all important to get a better picture of the current flexible film supply chain and the actors involved. For this, a supply chain analysis is performed. This analysis shows that several actors are connected to the different processes within the flexible film supply chain, represent multiple links. This may lead to those actors having a greater role or influence in development of circularity than other actors in the supply chain. In addition, the market value of flexible film material increases for each link in the supply chain - from the mining of raw materials to the use of flexible film products - . After plastic is used and it ends up in the waste, however, the economic value drops, because of the need to process it. This results in a negative economic value for wasted flexible film. When flexible films are recycled into regranulate, the market value of the material is positive again. Nevertheless, the market value of the energy generated by incinerating a kilogram of flexible film is higher than the market value for a kilogram of regranulate. As a result, incineration for energy recovery seems more advantageous than recycling from an economic perspective. This provides one explanation for the high values of incineration energy recovery in comparison to the reapplied recycled content.

Moreover, the MFA displays that this ratio between incineration and recycling differs from the suggested national statistics. The flexible film supply chain shows to not be close to full circularity, more than 70% of the wasted flexible film content being processed linearly. This is despite the fact that there is currently a large stockpile of recycled content that could already be applied. If current practices are continued this stockpile would continue to grow, and a large amount of usable recycled content would stay unused. This might subsequently lead to spatial issues: where should all these growing stockpiles of unused regranulate in the future be stored? Through comparative cognitive mapping, it is discovered that the supply chain actors see flexible film demand to be a crucial factor for circularity of the supply chain. In addition, results show that institutional factors have a significant indirect influence on this demand, compared to technical and socio-economic factors. This explains why the supply chain actors also showed to feel dependent on governmental institutions and actions in the context of creating circularity in the chain. The constructed dominant techno-institutional regime visualizes the current technical, institutional and socio-economic structures associated with the flexible film supply chain. This visualization displays the crucial role of the institutional system - which entails governmental institutions and actions, regulations and policies - in initiating and accelerating circular innovation through governmental (policy) triggers.

Since recycled flexible film demand showed to be a crucial factor, flexible film demand and supply are extensively analysed through dynamic modelling. The flexible film supply chain and the relevant influential factors are simulated towards 2025 for different scenarios. Only in the high scenario, demand exceeds supply, resulting in a positive stimulus for developing circularity for the supply chain. Subsequently, the reapplied recycled content increases significantly in the high scenario, which shows a positive development on the ratio between the incinerated and reapplied recycled content. This trend is also visible in the low scenario, but to a much lower degree. Moreover, only in the high scenario, the large stockpile of recycled content seems to decrease eventually towards 2025, caused by the demand exceeding supply in the last two years. Of the institutional factors, especially the extension of the strict food grade regulation concerning recycled films shows to be a crucial factor to consider, as loosening this regulation could open a whole new market for recycled films. Based on the results of the different methods, it can be concluded that the current conditions do not stimulate the development towards a circular flexible film supply chain. Nonetheless, some positive trends are visible that push towards circularity, when stimulated in the right way. In the short term, governmental action seems to be most important here, due to its activating role for technological and socio-economic development for recycled flexible films. This shows to be crucial in preventing the current technical, institutional and socio-economic structures from hampering innovation towards a circular flexible film supply chain.

9. Discussion

As stated in the conclusion, the results show that incineration for energy recovery is currently applied even more, relative to recycling, than national statistics suggest. The supply chain analysis shows that this may be related to higher revenues for energy generation from waste incineration than for recycling. This underpins the belief of Gradus et al. (2016) about the low cost-effectiveness of recycling compared to incineration. In addition, as long as society is still largely dependent on energy from fossil fuels, waste incineration offers a good alternative. Nevertheless, it should be considered that plastic is made from an exhaustive fossil fuel: oil. Furthermore, it is important to take into account the government's ambitions for nature and society to move towards a zero-emission circular economy towards 2050 (Ministerie van Infrastructuur en Waterstaat, 2019). In this context, a change needs to be made in the amount of waste that is now incinerated, including plastic waste.

The current technical, socio-economic and institutional structures associated with the flexible film supply chain together form the techno-institutional regime. Techno-institutional lock-in describes a persistent state constituting systemic market and policy barriers to environmentally superior technological alternatives (Könnölä, Unruh & Carrillo-Hermosilla, 2006). This also seems to be the case in the context of the flexible film supply chain, where social and market structures keep the demand for recycled flexible films low and current policies do not encourage improvement of the market position and the quality of recycled films. Nevertheless, it seems that techno-institutional lock-in can be avoided through governmental action. It is remarkable to see that barriers in the socio-economic and technical spectrum emerge more often, quickly and superficially, but institutional factors seem to indirectly have a significant effect on the supply chain. This finding provides food for thought for public and scientific debate, as technical and socio-economic factors are discussed to a greater extent (Kawecki, Scheeder & Nowack, 2018; Verrips et al, 2017; Simon, 2021; CE Delft, 2019). For the supply chain actors, it might be possible that the discussion is taking place in the socio-economic and technical fields, because the institutional structures seem intangible. An explanation for this may be that the average consumer, producer, waste processor and recycler may feel that they have no real influence on governmental action and policy development. Researching this phenomenon in the future could provide relevant insights for supply chain development and governmental action.

The main reason for the current strict policy on the application of recycled films is explained by the low quality of recycled films, compared to virgin plastics. But this is precisely the reason why policy incentives are needed: to make it more attractive to invest in technological development of this quality. When the government stimulates the development of product quality and also improves the market position of recycled plastics, it becomes more attractive for recyclers to enter and invest in this industry. In addition to the environmental and societal benefits of promoting circularity for flexible film supply chains, it is also in government self-interest to pursue this. One of the targets set by the government in context of their ambitions for a circular economy, is to achieve 30% recycled content, compared to overall annual production, for each type of plastic in 2025 (RIVM, 2019). This can only be achieved when the influential factors develop as estimated in the simulated high scenarios, especially in terms of institutional factors. Moreover, only the high scenarios display an eventual decrease in the recycled flexible film stock, which would otherwise grow to problematic proportions and might cause spatial storage issues. Due to the crucial role of policy triggers and policy implementation in this context, it is strongly recommended that governmental action is taken for providing a level playing field within the plastic industry.

An important action that the government can take for this purpose is to transfer the EU plastic tax to the producers, which will increase the price of virgin plastic and improve the market position of recycled plastic. In addition, it appears that the strict food grade regulation makes qualitative application of recycled films very difficult. It is understandable and important to consider food safety when using recycled content. Nevertheless, there is still a large gap between food grade products and low grade products such as garbage bags, as represented by the constructed value pyramid. Currently, these strict regulations imply that recycled plastic can also not be applied in in higher-value consumer goods. Although safety is of course paramount, the regulations for plastics seem disproportionate to other materials, such as paper. Recycled paper is currently used in food-contact products and packaging, while according to a report by the FoodWatch foundation (n.d.) this also entails possible health risks. Even though there are discussions about this in political discourse (FoodWatch, n.d.), the regulations for recycled plastics are still seem relatively extensive and strict. As a consequence, a large 'safer' market of higher quality consumer goods is currently unavailble for recycled films. Regulative and policy action taken by the government could, subsequently, break reinforcing technical and socio-economic loops and initiate change within rigid structures. In this way, the development towards a circular flexible film supply chain can fostered and accelerated and techno-institutional lock-in of the techno-institutional regime is avoided.

In this research, several research methods are applied for answering the different sub-questions and eventually the main research question. This mixed method approach contributes to the validity and reliability of the research, through methodical and data triangulation (Flick, 2018). This means that, by using different qualitative and quantitative data collection and analysis techniques, the study creates a more complete understanding of the problem and a more detailed and balanced picture of a situation.

Moreover, this study proposes unique perspective, by looking beyond the focus from a supply chain perspective to this complex problem from a multidisciplinary angle. Through mapping institutional, technical and socio-economic factors and obstacles, and visualizing their interactions and influence, this study provides a contribution to the current scientific knowledge in this area. Whereas previous studies mainly focused on one of these three categories (Brouwer et al., 2020; Bergsma & Bijleveld, 2017; TNO, 2020; Boragno et al., 2012), this research offers a helicopter perspective of the flexible film supply chain system. It reflects and displays the cohesion of technical, institutional and socio-economic structures. This study is therefore an example of Industrial Ecology's conviction as a research field about the importance of interdisciplinarity in the context of sustainability issues. In addition, the research serves as an example for the scientific community to recognize and build upon the symbiotic relationship between technical, institutional and socio-economic structures in further research.

Nevertheless, there are limitations to this study that should be noted and considered when interpreting the results. First of all, several limits are known for the individual methods solely, which are summed up through the use a mixed method approach. The supply chain analysis only shows the economic price - revenues - of the product throughout the supply chain, but does not mention the costs per link. Although this choice was made to mainly reflect the value given to the product per phase, this visualization without a cost-estimate may give an incomplete picture. It is therefore interesting for future research to also include the costs per phase in the supply chain. Moreover, a problem could arise about the information derived from interviews. It could be possible that respondents provide incorrect information by accident. This could, subsequently, lead to incorrect data for the comparative cognitive mapping, which should be kept in mind. By mainly using aggregated results from the various interviews, this risk has been partially reduced. Furthermore, both for material flow analysis and dynamic modelling, there has been missing data. This is especially the case for the dynamic modelling analysis, where an estimate has been made about future scenarios. For this reason, various estimations have been made on the basis of extensive desk research and calculations. Nevertheless, The future can never be predicted with certainty and this must be taken into account in the robustness of the results. The implications of the assumptions have therefore always been kept moderate. It is also possible that certain relevant factors have not been included in the simulation, which would then be at the expense of validity. Furthermore, the nowcasting of the 2017 MFA model into a 2020 model is risky in itself, because an assumption is made about a proportional growth across the supply chain. The 2020 MFA model was crucial for this study and making future predictions, and due to the lack of more recent this nowcasting method was required. The assumed growth rate for the nowcasting has therefore been aggregated to an average of several sources, thus reducing the risk of misconceptions and erroneous estimates. Nevertheless, the sensitivity of misconceptions when using this method should be mentioned as a limitation

For the future, it is recommended to keep track of the flows of flexible film and to make the data available for research. In addition, this research only focuses on flexible films, but there are still various types of plastic about which there is little insight, that still have a problematic recycling chain. More research into the other types of plastic is a strong recommendation. In addition, it is very interesting to include government institutions in follow-up research, to offer their perspective on the situation and to ask why so far there has been little policy incentives to accelerate the supply chain towards more circularity. This would add more dept to the current supply chain perspective that this study has focused on. Lastly, due to the many assumptions that had to be made, it is a good idea to execute a follow-up research when there is more recent information or clarity about certain estimates and assumptions. This follow-up study should then also consider the other limitations attached to this study. This could add to the extensive systems perspective of this study and possibly provide an even more accurate picture of future predictions for circularity of flexible film supply chain.

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11. Appendices

Appendix A.

Material Flow Analysis

A.1. Desk Research including estimations, equations and assumptions for Inventory Analysis

Flexible films on the Dutch market

In this section, the amount of flexible films on the Dutch market is elaborated on. The next sections describe the total amount of plastics on the Dutch market, the amount of flexible films on the Dutch market and the imported flexible films. Figure 11.1 already represents the proportion of flexible films, produced in and imported into the Netherlands, relative to the total amount of plastics on the market. This is based on the elaborations and equations in the following sections.

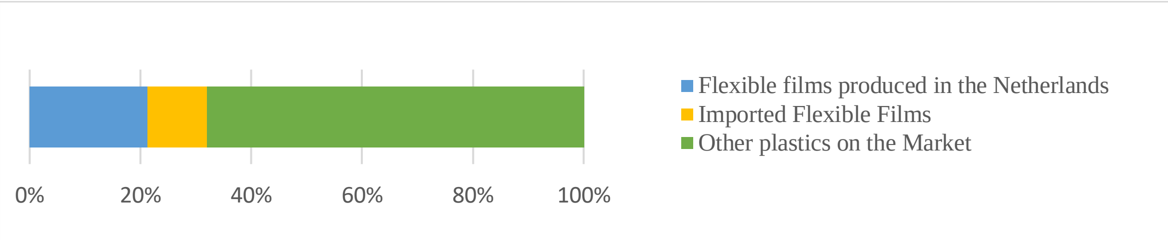


Figure 11.1
Stacked bar representing the proportion of flexible films, produced and imported in the Netherlands, relative to the amount of other plastics on the Dutch market.

Plastic and flexible film on the Dutch market

In 2017, 1,900 kilotons of plastic were available on the Dutch market (CE Delft, 2019). The distribution according to types of plastic in 2017 that were marketed in the Netherlands is given by RIVM (2019). Table 11.1 states the share of HDPE, LDPE and PP on the Dutch market, both in rigid and flexible form. Furthermore, the representation of each plastic type in flexible film is calculated. Based on the calculations in Table 11.1, the share of flexible PE and PP films on the Dutch market was about 32% of the total plastic market for all sectors. For the remainder of this analysis, this will be summarized under the term 'flexible films'. Assuming the plastic distribution from RIVM (2019), 32% of the 1,900 kilotons of plastics in the Netherlands consists of flexible films, which means 608 kilotons flexible films were available on the Dutch market in 2017.

Table 11.1
Share of LDPE, HDPE and PP on the total Dutch plastic market, in rigid and flexible form and the representation of each type within the flexible film market in 2017, based on RIVM (2019).

Type of plastic	Proportion on the total plastic market – Rigid (RIVM, 2019)	Proportion on the total plastic market – Flexible (RIVM, 2019)	Representation in flexible film market
Unit	(%)	(%)	(%)

LDPE*	2	16	$\frac{16}{32 \div 100} = \mathbf{50}$
HDPE	1	3	$\frac{3}{32 \div 100} = \mathbf{9.38}$
PP	10	13	$\frac{13}{32 \div 100} = \mathbf{40.62}$
Total	13	32	100

*Including MDPE (RIVM, 2019) and assumed to include LLDPE.

Import

In 2017, 635 kilotons of plastic were imported in the Netherlands (CE Delft, 2019). For import, the same distribution of plastic types as on the general market is assumed, which is 32% (Table 11.1). This means that the imported amount of flexible films is 203.20 kilotons.

Beside the amount of flexible films that is imported, an amount is produced and manufactured within the Netherlands. The amount that is produced within the Netherlands can be calculated the following way:

$$\begin{gathered} Flexible\ films\ on\ the\ Dutch\ market \\ -\ Imported\ flexible\ films \\ =\ Produced\ flexible\ films \end{gathered}$$

$$608 - 203.20 = \ 404.80\ kilotons\ produced\ flexible\ films\ in\ the\ Netherlands$$

Moreover, the proportional division of material flows from import, as given by Kawecki et al. (2018), is assumed. This means that, of the total import of flexible films, approximately 7% is directly present in packaging, 7% in electrical and electronic equipment and the remaining 86% flows to manufacturing processes. These percentages are also assumed in this 2017 model. The amount of flexible films flowing to the manufacturing process is needed for calculations later, so the following calculation is provided:

$$203.20 \times\ 0.86 = \ 174.75\ kilotons\ imported\ flexible\ film\ for\ manufacturing$$

Production & Manufacturing

The amount of flexible film content produced within the Netherlands consists partly of recycled flexible films and partly of newly produced flexible films from raw materials. The recycled flexible films are often incorrectly referred to as rLDPE. This is despite the fact that these are recycled PE films (rPE films), which consists mainly of LDPE, but also, in a smaller quantity, of flexible HDPE, MDPE, LLDPE and PP (interview with the waste processor / recycler, 2021). The output is a mix of these polymers, mostly consisting of LDPE, yet this is incorrectly referred to as rLDPE. Subsequently, this output is compared by the RIVM (2019) with the applied virgin content LDPE, which gives a distorted picture. Nevertheless, further calculations can be done with this information. The recycled flexible rLDPE content in relation to the entire LDPE market in the Netherlands was 19% in 2017 (RIVM, 2019). The rLDPE films are, thus, assumed to refer to rPE films with a relatively larger LDPE content than HDPE, MDPE, LLDPE and PP content.

Since the recycled content proportion (19%), given by RIVM (2019), is relative to the total flexible LDPE market, this value fist needs to be calculated. In the previous section it was estimated that the total amount of plastics on the Dutch market in 2017 was 1,900. Furthermore, the flexible LDPE content of this amount is 16%, assuming the proportions as given by RIVM (2019) for 2017 (Table 11.1). This gives the following calculations for the kilotons flexible LDPE on the Dutch market:

$$1{,}900 \times 0.16 = 304 \; kilotons \; LDPE \; on \; the \; Dutch \; market$$

The amount of flexible LDPE on the Dutch market is, thus, 304 kilotons. The recycled proportion of this amount is 19% (RIVM, 2019), which actually defines the rPE film content on the Dutch market. This provides the following calculation:

$$304 \times 0.19$$
$$= 57.76 \; kilotons \; flexible \; films \; recycled \; content$$

This amount is assumed to be the current demand for recycled flexible film content, since this is all that is applied, and therefore demanded, on the Dutch market. To calculated what the recycled content of rPE films is, relative to the total amount of flexible films on the Dutch market (608 kilotons), the following calculation can be made:

$$57.76 \div 608 = 0.095$$
$$Recycled \; content \; on \; the \; flexible \; film \; market = 9.5\%$$

Knowing the recycled content, the following calculation for the amount of newly produced flexible films is given:

$$404.80 - 57.760$$
$$= 347.04 \; kilotons \; newly \; produced \; flexible \; films$$

The efficiency of the production process is difficult to determine, because of the different types of plastic that are represented in flexible films. The efficiencies of the production processes of LDPE, HDPE and PP have been estimated, on the basis of a study by Kawecki et al. (2018), and are given in Table 11.2. Based on the representation per type of plastic on the flexible film market (as calculated in Table 11.1), the production efficiency is determined for the 2017 MFA model. As can be seen by the equations in Table 11.2, a production efficiency of 99.41% is assumed for the flexible film production process.

Table 11.2
Calculation of the efficiency of the flexible film production process, based on the representation of each plastic type in the flexible film market and the efficiencies of their production processes.

Type of plastic	**Representation in flexible film market**	**Efficiency production process (Kawecki et al., 2018)**	**Efficiency flexible film production process**
Unit	(%)	(%)	(%)

LDPE*	50	99.43	$0.50 \times 99.43 = \mathbf{49.71}$
HDPE	9.38	99.40	$0.0938 \times 99.40 = \mathbf{9.32}$
PP	40.62	99.40	$0.4062 \times 99.40 = \mathbf{40.38}$
Total			99.41

*Including MDPE (RIVM, 2019) and assumed to include LLDPE.

To determine the efficiency of the manufacturing process, the same method is applied as for the production efficiency. The estimated efficiencies of the manufacturing processes of LDPE, HDPE and PP, on the basis of Kawecki et al. (2018), are given in Table 11.3. Based on the representation per type of plastic on the flexible film market, the manufacturing efficiency is determined for the 2017 MFA model. The equations in Table 11.3 estimate a manufacturing efficiency of 93.32% for flexible films in the 2017 MFA model.

Table 11.3
Calculation of the efficiency of the flexible film manufacturing process, based on the representation of each plastic type on the flexible film market and the efficiencies of their manufacturing processes.

Type of plastic	Representation in flexible film market	Efficiency manufacturing process (Kawecki et al., 2018)	Efficiency flexible film manufacturing process
Unit	(%)	(%)	(%)
LDPE*	50	93.83	$0.50 \times 93.83 = \mathbf{46.91}$
HDPE	9.38	93.49	$0.0938 \times 93.49 = \mathbf{8.77}$
PP	40.62	92.66	$0.4062 \times 92.66 = \mathbf{37.64}$
Total			93.32

*Including MDPE (RIVM, 2019) and assumed to include LLDPE.

Use

After manufacturing, the flexible films are applied in different aggregated use categories. Also, some manufactured content is exported. The different aggregated use categories are chosen, based on a study by Kawecki et al. (2018). The amount of flexible film in the different use categories and the amount of exported flexible films are elaborated on in this section. Figure 11.2 already represents the proportional divisions of the outflows of the manufacturing process to the different use categories.

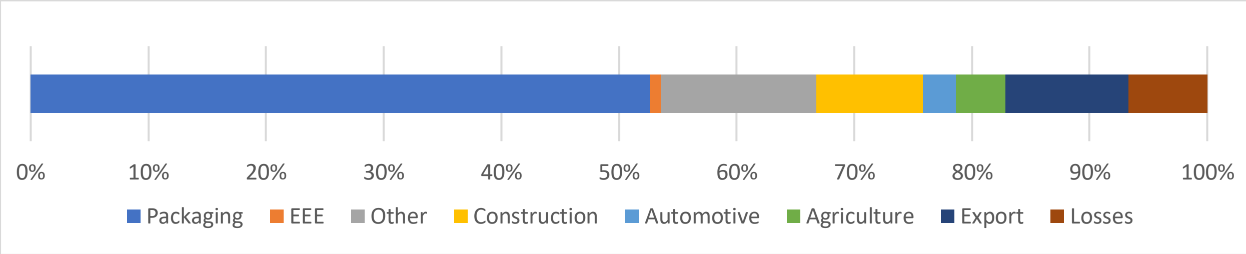


Figure 11.2
Stacked bar representing the proportional division of outflows of the flexible film manufacturing process to the different aggregated use categories, export and losses.

Packaging

One of the main aggregated use categories for flexible film is packaging. In 2017, there was approximately 530 kilotons of plastic packaging on the Dutch market (KIDV, 2017b). The distribution of plastic types for packaging is a bit different than the distribution on the general plastic markets. Plastic packaging consisted, back in 2015, for 35% out of LDPE, for 15.50% out of HDPE, for 16.50% out of PP and for 33% out of other plastics (CE Delft, 2019). For this analysis, this composition is assumed to be the same for 2017. Nevertheless, the percentages mentioned above do also consider rigid types of plastic packaging. From RIVM (2019), the distribution between rigid and flexible for these types of plastic on the market is given and is assumed to be the same for packaging. In Table 11.4, it is stated how the amount of flexible films in consumer packaging is calculated. Based on the calculations in Table 11.4, it is assumed that 52.19% of packaging consists of flexible films. Subsequently, the following calculation is formed:

$$530 \times 0.5219$$
$$= 276.61 \; kilotons\ of\ flexible\ films\ in\ packaging$$

Table 11.4
Calculations for the presence of flexible films in packaging. Based on measurements from RIVM (2019) and CE Delft (2019).

Type of plastic	Proportion of the total plastic market – Rigid (RIVM, 2019)	Proportion of the total plastic market – Flexible (RIVM, 2019)	Proportion flexible plastic per plastic type	Proportion of plastic type in packaging (CE Delft, 2019)	Proportion flexible plastic in plastic packaging
Unit	(%)	(%)	(%)	(%)	(%)
LDPE*	2	16	$\frac{16}{(16+2) \div 100} = \mathbf{88.88}$	35	$0.89 \times 35 = \mathbf{31.15}$
HDPE	1	3	$\frac{3}{(1+3) \div : 100} = \mathbf{75}$	15.5	$0.75 \times 15.5 = \mathbf{11.63}$
PP	10	13	$\frac{13}{(13+10) \div 100} = \mathbf{56.52}$	16.5	$0.57 \times 16.5 = \mathbf{9.41}$
Total					52.19

*including LLDPE and MDPE

Construction

In 2014, 290 kilotons plastic were applied in construction (CE Delft, 2019). The average waste generated from construction in Europe in 2018, consisted for 5.10% out of LDPE, for 12.80% out HDPE, for 7.40% out of PP and for 74.70% out of other plastic types (PlasticsEurope, 2018). This distribution is also assumed for the plastics applied in construction in the Netherlands. Considering the Dutch plastic distribution between flexible and rigid (RIVM, 2019), Table 11.5 provides the calculations the amount of flexible films in construction.

Table 11.5
Calculations for the presence of flexible film content in construction. Based on measurements from RIVM (2019) and PlasticsEurope (2018).

Type of plastic	**Proportion flexible plastic per plastic type** (RIVM, 2019)**	**Proportion of plastic type in construction (Plastic Europe, 2018)**	**Proportion flexible plastic of total plastic in construction**
Unit	(%)	(%)	(%)
LDPE*	88.88	5.1	$0.89 \times 5.1 = \mathbf{4.53}$
HDPE	75	12.8	$0.75 \times 12.8 = \mathbf{9.60}$
PP	56.52	7.4	$0.57 \times 7.4 = \mathbf{4.22}$
Total			18.35

*including LLDPE and MDPE
**For calculation of these values, see Table 1.14 (fourth column).

Based on the calculations described in Table 11.5, it is estimated that 18.35% of plastic applied in construction comprises flexible films. Assuming the annual growth rate of 4% (Table 5.1) and the three year leap between 2014 and 2017, the following calculation is formed:

$$290 * 0.1835 \times 1.04^3$$
$$= 59.86\ kilotons\ flexible\ films\ used\ in\ construction$$

This amount includes recycled content of flexible film being applied in construction, which is around 12.35 kilotons. This is based on the sectoral division of demand for recycled flexible films. The explanation behind this value is elaborated in the section ‘Manufacturing of rPE from consumer waste and commercial waste’. This results in 47.51 kilotons newly produced film applied in construction.

Automotive

Moreover, in 2017, 48 kilotons plastic were applied in the automotive sector (CE Delft, 2019). The average distribution of plastics in cars between 2016 and 2020 is estimated to exist for 44% out of PP, for 7% out of PE and for 49% out of other plastic types (Emilsson, Dahllöf & Ljunggren Söderman, 2019). This distribution is also considered in this study. Furthermore, the 7% of PE comprises all types of PE. Therefore, this percentage of PE in cars is assumed to be distributed in the same way as on the total plastic market, consisting for 4% out of HDPE and for 18% out of LDPE (including MDPE and LLDPE), as estimated by RIVM (2019) (described in Table 11.1). Subsequently, the following calculations are formed for the ratio between LDPE and HDPE:

$$\frac{18}{(18+4) \div 100} = 81.82\ LDPE$$
$$\frac{4}{(18+4) \div 100} = 18.18\ HDPE$$

The equations above display that the ratio on the Dutch market between LDPE and HDPE is, thus, 81.82% against 18.18%, respectively. If this distribution is assumed for the PE content in cars (7%) as well, the following calculations are formed:

$$0.8182 \times 7 = 5.73\%\ LDPE\ in\ automotive$$
$$0.1818 \times 7 = 1.27\%\ HDPE\ in\ automotive$$

These estimated proportions comprises both rigid and flexible PE. Considering the Dutch plastic distribution between flexible and rigid (RIVM, 2019), Table 11.6 is formed for calculating the amount of flexible films in the automotive sector.

Table 11.6
Calculations for the presence of flexible films in automotive. Based on measurements from RIVM (2019) and Emilsson, Dahllöf & Ljunggren Söderman (2019).

Type of plastic	**Proportion flexible plastic per plastic type**** **(RIVM, 2019)**	**Proportion of plastic type in automotive** **(Plastic Europe, 2018)**	**Proportion flexible plastic of total plastic in automotive**
Unit	(%)	(%)	(%)
LDPE	88.88	5.73	$0.89 \times 5.73 = \mathbf{5.10}$
HDPE	75	1.27	$0.75 \times 1.27 = \mathbf{0.95}$
PP	56.52	44	$0.57 \times 44 = \mathbf{24.87}$
Total			30.92

*including LLDPE and MDPE
**For calculation of these values, see Table 1.14 (fourth column).

Based on the calculations in Table 11.6, the following calculation is formed:

$$48 \times 0.3092 = 14.84\ kilotons\ flexible\ films$$
$$used\ in\ the\ automotive\ sector$$

Electrical and Electronic Equipment

In 2017, approximately 417 kilotons of electrical and electronic equipment (EEE) were marketed in the Netherlands. This consisted for about 53 kilotons out of plastic (CE Delft, 2019). This makes for an average plastic content in EEE products 12.70%. PP is mentioned as a one of the most prominent plastic types in EEE (CE Delft; Buekens & Zhou, 2014). The application of PE in EEE, however, is less prominent. Data from WEEE plastic compositions in Europe, provided by MGG Polymers (2020), are displayed in a pie chart in Figure 11.3.

The pie chart displays that, besides plastics, this plastics mix WEEE contains for 16% of other materials and dirt (ood & fluff, cables, glass & stones, metal containing parts and fines and

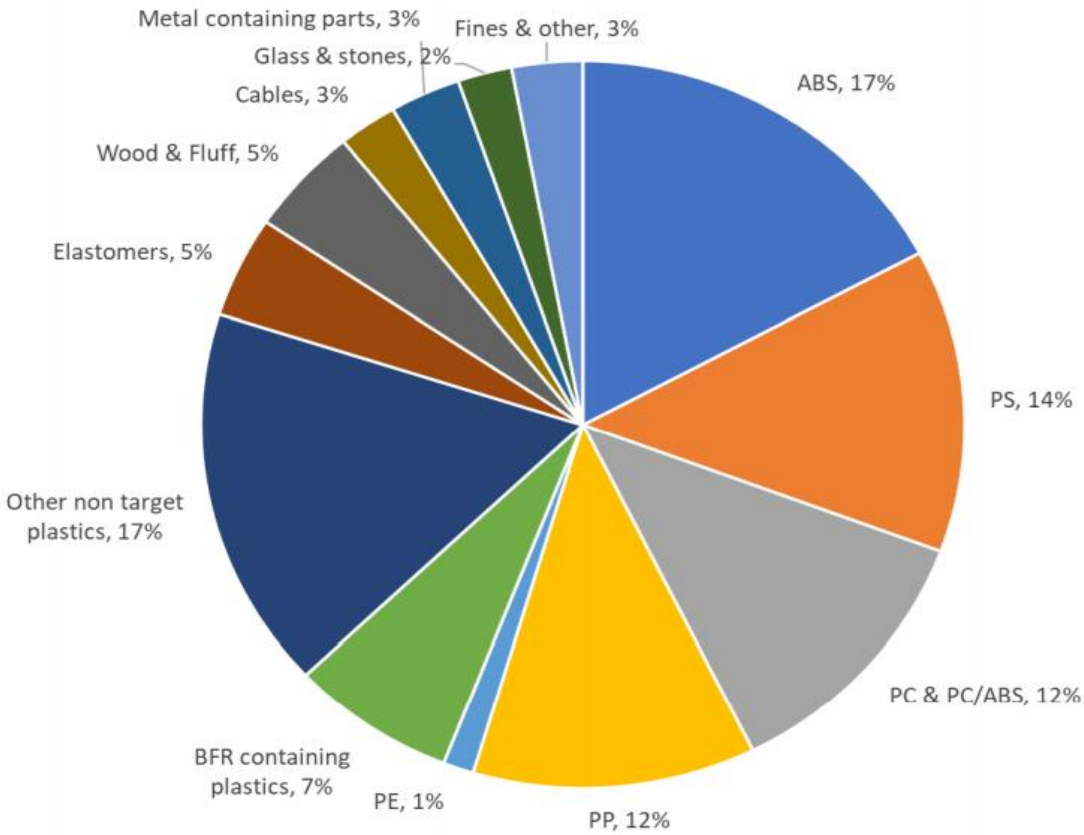


Figure 11.3
Average composition of WEEE plastics mix in Europe in 2020. This still contains an amount non-plastic (wood & fluff, cables and glass and stones).
Note: Reprinted from "Volume and composition of WEEE plastics in Europe", by MGG polymers, 2020. https://mgg-polymers.com/news/blog/volume-and-composition-of-weee-plastics-in-europe

other). The remaining 84% comprises the plastic composition of WEEE. This gives the following calculations for PE and PP content out of the total plastic content plastics in WEEE:

$$PE\ in\ plastic\ mix\ from\ WEEE = 1\%$$
$$PLastics\ in\ plastics\ mix\ from\ WEEE = 84\%$$
$$1 \div 84 = 0.0119$$
$$PE\ content\ of\ plastic\ in\ WEEE = 1.19\%$$

$$PP\ in\ plastics\ mix\ from\ WEEE = 12\%$$
$$PLastics\ in\ plastics\ mix\ from\ WEE = 84\%$$
$$12\ \div 84 = 0.1429$$
$$PP\ content\ of\ plastic\ in\ WEEE = 14.29\%$$

Due to a lack of data about plastics applied in EEE, the WEEE plastic composition displayed in Figure 11.3 are assumed as plastics applied in EEE for this study. Again, PE is provided as one category. Therefore the ratio between LDPE (including MDPE and LLDPE) and HDPE is assumed to be 81.82% versus 18.18%, respectively (section 'Automotive'). This provides the following calculations:

$$1.19 * 0.8182 = 0.97\%\ LDPE\ content\ of\ plastics\ in\ EEE$$
$$1.19 * 0.1818 = 0.22\%\ HDPE\ content\ of\ plastics\ in\ EEE$$

Based on these calculations, Table 11.7 describes how the flexible film content in EEE is estimated, considering the Dutch plastic distribution between flexible and rigid plastics (RIVM, 2019). Based on the calculations in Table 11.7, the following calculation is formed:

$$53 \times 0.091$$
$$= 4.82\ kilotons\ flexible\ films\ used\ in\ EEE$$

Table 11.7
Calculations for the presence of flexible films in EEE. Based on measurements from RIVM (2019) and MGG Polymers (2020).

Type of plastic	**Proportion flexible plastic per plastic type*** **(RIVM, 2019)**	**Proportion of plastic type in EEE** **(Plastic Europe, 2018)**	**Proportion flexible films of total plastic in EEE**
Unit	(%)	(%)	(%)
LDPE	88.88	0.97	$0.89 \times 0.97 = \mathbf{0.86}$
HDPE	75	0.22	$0.75 \times 0.22 = \mathbf{0.17}$
PP	56.52	14.29	$0.57 \times 14.29 = \mathbf{8.08}$
Total			9.10

*including LLDPE and MDPE
**For calculation of these values, see Table 1.14 (fourth column).

Agriculture

Around 44 kilotons of plastic were applied in agriculture in 2016 (CE Delft, 2019). In 2011, flexible films represented about 77.10% of the plastics applied in agriculture (Jetten, Merkx, Krebbekx & Duivenvoorde, 2011). Assuming that this representation of flexible films in agriculture is kept the same and considering the general annual growth rate of 4% per year (Table 5.1) the following calculation is formed for 2017:

$$44 \times 1.04 \times 0.771$$
$$= 35.28\ kilotons\ flexible\ films\ used\ in\ agriculture$$

The abovementioned amount is including the recycled content of flexible films. The recycled content applied in agriculture is about 13.43 kilotons This is based on the sectoral division of demand for recycled flexible films. The explanation behind this value is elaborated in the section ‘Manufacturing of rPE from consumer waste and commercial waste’. This results in 21.85 kilotons newly produced film used in agriculture.

Export

An amount of flexible films is directly exported after manufacturing. The exported amount of flexible film from The Netherlands to other countries in the world was, in total, around 55.15

kilotons in 2017 (World Integrated Trade Solution, n.d.). This is assumed to only be the manufactured amount of flexible films and not flexible film content incorporated in products. Moreover, some flexible film content is also exported from other categories (EEE and Automotive),. The exported flexible film content from these categories is incorporated within the EEE and automotive products and is not included in this 55.15 kilotons exported flexible films.

Other

Lastly, an amount of flexible films is assumed to flow to other aggregated uses from manufacturing (Kawecki et al., 2018). Therefore, the remainder of manufactured flexible films is assumed to go to this category.

Waste Collection & Sorting

After the products involving flexible films are used, they go to waste collection and sorting systems. There are various types of plastic waste collection available in the Netherlands, deviation from residual waste collection and sorting to separate plastic waste collection and sorting, for several different types of waste (CE Delft, 2019; Kawecki et al., 2018; Brouwer et al., 2019). For each aggregated use product, the waste collection and sorting process is elaborated on in the following sections.

Packaging

With plastic packaging, a distinction must be made between consumer (households) use of plastic packaging, commercial (business) use of plastic packaging and composite plastic packaging.

Consumer Packaging

In 2017, the amount of post-consumer plastic packaging waste (PCPPW), excluding commercial plastic waste, was 350 kilotons (Brouwer et al., 2019). Again, the proportion of flexible films in packaging is assumed to be 52.19%, as explained in Table 11.4. The calculation for PCPPW flexible film content is as follows:

$$350 \times 0.5219$$
$$= 182.67 \; kilotons\ of\ flexible\ films\ in\ PCPPW$$

Of this amount, 14.50 kilotons are assumed to be from recycled flexible films, mostly in garbage bags. This is based on the sectoral division of demand for recycled flexible films. The explanation behind this value is elaborated in the section ‘Manufacturing of rPE from consumer waste and commercial waste’. For now, this provides the following calculation for newly produced flexible film in consumer packaging:

$$182.60 - 14.50 = 168.16 \; kilotons\ of\ newly\ produced\ flexible\ films\ to\ packaging$$

Consumer plastic is collected and sorted through several different collection systems, which is elaborated on in the next sections. First, it is important to note that plastic packaging waste is sorted according to the DKR standards (In De Keten, 2015). These standards differ per type of plastic. After sorting, films must be empty, with surfaces in accordance with DKR standard 310 standard

310 larger than A4 size, such as bags, wrappers and pouches (In De Keten, 2015). The DKR 310 flow encompasses the sorted film flow that arrives at recyclers (In De Keten, 2015; Krebbekx et al., 2017). Between 2014 and 2017, the correctly sorted PE films has decreased (DKR 310), whereas the amount of PE films ending up in mixed plastic (DKR 350) has increased (Brouwer et al., 2019).

Consumer separate waste collection and sorting

In 2017, 80% of plastic packaging waste was collected in municipalities through source separation (Kerstens & Blanksma, 2019). Plastics are collected separately in many municipalities in PMD waste, consisting of plastic, metal and beverage cartons waste (CE Delft, 2019). Moreover, the collection efficiency was between 60% and 70% (Kerstens & Blanksma, 2019). These percentages are also assumed for this analysis. This results in the following calculation:

$$0.80 \times 0.65 = 0.52$$
$$Proportion\ of\ consumer\ packaging\ collected\ through\ source\ separation = 52\%$$

The remainder of the 80%, that should normally be collected through PMD source separate collection, is assumed to end up in residual waste.

Furthermore, the percentage of flexible films correctly sorted to films (DKR 310) from separate collection was, on average for all plastic types in flexible films, 48.66% (Brouwer & Thoden van Velzen, 2017). This percentage is assumed to be sorted correctly into DKR 310. A part of this separately collected waste flow is, however, faulty sorted into other products and partly incinerated (Brouwer et al., 2019). Since it is unknown to which fault products the films were sorted, it is assumed to be incinerated in this study. The average proportion of the different types of plastic films, faulty sorted to other products or incinerated is 11%. Moreover, a big part of the flow is also faulty sorted to mixed plastic in 2017 (Brouwer et al., 2019). Besides DKR 310, there is DKR 350, which is the packaging waste gathered from household mix waste. This flow also partly consists of PE films (Krebbekx et al., 2017). Therefore, the remainder of the source collected waste flow is assumed to go to mixed plastic recycling in DKR350 in the MFA model.

Post-separated waste collection and sorting

The remaining 20% of consumer plastic waste was collected in municipalities through post-separation in 2017 (Kerstens & Blanksma, 2019). Moreover, little public data is available about the exact yields of the current post-separation installations (Kerstens & Blanksma, 2019). In 2017, of the plastic waste that arrives at post-separation collection, around 3.90 kilotons net plastic films were sorted out for mechanical recycling in 2017 (Brouwer et al., 2019). This amount goes to DKR 310 recycling.

Moreover, of the plastic waste that arrives at post-separated collection and sorting, around 5.10 kilotons net plastic mix (DKR 350) were sorted out for mechanical recycling in 2017 (Brouwer et al., 2019). In 2015, the sorted DKR 350 flow arriving at recyclers consisted for around 30% of PE films (Krebbekx et al., 2017). This proportion is assumed for 2017 as well, which provides the following calculation:

$$5.10 \times\ 0.30\ =\ 1.53\ kilotons\ of\ PCPPW\ flexible\ film\ to\ DKR\ 350\ from\ postseparation$$

Residual waste collection

As stated before, a part of the waste flows from municipalities applying source separated collection ends up in residual waste. Furthermore, some waste flows from the other aggregated use categories ends up in this flow, which is explained further in the relevant sections. All residual waste is incinerated for energy recovery (ROV, n.d.).

Commercial Packaging

Commercial plastic waste determines the waste from businesses. This is also collected through a separate collection system. Moreover, there is a residual waste stream from businesses, consistent of flexible film waste as well.

Separate Commercial Waste Collection

Businesses in the Netherlands are obliged to separately collect certain types of waste, including plastics (Ministerie van Algemene Zaken, 2019). The amount of plastic packaging that ends up in the commercial residual waste is not exactly known. However, since the ban on the export of plastic to China, more plastic is present in the commercial residual waste. The difference in separate collection from companies was approximately 11 kilotons between 2016 and 2017, which is when the export ban came in place (CE Delft, 2019). It appears that the amount of plastic waste that was not exported to China, ended up in commercial residual waste in 2017.

In the case of commercial plastic waste, the source-separately collected return (largely logistics aids and mono-flows) was approximately 57% in 2017 (Ministerie van Infrastructuur en Waterstaat, 2020). Mono-flows, in this case, are predominantly plastic foils (Ministerie van Infrastructuur en Waterstaat, 2020), so the same separate collection efficiency for commercial plastic packaging waste is assumed. This collection rate does probably define the difference in commercial waste between business-to-business (B2B) post-commercial waste, with relative clean mono-flows, and post-commercial plastic packaging disposed of at companies, institutions, railway stations and offices. These waste flows were too heterogeneous for profitable recycling and therefore not collected and recycled in 2017.

Thus, the collected amount of commercial waste largely consists of mono-flows. For that reason, it can be offered for recycling immediately, without a sorting step (KIDV, 2017b). The separately collected commercial packaging waste subsequently goes to commercial plastic waste recycling.

Commercial Residual Waste

Commercial residual waste was rarely separated afterwards and presumably ended up in the incinerator in 2017 (CE Delft, 2019). Whereas municipal waste is post-separated, this was not the case for residual commercial waste (CE Delft, 2019). Therefore, this residual waste flow is assumed to go to residual waste collection, after which it is incinerated.

Composite plastic packaging

Besides packaging consisting of only plastic, there are packaging products that consists of multiple materials. The most common example of this are beverage cartons, existing of paper and plastic. Of other types of composite plastic packaging (like chips bags) the amount of plastic used is unknown (CE Delft, 2019). Moreover, these other types of packaging are difficult to recycle. Therefore, these are not considered in this study and only beverage cartons are considered.

Beverage cartons are collected separately in many municipalities in PMD waste (CE Delft, 2019). In 2015, there were about 70 kilotons of beverage cartons on the Dutch market. An average beverage carton consists of 23.6% plastic (KIDV, 2017a; in CE Delft, 2019). Furthermore, Ebadi et al. (2015) state that drink cartons consist for 20% out of LDPE, from flexible plastics. Since no distinction is made between the different types of plastics in flexible films, the beforementioned percentage (20%) is assumed to be the flexible film content in this analysis. Moreover, for this study, it is assumed that the number of plastic beverages to have increased in the same rate as plastic packaging, with the annual growth rate of 2.60% (Table 5.1). This provides the following calculation for flexible film in beverage cartons in 2017:

$$70 * 0.20 * 1.026^{2}$$
$$= 14.74\ kilotons\ flexible\ films\ in\ beverage\ cartons$$

In 2018, carton beverages were separately collected for 52% (Milieu Centraal, n.d.). This aligns with the calculations for household plastic packaging waste, where 80% of plastic packaging was collected through source separation with a collection efficiency of 65% (Kerstens & Blanksma, 2019). Therefore, the 52% is again assumed to go to separate waste collection and 20% is assumed to go to post-separation (Kerstens & Blanksma, 2019). The remainder flows to residual waste collection. The average sorting efficiency of separate collection systems for beverage cartons is around 73% (Thoden van Velzen et al., 2017). For mechanical recovery at post-separated waste collection and sorting, this efficiency is 75% (Thoden van Velzen et al., 2017). The sorted beverage cartons go to the recycler. The remaining collected beverage cartons, are assumed to be incinerated.

Plastic Litter

In 2017, there was approximately 9 kilotons of plastic that ended up in litter (KIDV, in CE Delft, 2019). Litter on land is defined as all the waste that is disposed of on the streets or in nature (de Waart et al., 2015). It is consciously or unconsciously disposed of by people in places that are not intended for that purpose. Litter mainly consists of cigarette butts, chewing gum and packaging (de Waart et al., 2015). Therefore, in this study, we assume the amount of flexible film that ends up in litter, to come from the packaging category. For the MFA model from 2017, assuming the 45.68% proportion of flexible films, the following calculation is made:

$$9 \times 0.5219$$
$$= 4.70\ kilotons\ of\ flexible\ film\ ending\ up\ in\ litter$$

The actual amount of plastic in litter that ends up in the plastic soup is unknown (CE Delft, 2019), so this is not visualized in the MFA model.

Electrical and Electronic Equipment

After use, about 8% was exported for reuse and 9% was exposed of in waste bins (residual waste) in 2018 (Baldé, van den Brink, Forti, van der Schalk & Hopstaken, 2020). These proportions are assumed to have been the same in 2017. In the Netherlands, Wecycle is responsible for the collection and recycling of EEE from municipalities. The processing of all EEE waste (WEEE) is reported every year by the National (W)EEE Register. For this study, all collected WEEE is assumed to be collected by Wecycle. Recycling takes place at the same location but is discussed in the next section about waste processing. In 2017, 22.50 kilotons of plastic were collected within the EEE category. The same proportion of flexible film content in EEE is assumed as before (Table 11.7), which was 9.10%. Furthermore, the growth rate of Verrips et al. (2017) is applied again. Based in this, the following equation is formed:

$$22.5 \times 0.091 = 2.05\ kilotons\ flexible\ film\ in\ collected\ EEE$$

The remainder of flexible film in EEE is assumed to be still in use after one year, as EEE can have a lifespan from one up until 20 years (CE Delft, 2019).

Construction

Since the average lifespan of construction material is about 50 years (CE Delft, 2019), quite some flexible film inflow is in use for a while. About the plastic waste flows from construction, values are undetermined. Nevertheless, CE Delft (2019) estimated, based on values from various sources of previous years, that the amount of plastic waste from construction in 2017 was about 68 kilotons. Considering the flexible film content of 18.35% in plastics from construction (Table 11.5), the following equation is formed:

$$68 \times 0.1835 = 12.48\ kilotons\ of\ flexible\ film\ in\ collected\ construction\ waste$$

The remainder is assumed to still be in use, therefore presented as a stock in the MFA model.

Agriculture

The average Lifespan of agricultural plastic films can vary from several months to three to four years. Therefore, some of the flexible film content in agriculture are assumed to be kept in use. According to Plastics Europe (NRK, 2018, in CE Delft, 2019), 44 kilotons of plastic from agriculture was processed, based on all the plastic that was released in this sector around 2016. If the flexible film content of 77.10% is assumed again, the following equation can be made:

$$44 \times 0.771 = 33.92\ kilotons\ of\ flexible\ film\ collected\ from\ agriculture$$

The remainder is assumed to be still in use after a year and is therefore represented as a stock in the MFA model.

Since agricultural waste can be seen as waste from a business and it is separately collected, this waste flow is assumed to go to commercial separate waste collection. In 2011, about 42.11% of the collected flexible films in agriculture consisted of horticultural foils, for which recycling was economically problematic due to high pollution degree (Jetten et al., 2011). Due to lack of more recent data, this proportion is assumed to be sorted out and incinerated in this study. After sorting, the remainder of this flow goes to commercial plastic waste recycling.

Automotive

Based on the plastic material flows from Kawecki et al. (2018), estimations are made of the proportion of PP, HDPE and LDPE - in both rigid and flexible form - exported from the automotive category. For PP, about 18.61% is exported. For HDPE and LDPE, this is 17.39% and 18.18% respectively. The proportion of each of these types in flexible form in automotive products, relative to the total amount of plastic in this sector has already been calculated (Table 11.6). Table 11.8 elaborates on calculating the total amount of exported flexible films from the automotive sector. Based on the calculations in Table 11.8, the proportion of flexible film exported from the automotive sector is 5.72%.

Moreover, around 27 kilotons of plastic in automotive waste were collected in 2017. For automotive products, collection is done separate from other products. Auto Recycling Nederland is the largest representative in this branch (CE Delft, 2019). Considering the flexible film content of total plastic in automotive products, which is 30.92% (Table 11.6), the following calculation can be made:

$$27 \times 0.3092 = 8.35\ kilotons\ of\ flexible\ film\ collected\ in\ automotive\ waste$$

The remainder of flexible film content is assumed to be still in use after a year, due to the average lifespan of vehicles of 17.9 years (CE Delft, 2019). This is represented as a net addition to stock in the MFA model.

Table 11.8
Calculations for the exported proportion of flexible films in automotive products.

Type of plastic	Proportion flexible film of total plastic in automotive	Proportion plastic exported in automotive	Proportion flexible film exported in automotive
Unit	(%)	(%)	(%)
LDPE	5.10	18.18	$5.10 \times 0.1818 = \mathbf{0.93}$
HDPE	0.95	17.39	$0.95 \times 0.1739 = \mathbf{0.17}$
PP	24.87	18.61	$24.87 \times 0.1861 = \mathbf{4.63}$
Total			5.72

*including LLDPE and MDPE

Other

From the ‘other’ category, it is assumed that 100% goes to residual waste collection. This is done due to the high diversity of types of products that this category can encompass. Moreover, Kawecki et al. (2018) also represent the waste flow of this category to fully go to mixed residual waste collections instead of a separate collection system. Based on the considerations mentioned, the flexible film content in the ‘other’ category is assumed to be fully disposed of through residual waste collection.

Waste Processing: Recycling, Incineration & Landfill

After the plastic flexible film waste is collected and sorted, it is processed either through recycling, incineration for energy recovery or landfilling. In this section, the calculations and material flows for flexible film waste processing are described.

Mechanical Recycling from DKR 310

The efficiency of household (consumer) plastic packaging waste was set to be between 57% and 65% in 2017 (Kerstens & Blanksma, 2019). For this study, an average recycling efficiency of 61% is therefore estimated for this flow. The remaining 39% is assumed to be incinerated. DKR originating from post-separation was until recently not generally accepted due to odour issues and was exported to Germany (TNO, 2017). Even though innovation is expected, for the MFA model of 2017, it is assumed this fraction is exported to Germany. The fraction of DKR310 from separately collected consumer waste goes to manufacturing of rPE from consumer waste.

Mechanical Recycling from DKR 350

Through the mechanical recycling process of the DKR 350 stream, the same recycling efficiency of 61% from Kerstens and Blanksma (2019) is chosen, as this also is a consumer waste flow. This flow of recycled mixed plastics was, in 2017, processed in Germany and used in products to replace wood, steel, concrete or virgin plastics (KIDV, 2017a). For the MFA model of 2017, this flow is therefore assumed to be exported. The remaining 39% is assumed to be incinerated.

Beverage Cartons Recycling

The recycle rate for beverage cartons is roughly estimated to be on average around 85% (Thoden van Velzen et al., 2017). For this study, the same efficiency is assumed for the flexible films in these products. The remainder is assumed to be incinerated.

Plastics are described as the by-products of the recycling process of beverage cartons. There have been several initiatives and tests between 2013 and 2017 for converting these by-products into a plastic re-granulate. These applications, however, suffered from odour issues. These issues are said to be resolved by the director of WEPA Nederland. Nevertheless, the by-products are currently still only sold as fuel to cement kilns (Thoden van Velzen et al., 2017). The same is therefore assumed for the 2017 MFA model.

Wecycle Plastic Recycling

As mentioned before, Wecycle is responsible for the collection and recycling EEE waste for municipalities in the Netherlands. Based on the average recycling results of the various EEE product categories, the proportion of plastic in reused material in 2017 is calculated by CE Delft (2019). From the plastic in WEEE that is collected, 71% is reused, 27% is incinerated and 2% is landfilled (CE Delft, 2019).

Automotive Plastic Waste Recycling

ARN is responsible for the processing of automotive waste in the Netherlands. This means recycling takes place here as well. The automotive recycling process consists of three steps: disassembly, shredding and post-shredder engineering at the PST plant (post shredder engineering factory). Of the automotive collected plastic waste arriving at the recycling process, the proportional division from 2017 is taken (CE Delft, 2019). This means that, of the collected automotive flexible film waste, 40% is recycled, 52% is incinerated and 8% is landfilled. The assumption here is that all plastic – minus dismantled car bumpers at an assembly company – in the shredder residue ends up at the PST plant and that all landfilling occurs from the processes at the PST plant (CE Delft, 2019). The recycled plastic in shredder residue is assumed flow to manufacturing of rPE from post-commercial plastic.

Construction Plastic Waste Recycling

From the amount of plastic in collected construction waste, it is estimated that 25% was recycled, 65% was incinerated and 10% was landfilled in 2017 (CE Delft, 2019). The same proportional distribution is assumed for this study. The recycled plastic is assumed to flow manufacturing of rPE from post-commercial plastic.

Commercial Plastic Waste Recycling

The collected and sorted commercial waste content from commercial packaging and agricultural films is assumed to be recycled as commercial waste. Kerstens and Blanksma (2019) mention that the recycling efficiency of commercial and industrial plastic waste in 2017 was set at 85% to 90% by Wageningen University & Research (2019, in Ministerie van Infrastructuur en Waterstaat, 2020). Since post-industrial waste is considered to be of a higher quality than post-commercial waste (DEISS, n.d.), an efficiency of 85% is assumed for flexible film commercial recycling in this study. This amount goes to manufacturing of rPE from commercial waste, whereas for post-industrial waste, a recycling efficiency of 90% is assumed. The remainder of this flow is incinerated.

Industrial Plastic Waste Recycling

As mentioned in the previous section, an efficiency of 90% is assumed for flexible film industrial recycling in this study, since this is a higher quality waste stream than post-commercial plastic waste presents (DEISS, n.d.). It is unsure where the remainder of this waste stream goes to (CE Delft, 2019). In this study, it is therefore assumed that this is incinerated.

Remanufacturing

As explained in the previous section, some recycled content is exported. The other recycled contents are manufactured and, hereafter, reapplied in different sectors for different uses in the Netherlands. The following sections explain this for the different manufacturing processes.

Much filtering and losses occur already during recycling of flexible films. The rPE flakes can be manufactured the same way as virgin flakes, but some strength, odour and colour issues occur with rPE. This is most evident with rPE from consumer waste, followed by rPE from commercial waste and, lastly rPE from industrial waste. This means that the recyclate is currently not produced for the same high-quality products as virgin flexible films. For this reason, the recyclate from these waste types is currently used in lower-quality products. The losses due to the difference in quality of the different rPE types (consumer, commercial and industrial) is assumed to be visible through the losses that have already occurred during the different recycling processes, rather than during the remanufacturing processes.

Therefore, the relatively lower quality of rPE compared to virgin plastic will not make much difference in the efficiency of the remanufacturing process, as it is not applied in the same quality-level products and most losses are accounted for during recycling itself. This means that the losses are assumed to be the same as with the regular manufacturing process, but the output is a lower quality product than is the case with virgin flexible film. This means that an efficiency of 93.32% is assumed for the remanufacturing processes.

Manufacturing of rPE from consumer waste and commercial waste

Based on the beforementioned reasoning, an efficiency of 93.32% is assumed for the remanufacturing processes. The remainder of both processes is assumed to be incinerated. Both post-consumer and post-commercial content are, after recycling, summarized under the term post-consumer recycled (PCR) (DEISS, n.d.). That is why these are explained under one heading in this study. The mass of recycled plastics used has been broken down by origin by RIVM (2019), with 93% of the reported recyclate consisting of post-consumer plastic and 7% of post-industrial plastic. From previous calculations it became clear that 57.76 kilotons of recycled flexible films are applied on the Dutch market. This gives the following calculation for the amount of reapplied PCR rPE films:

$$57.76 \times 0.93 = 53.72 \; kilotons\; of\; reapplied\; PCR\; rPE$$

Moreover, this flow of manufactured rPE is used for, among other things, garbage bags, agricultural film and logistical resources with a structural application. Examples of logistical resources are planks, pallets, posts, beams, panels, blocks and storage aids (Bergsma & Bijleveld, 2017; Partners for Innovation & Rebel, 2018). No proportional division is known between these product types. Nonetheless, a research from Deloitte Sustainability (2017), based on statistics from 2015, gives the sectoral demand per resin. The report states that the highest demand of the recyclates of flexible film is observed in packaging (27%), construction (mainly for pipes production, insulation or carpets) (23%) and industries and other end markets (50%) (Deloitte Sustainability, 2017). Half of the amount for other industries and other end markets (25%) is assumed to go to agriculture, because recycled content is often applied for agricultural films in The Netherlands (Bergsma & Bijleveld, 2017; Partners for Innovation & Rebel, 2018). The other half (25%) goes to the 'other' category. The 'other' category includes, according to the research from Deloitte Sustainability (2017), smaller markets, such as furniture and non-film consumer goods like clothes hangers and boxes. This category is also assumed to include the logistical resources with a structural application. The following calculations provide the applied PCR rPE in within the different sectors:

$$53.72 \times 0.27 = 14.50 \; kilotons\; PCR\; rPE\; applied\; in\; packaging$$

$$53.72 \times 0.23 = 12.36 \; kilotons\; PCR\; rPE\; applied\; in\; construction$$

$$53.72 \times 0.25 = 13.43 \; kilotons\; PCR\; rPE\; applied\; in\; agriculture$$

$$53.72 \times 0.25 = 13.43 kilotons\; PCR\; rPE\; applied\; in\; other$$

Manufacturing rPE from industrial plastic waste

Another recycling stream is PIR: post-industrial recycle or regrind. This is waste that is created during the production process of products. This could be material that got onto the factory floor or material with a manufacturing defect (KIVO, n.d.-a). As stated before, 7% of the rPE content (57.76

kilotons) measured by RIVM (2019), originated from industrial waste. This gives the following equation:

$$57.76 \times 0.07 = 4.04\ kilotons\ of\ reapplied\ PIR\ rPE$$

Moreover, many companies already recycle their own stream of post-industrial waste, which means that this material is not available on the free market (KIVO, n.d.a). Therefore, after recycling, there is no separate process for remanufacturing PIR rPE films form industrial waste. Rather, the reapplied PIR rPE flows back to the initial manufacturing process.

A.2 Results for linearly and circularly processed content

The table below displays the proportional division between linearly and circularly processed, and subsequently, the proportion incinerated for energy recovery and recycled content being reapplied. This is done relative to (1) the amount of flexible films produced in the Netherlands, (2) the amount of flexible films brought on the Dutch market and (3) the total amount of processed flexible film waste (excluding flexible film content still in use and littered).

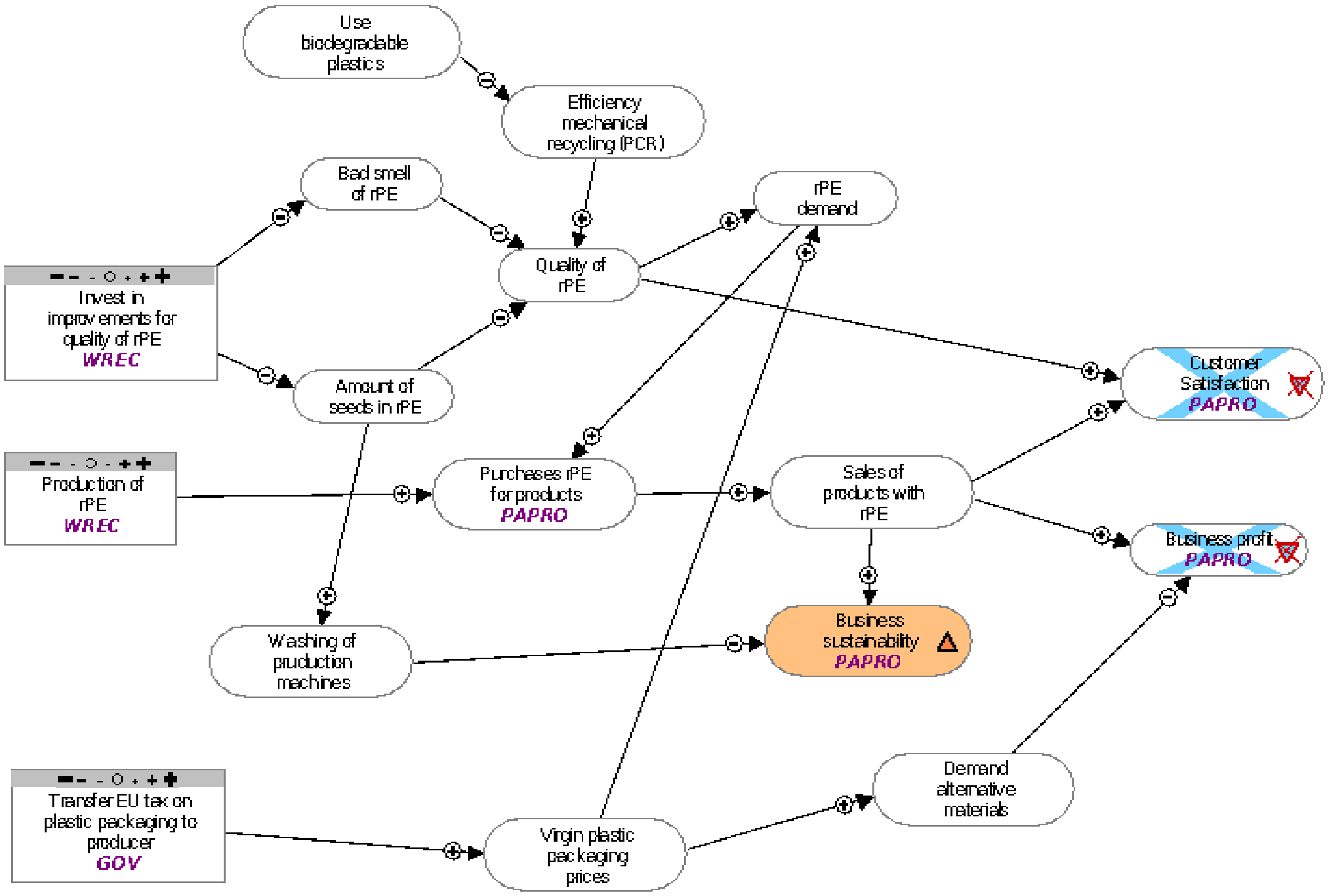
Processing category / Destination	Unit	Value
Flexible films produced in the Netherlands (excluding flexible films imported for manufacturing)	Tons	390,372.85
Linearly processed	%	91.47
Circularly processed (reused, reapplied and unused)	%	38.25
Incinerated	%	89.07
Reused and reapplied	%	17.06
Flexible films brought on the Dutch market	Tons	683,917.31
Linearly processed	%	52.21
Circularly processed (reused, reapplied and unused)	%	21.83
Incinerated	%	50.84
Reused and reapplied	%	9.74
Total Processed Flexible film waste	Tons	505,374.46
Linearly processed	%	70.52
Circularly processed (reused, reapplied and unused)	%	29.48
Incinerated	%	68.67
Reused and reapplied	%	13.15

Appendix B

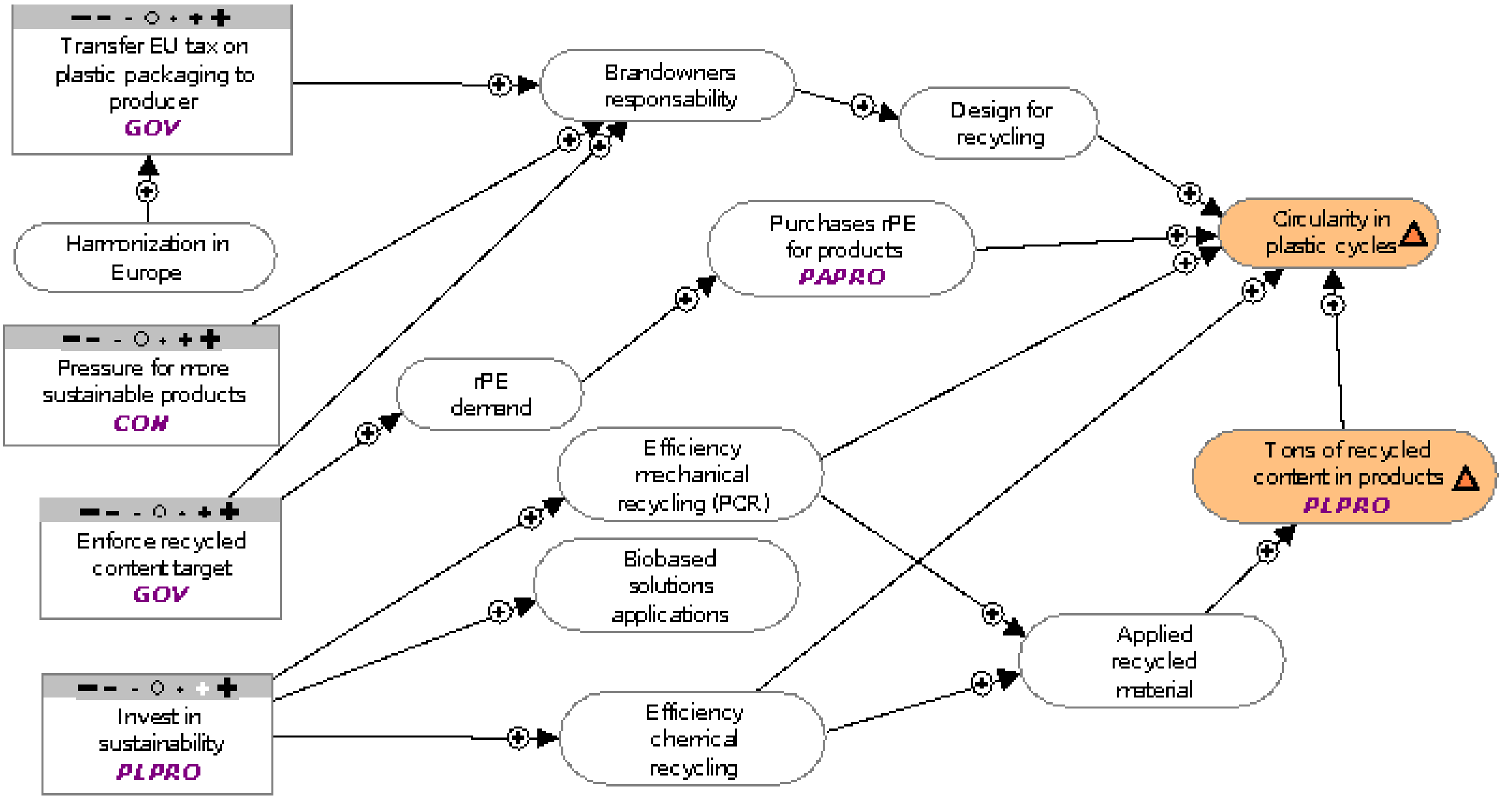
Comparative Cognitive Mapping

B.1. Causal cognitive maps of all the interviewed respondents in the context of circular flexible film supply chain

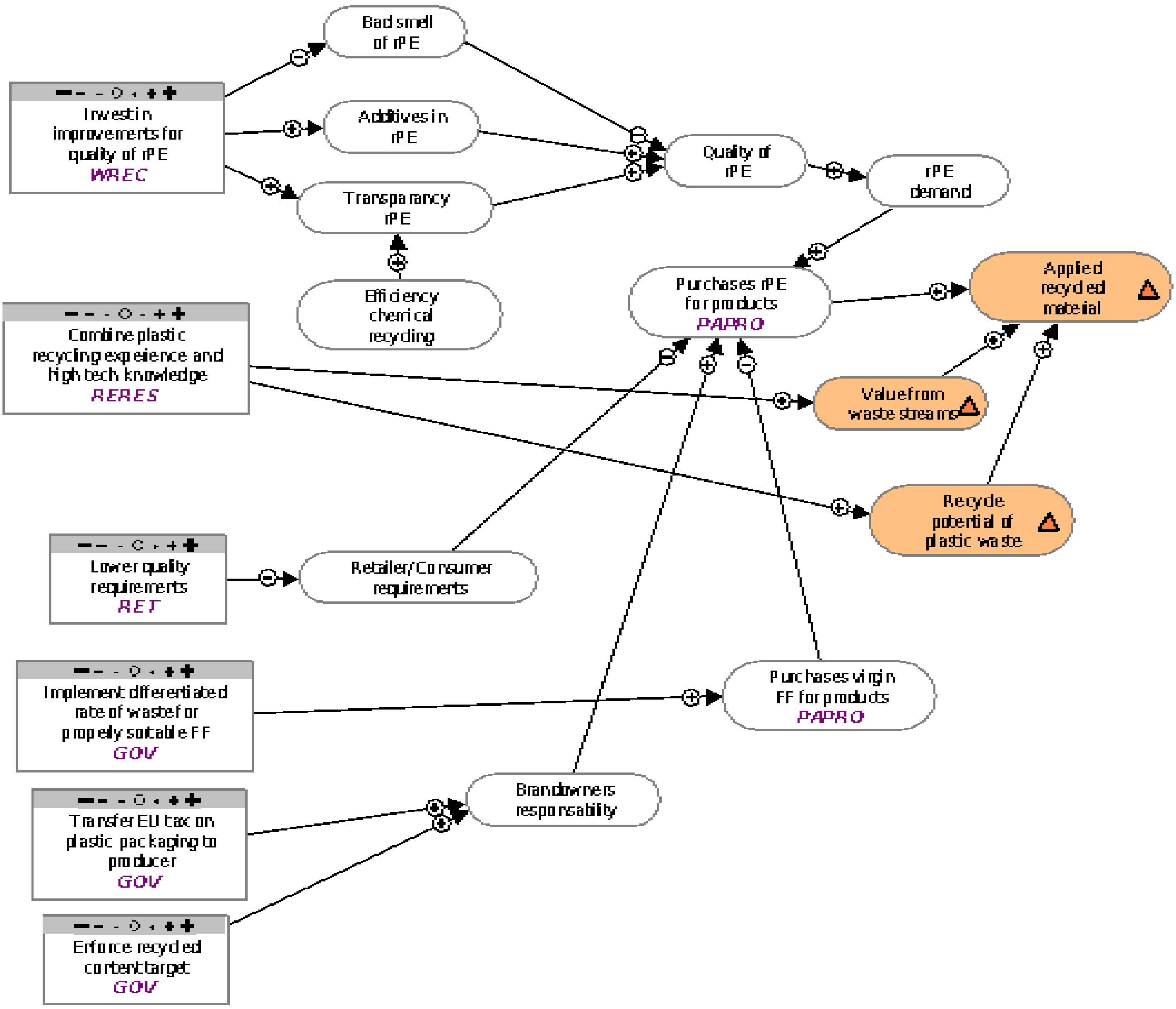
Packaging producer:



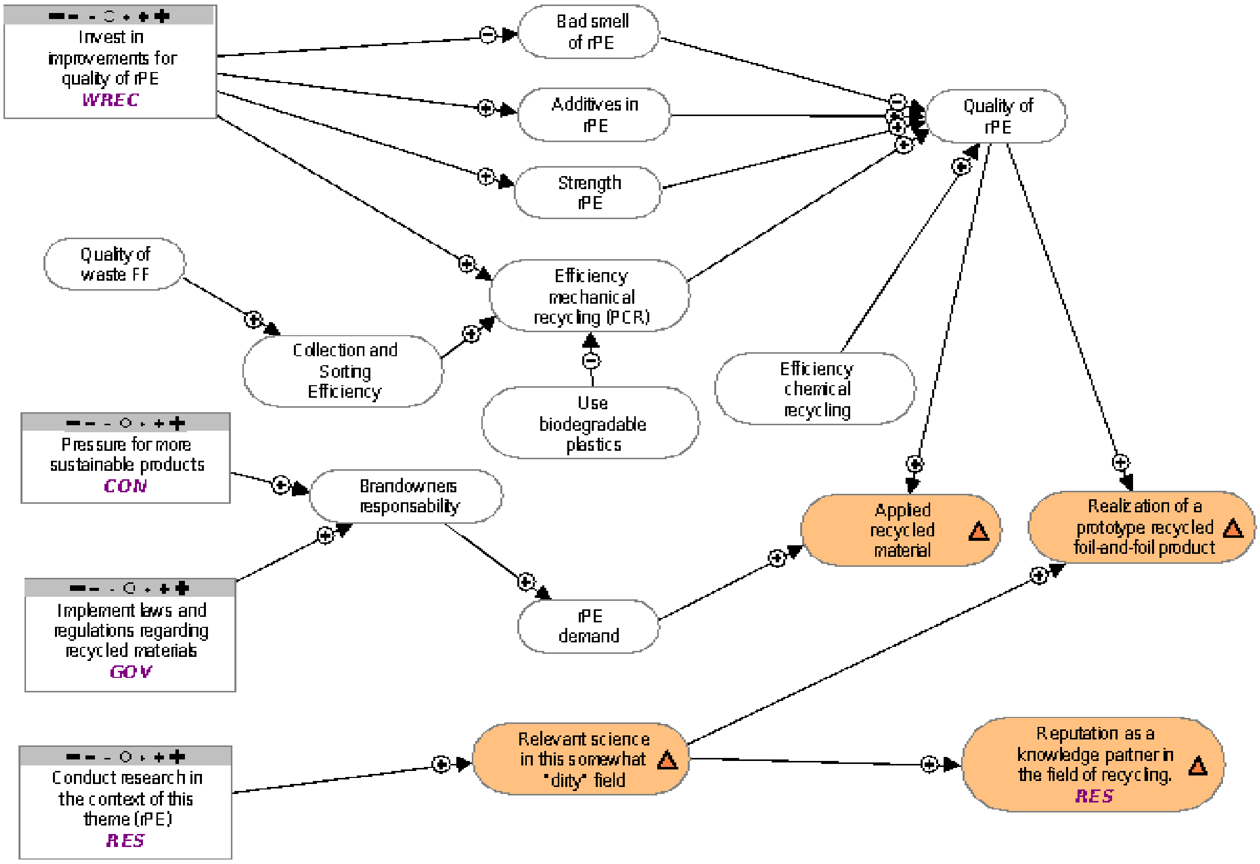
Plastic producer:



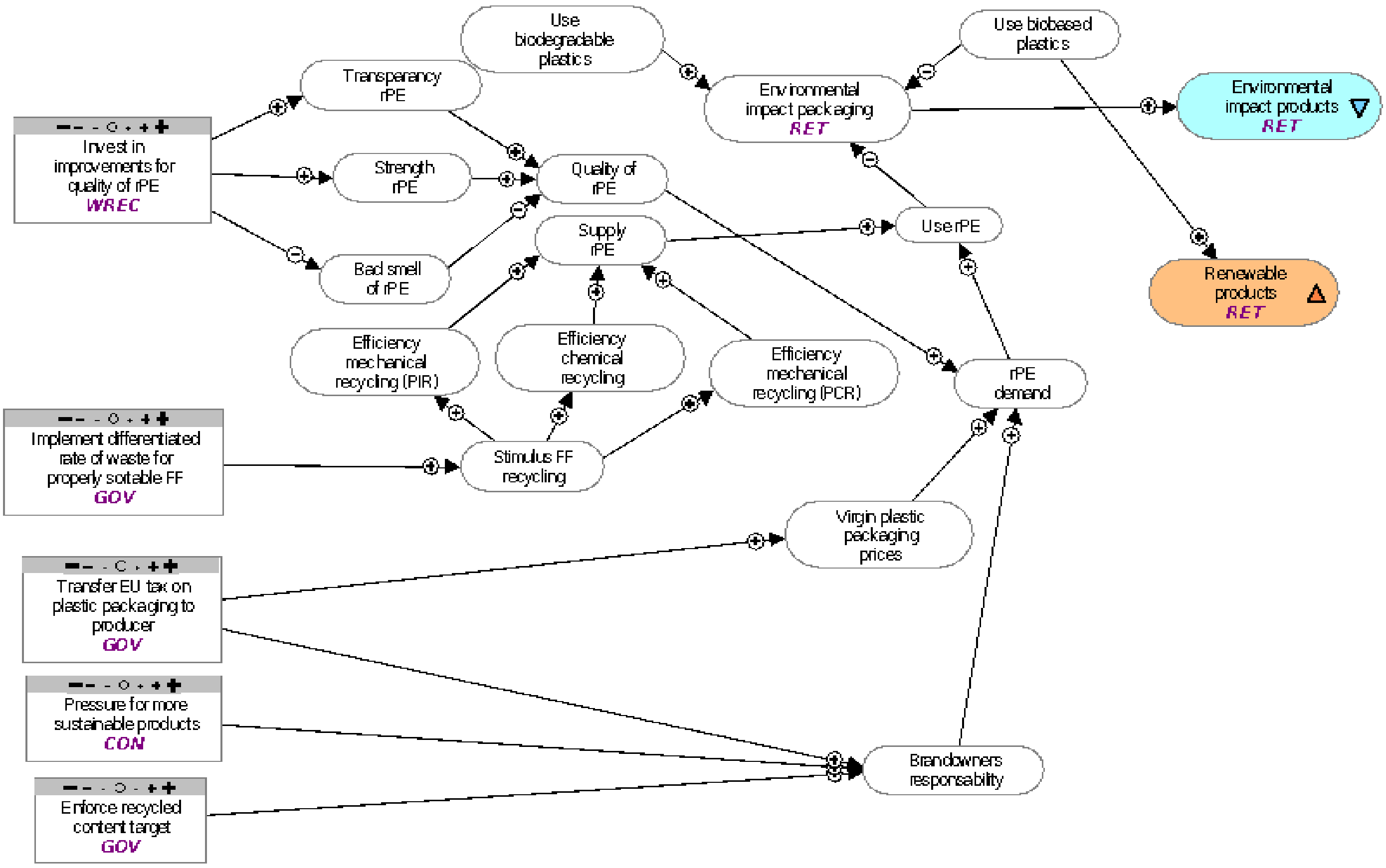
Recycle Research Entity:



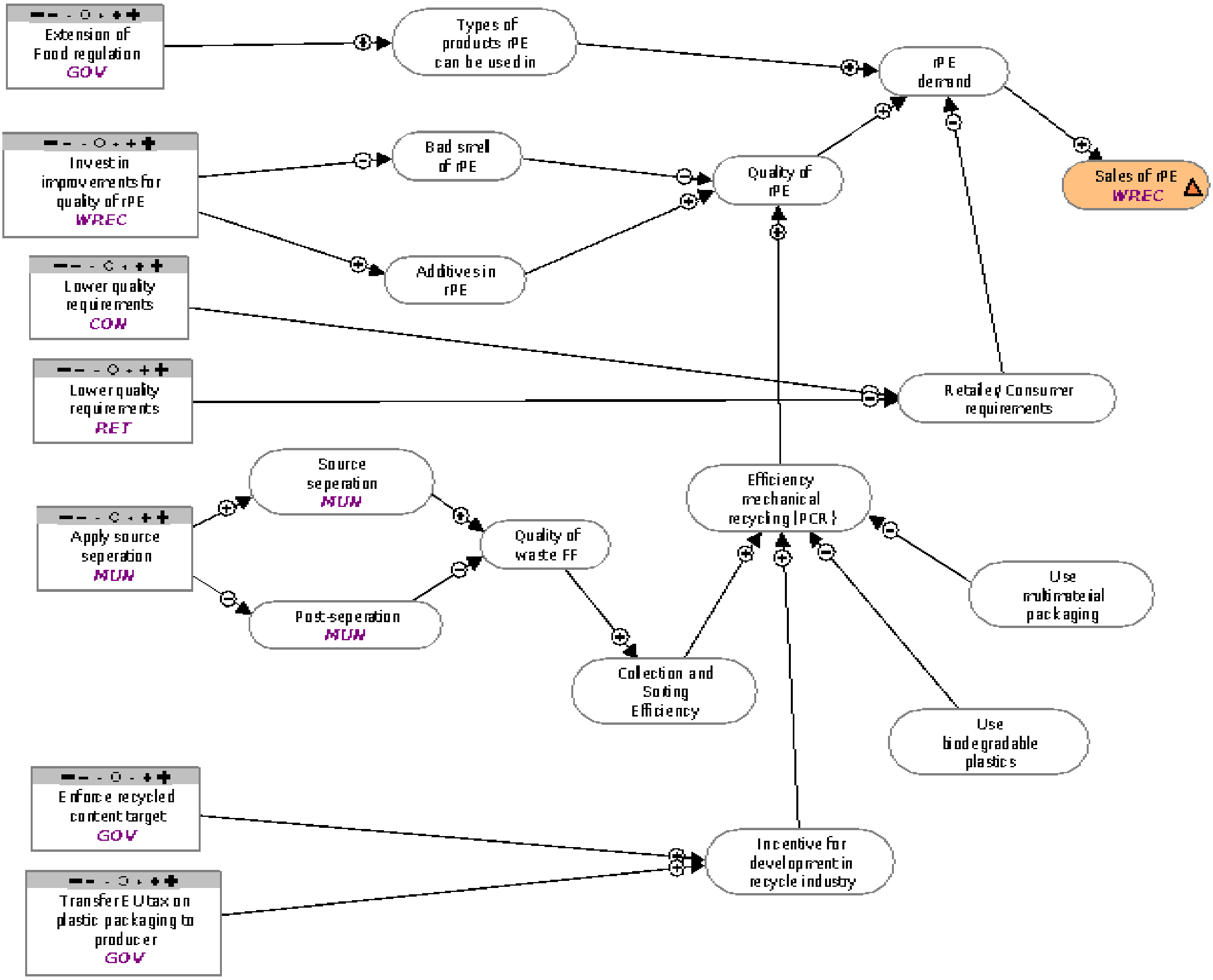
Research Institute:



Retailer:


Use biodegradable plastics
Use biobased plastics
Transparency rPE
Environmental impact packaging
RET
Environmental impact products
RET
Invest in improvements for quality of rPE
WREC
Strength rPE
Quality of rPE
Supply rPE
Use rPE
Bad smell of rPE
Renewable products
RET
Efficiency mechanical recycling (PIR)
Efficiency chemical recycling
Efficiency mechanical recycling (PCR)
rPE demand
Implement differentiated rate of waste for properly sortable FF
GOV
Stimulus FF recycling
Virgin plastic packaging prices
Transfer EU tax on plastic packaging to producer
GOV
Pressure for more sustainable products
CON
Brandowners responsability
Enforce recycled content target
GOV

Waste processor/Recycler:



B.2. Results for measuring the relevance of different factors

The table below shows the results of the CCM analysis for estimating relevance, for each factor in the perception graphs. Relevance is measured by number of occurrences of a certain factor and percentage of occurrences divided by the amount of actors. Subsequently, in the following table, connectivity and centrality are assessed for each factor, through associated links divided by actors and paths divided by actors.

Relevance

Arena I→		
Actor A→		
Factors	#Occurrences	%Occ / actor
Additives in rPE	3	50%
Amount of seeds in rPE	1	17%
Applied recycled material	3	50%
Apply source seperation ***[MUN]***	1	17%
Bad smell of rPE	5	83%
Biobased solutions applications	1	17%
Brandowners responsibility	4	67%
Business profit ***[PAPRO]***	1	17%
Business sustainability ***[PAPRO]***	1	17%
Circularity in plastic cycles	1	17%
Collection and Sorting Efficiency	2	33%
Combine plastic recycling experience and high-tech knowledge ***[RERES]***	1	17%
Conduct research in the context of this theme (rPE) ***[RES]***	1	17%
Customer Satisfaction ***[PAPRO]***	1	17%
Demand alternative materials	1	17%
Design for recycling	1	17%
Efficiency chemical recycling	4	67%
Efficiency mechanical recycling (PCR)	5	83%
Efficiency mechanical recycling (PIR)	1	17%
Enforce recycled content target ***[GOV]***	4	67%
Environmental impact packaging ***[RET]***	1	17%
Environmental impact products ***[RET]***	1	17%
Extension of Food regulation ***[GOV]***	1	17%
Harmonization in Europe	1	17%
Implement differentiated rate of waste for properly sortable FF ***[GOV]***	2	33%
Implement laws and regulations regarding recycled materials ***[GOV]***	1	17%
Incentive for development in recycle industry	1	17%
Invest in improvements for quality of rPE ***[WREC]***	5	83%

Invest in sustainability ***[PLPRO]***	1	17%
Lower quality requirements ***[CON]***	1	17%
Lower quality requirements ***[RET]***	2	33%
Post-seperation ***[MUN]***	1	17%
Pressure for more sustainable products ***[CON]***	3	50%
Production of rPE ***[WREC]***	1	17%
Purchases rPE for products ***[PAPRO]***	3	50%
Purchases virgin FF for products ***[PAPRO]***	1	17%
Quality of rPE	5	83%
Quality of waste FF	2	33%
Realization of a prototype recycled foil-and-foil product	1	17%
Recycle potential of plastic waste	1	17%
Relevant science in this somewhat "dirty" field	1	17%
Renewable products ***[RET]***	1	17%
Reputation as a knowledge partner in the field of recycling. ***[RES]***	1	17%
Retailer/Consumer requirements	2	33%
rPE demand	6	100%
Sales of products with rPE	1	17%
Sales of rPE ***[WREC]***	1	17%
Source seperation ***[MUN]***	1	17%
Stimulus FF recycling	1	17%
Strength rPE	2	33%
Supply rPE	1	17%
Tons of recycled content in products ***[PLPRO]***	1	17%
Transfer EU tax on plastic packaging to producer ***[GOV]***	5	83%
Transparency rPE	2	33%
Types of products rPE can be used in	1	17%
Use biobased plastics	1	17%
Use biodegradable plastics	4	67%
Use multi-material packaging	1	17%
Use rPE	1	17%
Value from waste streams	1	17%
Virgin plastic packaging prices	2	33%
Washing of production machines	1	17%

Connectivity and centrality

Arena I→	Dutch FF value chain	
Actor A→	Actor group	
Factors	Links / actor	Paths / actor

Additives in rPE	1	3.8
Amount of seeds in rPE	0.50	3.5
Applied recycled material	1.3	8.7
Apply source seperation ***[MUN]***	0.33	2.3
Bad smell of rPE	1.7	8.5
Biobased solutions applications	0.17	0.17
Brand Owners responsibility	2.3	8.2
Business profit ***[PAPRO]***	0.33	2.7
Business sustainability ***[PAPRO]***	0.33	2.7
Circularity in plastic cycles	0.83	3.2
Collection and Sorting Efficiency	0.67	6.3
Combine plastic recycling experience and high-tech knowledge ***[RERES]***	0.33	0.67
Conduct research in the context of this theme (rPE) ***[RES]***	0.17	0.50
Customer Satisfaction ***[PAPRO]***	0.33	3.3
Demand alternative materials	0.33	0.83
Design for recycling	0.33	1.8
Efficiency chemical recycling	1.2	5.2
Efficiency mechanical recycling (PCR)	2.7	18
Efficiency mechanical recycling (PIR)	0.33	2.3
Enforce recycled content target ***[GOV]***	0.83	3.2
Environmental impact packaging ***[RET]***	0.67	9.2
Environmental impact products ***[RET]***	0.17	4.7
Extension of Food regulation ***[GOV]***	0.17	0.50
Harmonization in Europe	0.17	0.67
Implement differentiated rate of waste for properly sortable FF ***[GOV]***	0.33	3.2
Implement laws and regulations regarding recycled materials ***[GOV]***	0.17	0.50
Incentive for development in recycle industry	0.50	2.3
Invest in improvements for quality of rPE ***[WREC]***	2.3	13
Invest in sustainability ***[PLPRO]***	0.50	1.8
Lower quality requirements ***[CON]***	0.17	0.50
Lower quality requirements ***[RET]***	0.33	1
Post-seperation ***[MUN]***	0.33	2.2
Pressure for more sustainable products ***[CON]***	0.50	1.8
Production of rPE ***[WREC]***	0.17	0.83
Purchases rPE for products ***[PAPRO]***	1.7	16
Purchases virgin FF for products ***[PAPRO]***	0.33	0.83
Quality of rPE	4	35
Quality of waste FF	0.67	5.7
Realization of a prototype recycled foil-and-foil product	0.33	2.5

	Recycle potential of plastic waste	0.33	0.50
	Relevant science in this somewhat "dirty" field	0.50	0.83
	Renewable products ***[RET]***	0.17	0.17
	Reputation as a knowledge partner in the field of recycling. ***[RES]***	0.17	0.33
	Retailer/Consumer requirements	0.83	2.2
	rPE demand	2.8	33
	Sales of products with rPE	0.67	8.5
	Sales of rPE ***[WREC]***	0.17	3.8
	Source seperation ***[MUN]***	0.33	2.2
	Stimulus FF recycling	0.67	5.2
	Strength rPE	0.67	3
	Supply rPE	0.67	6.5
	Tons of recycled content in products ***[PLPRO]***	0.33	1.8
	Transfer EU tax on plastic packaging to producer ***[GOV]***	1.2	5.7
	Transparency rPE	0.83	4.2
	Types of products rPE can be used in	0.33	0.83
	Use biobased plastics	0.33	0.50
	Use biodegradable plastics	0.67	3.2
	Use multi-material packaging	0.17	0.67
	Use rPE	0.50	12
	Value from waste streams	0.33	0.50
	Virgin plastic packaging prices	0.83	4.3
	Washing of production machines	0.33	0.83

B.3. Results for measuring the similarity of perceived causality

The table below displays similarity of perceived causality. The cell values reflect how much of B's perception is shared by A. This is estimated in terms pg shared factors or a similar view in terms of path similarity.

		Actor A→	Packaging Producer		Plastic Producer		Recycle Research Institute		Research Institute		Retailer		Waste processor / Recycler	
Actor B ↓	Factors	Paths	% Shared factors	% Path similarity	% Shared factors	% Path similarity	% Shared factors	% Path similarity	% Shared factors	% Path similarity	% Shared factors	% Path similarity	% Shared factors	% Path similarity
Packaging Producer	17	98	100%	100%	24%	73%	35%	97%	35%	82%	47%	87%	41%	95%
Plastic Producer	15	44	27%	73%	100%	100%	47%	78%	40%	79%	47%	83%	27%	73%
Recycle Research Institute	19	62	32%	97%	37%	78%	100%	100%	42%	89%	53%	86%	47%	87%
Research Institute	19	60	32%	82%	32%	79%	42%	89%	100%	100%	53%	81%	47%	86%
Retailer	23	122	35%	87%	30%	83%	43%	86%	43%	81%	100%	100%	35%	81%
Waste processor / Recycler	22	90	32%	95%	18%	73%	41%	87%	41%	86%	36%	81%	100%	100%

B.4. Results for measuring action and goal conflicts between the supply chain actors

The table below displays the results for the CCM analysis for goal and action conflicts. The cell values indicate how strongly A is opposed to B's ideas in terms of goals and actions.

Actor A→	Packaging Producer		Plastic Producer		Recycle Research Institute		Research Institute		Retailer		Waste processor / Recycler	
Actor B ↓	μ Goal Conflict	μ Action Conflict	μ Goal Conflict	μ Action Conflict	μ Goal Conflict	μ Action Conflict	μ Goal Conflict	μ Action Conflict	μ Goal Conflict	μ Action Conflict	μ Goal Conflict	μ Action Conflict
Packaging Producer	0	0	0	0.25	0	0	0	0	0	0	0	0
Plastic Producer	0	0	0	0	0	0	0	0	0	0	0	0
Recycle Research Institute	0	0	0	0.13	0	0	0	0	0	0.29	0	0
Research Institute	0	0	0	0	0	0	0	0	0	0	0	0
Retailer	0	0	0	0.08	0	0.29	0	0	0	0	0	0
Waste processor / Recycler	0	0	0	0.13	0	0	0	0	0	0	0	0

B.6. Results for measuring the interdependency between actors

The table below displays the results for the CCM resource dependency analysis. Beside the interviewed stakeholders, the agents (government, municipalities and consumer) are added to the analysis. The cell values indicate how strongly A believes its goal achievement may be affected by B's actions. This is measured by the number of relevant actions of Actor B for Actor A.

	Actor A→	Packaging Producer	Plastic Producer	Recycle Research Institute	Research Institute	Retailer	Waste processor / Recycler	Central Government	Consumer	Municipalities
	Actor B ↓	# Relevant Actions	# Relevant Actions	# Relevant Actions	# Relevant Actions	# Relevant Actions	# Relevant Actions	# Relevant Actions	# Relevant Actions	# Relevant Actions
Packaging Producer		0	0	0	0	0	0	0	0	0
Plastic Producer		0	1	0	0	0	0	0	0	0
Recycle Research Institute		0	0	1	0	0	0	0	0	0
Research Institute		0	0	0	1	0	0	0	0	0
Retailer		0	0	1	0	0	1	0	0	0
Waste processor / Recycler		2	0	1	1	1	1	0	0	0
Central Government		1	1	3	1	3	3	0	0	0
Consumer		0	1	0	1	1	1	0	0	0
Municipalities		0	0	0	0	0	1	0	0	0

Appendix C

Dynamic Modelling

C.1. Elaboration on interview analysis, desk research and equations behind the trends for and relationships between the different factors

Several technical, institutional and market components will affect the demand of rPE in the coming five years. In this section, the factors that emerged during the interviews are elaborated on with regard to rPE demand. Nevertheless, during the analysis it was discovered that some factors rather display a relationship with supply of rPE than demand. Attention is paid to this during the explanation of the relevant factors. The factors that are incorporated in the remaining four themes, are qualitatively explained, from which quantitative estimations are made for future developments influencing rPE demand (or supply).

Trend rPE Market

Price of oil

Market characteristics can have an influence on the demand of rPE. First of all, the recycling PE films is not yet profitable with respect to the market value (Verrips et al., 2017). Currently, virgin plastic has a very low price, due to the historically low oil prices (Gimbrère & van de Keuken, 2020). WREC explains how currently the selling of rPE to packaging producers is difficult, because the relative costs of producing are higher for rPE than virgin films. This is acknowledged by PAPRO, even though the market price of virgin flexible film is currently higher (Nederlands Verpakkingscentrum, n.d.). This has to do with extra operations for additional treatment that have to be carried out with rPE in comparison to virgin LDPE, due to the lower quality of the regranulate. PAPRO acknowledges this obstacle and states that one of the problems with rLDPE in the foil producing machines in comparison to virgin flexible films:

"*I think application-oriented […] production is [important]. I think it is important that these granulates do not become an obstacle in the machine. Still a factor in production is die build-up. This means the die will be contaminated and the burnt material can come off and get into the film or can cause the film to break*[6]."

RERES also states that virgin LDPE is still cheaper and easier to work with. He states about the application of recycled materials that "*you have to really want it*". RET explains the same thing, by stating:

"*Customers find it an interesting story. They all ask what you can do in the field of sustainable packaging, but (…) if it's more expensive there's an extra barrier to deal with.*[7]"

[6] This quote was altered a bit by respondent after the interview. The last part of the quote originally stated: "(…) In the machine. We call this 'head pollution' or 'beard growth'. The ring the [product] comes out of, dirt particles can get caked on. This can cause the foil to break". Afterwards, the respondent expressed this in a more elaborate manner, which is represented by the current quote.

[7] The last part of this quote was added by respondent after the interview. The last sentence of the quote origionally stated: "(...) *but if it is more expensive it will not work anyway*". Afterwards, the respondent expressed this in a more nuanced manner, which is represented by the current quote.

For the low scenario, the expectation is that the price of oil and thus virgin plastic from oil will decrease, positively influencing demand. This is due to increasing demand for renewables, especially in the transport sector (Gimbrère & van de Keuken, 2020). When a reasonably harmonious global development takes place, in which countries can easily reach agreements, strict and enforceable arrangements can be made for a sustainable future (Verrips et al., 2017). In context of global climate policy, this could imply far-reaching CO_2 emission reductions, which subsequently has a strong depressing effect on the demand for oil. In addition, international trade relationships thrive in such a world, promoting international competition. This stimulates innovative technological development, as a result of which alternatives to fossil fuels also become cheaper relatively quickly. Finally, it is in line with this world view that geopolitical tensions are limited. So, although global economic growth is high, the demand for fossil fuels is declining rapidly and the price increase is limited (Verrips et al., 2017). This presents the picture in the High scenario of the Future Outlook on Welfare and the Living Environment (WLO; CPB & PBL, in Verrips et al., 2017) outlined for the coming decades.

Nonetheless, another scenario could also take place, as outlined in the WLO Low scenario (Verrips et al., 2017). In this scenario, major geopolitical tensions are assumed, that in themselves could push up oil prices. This would mean that no far-reaching climate agreement appear to be achievable. In this scenario, the world is unable to realize a meaningful CO_2 emission reduction. The share of oil and other fossil fuels in the energy supply remains stubbornly high. In addition, the world is fragmenting into trading blocks, which restricts competition and slows down technological innovation. In this scenario, therefore, demand for oil and other fossil fuels remains relatively high, which ensures a high oil and, thus, virgin plastic price (Verrips et al., 2017). Even though this is mentioned as the low scenario by Verrips et al. (2017), for this analysis it is considered for the high scenario. This is because a drop in oil and virgin plastic prices has a negative influence and a price increase a positive effect on rPE demand.

Currently, the price of crude oil is around 62 dollars per barrel (Oilprice, 2021). According to estimations from Oilprice (2021), this price will decrease to around 56 dollars per barrel in 2025. This provides the following calculations for the overall growth rate:

$$Total\ growth\ rate = \left(\frac{Future}{Present}\right) - 1$$
$$Total\ growth\ rate = \left(\frac{56}{62}\right) - 1$$
$$Total\ growth\ rate = 0.9032 - 1$$
$$Total\ growth\ rate = -0.0968$$
$$Total\ growth\ rate = -9.68\%$$

This means that the oil price would decrease by 9.68% over 5 years. For the annual growth rate, the following equations are formed:

$$Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$
$$Annual\ growthrate\ of\ oil\ price = \left(\frac{56}{62}\right)^{\frac{1}{5}} - 1$$
$$Annual\ growthrate\ of\ oil\ price = -0.0202$$
$$Annual\ growthrate\ of\ oil\ price = -2.02\%$$

This means that, according to Oilprice (2021), prices are expected to drop towards 2025, with an annual rate of -2.02%. This value is applied for the low scenario. For the high model, the opposite is expected, assuming a total increase in oil prices of 9.68%, considering the second scenario from Verrips et al. (2017). This gives the following calculation:

$$Oil\ price\ in\ 2025 = 62 \times 1.0968$$
$$Oil\ price\ in\ 2025 = 68$$
$$Annual\ growthrate\ of\ oil\ price = \left(\frac{68}{62}\right)^{\frac{1}{5}} - 1$$
$$Annual\ growthrate\ of\ oil\ price = 0.0187$$
$$Annual\ growthrate\ of\ oil\ price = 1.87\%$$

In the high scenario, an annual oil price increase of 1.87% is assumed, based on the equations above.

The oil price has a influence on rPE-demand because of the positive cross elasticity between the two. The cross elasticity of demand measures the responsiveness of demand for product X, with respect to the price of product Y. This is formally defined as the percentage change in the demand for product X that would result from a 1% change in the price of product Y (Hausman & Leonard, 2005). In order to estimate the effect that a change in price of oil or virgin plastic has on the demand of rPE, the cross elasticity of demand should be defined. The cross elasticity of demand between recycled plastics and virgin plastic is said to be positive (Williams, 2018). Nonetheless, the exact value of the cross elasticity of demand for recycled plastics compared to a price change in virgin plastics or crude oil is yet unknown.

Nevertheless, For this study a cross elasticity of 0.18% is assumed, based on a study by Boyle (2017). This study explored what impact the price of virgin resources may have on the plastic material recycling industry as a whole. Boyle (2017) analysed the relationship between the benchmark price for crude oil produced in the US, West Texas Intermediate (WTI), and the producer price index (PPI), which indicates the changing condition of the plastic recycling industry by measuring the average changes in price received by domestic producers for their output. This study determined a significant positive correlation between WTI and PPI, indicating that a change of 1% in crude oil prices is accompanied by a change of 0.18% of PPI (Boyle, 2017). Since this coefficient is the closest to cross elasticity of demand for recycled plastics against crude oil price, it is applied in this study for estimations. This means that a price increase of 1% of oil results in 0.18% rise in rPE demand.

Retailer and Consumer Behaviour

There are also expectations from the buyer of plastic film. RET describes:

"*An important requirement is that the bag is and remains properly closed, also in the shop. That it has a good seal. [...] The constant quality of the film is important." [...] There is also an important marketing component: printing*."

For brand owners, labels are an important marketing component. Due to technical characteristical differences, such as smell and strength, this is more difficult with rPE than with virgin flexible films. Furthermore, the consumer is of influence. RET gives an example of a product made from recycled content (in this case not LDPE), where colour is apparently important for sale:

"*With the bottles you have to achieve a high masterbatch to maintain the green [...] colour. Then we thought: what if we do not use this for these bottles? Now they are grey bottles. That was very exciting. [...] there were a lot of discussions about it, but the difference seems big, people prefer to take the green bottle. You try to encourage the customer to take grey, but it seems that people prefer the green bottle a bit more. [...] the big step from green to grey bottles seems too big.*"

It is necessary to emphasize that the green and grey bottle were equally expensive, but the green version sold better than the grey one. Nonetheless, the respondent emphasizes that this does not stop them from continuing to sell the grey bottles. He states that "*maybe consumers have to get used to it, we will see.*[8]".

Moreover, PAPRO states that most brand owners rather have transparent virgin material than the black or greyish colour of rPE foil. He acknowledges that "*it must meet the customer's requirements*". Some other critical notes have also been made about the colour, smell and quality of recycled plastic, compared to its virgin competitor (Gimbrère & van de Keuken, 2020). This is also emphasized in the interview with PAPRO. RERES states that, in order to benefit the demand of rLDPE, some of the requirements about aesthetics should be moderated. He states it should no longer be expected for "*packaging to be transparent*". This already shows the interlinkage with the technical components, where the fifth theme is focussed on. Nevertheless, PLPRO thinks that brand owners feel "*the pressure of consumers* asking *for […] change*". RET states about this:

"*Eventually that demand will increase. […] it will go in that direction, whether that is a demand from consumer or retailer. It will just become the norm, so in that sense there is pressure. We would also like to be prepared for that.*"

RES is also convinced of this societal pressure. He thinks that "*everyone in the entire chain is equally involved in the entire trend*".

From Panel Wizard research commissioned by ABN AMRO involving more than 1000 Dutch people, it appears that the majority of consumers consider the sustainability of packaging important. A fifth of the respondents even indicated that they would like to pay up to 12% more for sustainable packaging (ABN AMRO, 2020). Sustainable consumption in the food sector also appears to have increased by 18% between 2018 and 2020 (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2020). This percentage is also used as a starting point for this study, because growth figures for sustainable consumption in the plastic industry are lacking. The increase in sustainable consumer behaviour is assumed to go hand in hand with decreasing retailer demands.

Nevertheless, the research by ABN AMRO (2020) shows that plastic is not perceived as sustainable. The research shows that many consumers think that plastic is the least sustainable option, while it does not have to be (ABN AMRO, 2020). The assumption for this study is that there is an increase in sustainable consumption and therefore less demanding consumer and retailer requirements. However, due to the bad reputation of plastic among consumers, the 18% increasing trend in two years is expected to be too ambitious. Therefore, half of this percentage is assumed for plastic consumption, leading to an increase in two years of 9%. If this is assumed to be a gradual increase over two years, the following calculation is formed:

[8] The last short sentence of this quote was added later after consultation with the respondent to emphasize that they are not going to stop selling the grey bottles. They think this product will eventually work just fine on the market.

$$Growthrate\ sustainable\ consumption\ in\ two\ years = 9\%$$
$$Growthrate\ sustainable\ consumption\ in\ two\ years = 0.09$$
$$Annual\ growthrate\ of\ sustainable\ consumption = (1.09)^{\frac{1}{2}} - 1$$
$$Annual\ growthrate\ of\ sustainable\ consumption = 0.0440$$
$$Annual\ growthrate\ of\ sustainable\ consumption = 4.40\%$$

Based on the calculation above, an annual increase of 4.40% in sustainable consumption is assumed for both scenarios. This is assumed to affect total demand with the same annual rate, as the sustainable consumption trend is assumed to influence businesses and industry in the same way.

Competing & Complement Markets

Bioplastics

Biobased is defined in European standard EN 16575 as ‘derived from biomass’. This means that a biobased product is wholly or partly derived from biomass. Biomass, subsequently, is a material of biological origin, which is not embedded in geological formations nor fossilized (Van den Oever et al., 2017). First, it is important to note that there is a distinction between biodegradable and non-biodegradable biobased plastics. If bio-based plastics are biodegradable, it can be broken down by microorganisms into water, biomass and naturally occurring gases like carbon dioxide and methane. For biobased plastics that are not biodegradable, this is not the case (Van den Oever et al., 2017).

RERES states how this often causes confusion for the consumer. Biobased plastics have to be disposed of with the plastic waste, but the biodegradable plastics should be disposed of with the organic waste. Nonetheless, since the degradation time of the plastic product is often longer than the time it stays in composting plants (interview with WREC), biodegradable plastics could probably better be disposed of as residual waste. This is often done wrong by the consumer. Biobased plastics have exactly the same composition as fossil-based polymers, as it only differs in source. Therefore, it causes no disruption during the recycling process and it can also not be detected in recycled material (WREC in interview, 2021). If biodegradable plastic waste, however, ends up in the DKR310 flow, it is seen as “*disruptive from the perspective of the recycling chain*”, according to WREC. Also, PAPRO emphasizes that this biodegradable plastic flow is not stimulating and even disruptive. This plastic type can, however, be applied in agriculture, PAPRO says, because it can compost directly there. RES states the following about biodegradable plastic:

“*I feel like it kind of lingers in the smaller volumes and, therefore, I think it is more of a distraction than that it provides results. In my opinion it is something that sounds good but does not work well*.”

Van den Oever et al. (2017) acknowledge the comments of the interviewees, to the extent that biodegradability can be a useful characteristic for specific marine and soil related applications like fishing lines and mulch films. WREC states that biobased plastic has the same chemical structure as fossil-based polymer and that biobased is therefore not disruptive, in contrast to biodegradable.

Currently, the share of bioplastics on the European market about 1% (Bergsma & Broeren, 2020). The same percentage applies approximately in the Netherlands. The expectation is that this is roughly evenly distributed over all types of plastic. This means that the assumption for both scenarios is that currently 1% of the flexible film market consists of bioplastics. Even though the respondents mention biodegradable plastic to be disruptive for the recycling process, a study at WFBR has shown that mixing up to 10% of a starch based film and up to 10% of a PLA film in a sorted plastic film mixture has no significant negative effect on mechanical properties of the recyclate (Van den Oever et al., 2017). Since bio-based plastics only form a very small percentage of the market, no decrease in efficiency within the recycling process is assumed for this study yet.

Furthermore, no ratios are given between the fraction of biobased and biodegradable plastics in the Netherlands. For this reason, the global distribution has been assumed, where approximately 43% of bioplastics is biodegradable and 57% is not (Bergsma & Broeren, 2020). Because biodegradable films are made from (combinations of) almost any type of biodegradable plastic, all of these types are included in this analysis as a competitor to rPE. For biobased plastics it is assumed that only biobased PE is a competitor for rPE films. Biobased PE is 9.70% of the total biobased plastics supply (Bergsma & Broeren, 2020). This gives the following calculation for the number of bioplastics on the Dutch market, competing with rPE films:

$$1 \times 0.43 = 0.43\%\ biodegradable\ plastics\ on\ the\ PE\ film\ market\ in\ 2020$$

$$1 \times (0.57 \times 0.097) = 0.06\%\ biobased\ plastics\ on\ the\ PE\ film\ market\ in\ 2020$$

Since bio-based plastics form a competition for rPE films, the assumption for both scenarios is that the rPE demand decreases with the number of bioplastics that is on the market.

RERES thinks that bioplastics will not occupy more than 1 to 2% of the rPE market. RET also acknowledges that he sees bioplastics rather as an in-between phase. He states that since it is still "*a virgin material […] we ultimately want to get rid of that and we want to focus on recycling*". PAPRO explains he thinks bioplastics will still be applied in certain applications, but that this will probably remain a small part. Nevertheless, some recent studies estimate that the market for biobased plastic is only increasing in the coming years. Molenveld and Bos (2019) state that many new factories and widely applied technologies are at the beginning of their learning curve. The launch of new biobased plastics therefore appears to have only just started.

For the market of biobased plastics itself, a growth of more than 20% per year is expected. Based on this prediction, biobased plastics will take up a modest share of the market the next decade. The expectation is that after 2020 the market for biobased materials will experience greater growth (Molenveld & Bos, 2019). The forecast from the latest market report on the future of bioplastics for packaging up to 2024, by research firm Smithers Pira (in Agro&Chemie, 2021), has slightly milder expectations. It states that the market for biobased plastic packaging is growing at an average annual rate of 16.20%. The two abovementioned growth rates are applied in the low and high scenario for non-biodegradable biobased plastics. For biodegradable plastics, the same growth is assumed for the high scenario as for non-biodegradable biobased plastic. Nonetheless, for the low scenario, an annual growth rate of 11.82% is assumed, as this is the expected compound annual growth rate up until 2026 by another report (Valuates Reports, 2020).

Chemical Recycling

Chemical recycling could provide a complementary solution for plastic waste, but it could also provide competition for mechanical recyclers. The recycling research institute interviewee states the following about the chemical recycling industry:

"*What I mainly see now is that things are beginning to start. In America, something has been going on for a while. […] It [the chemical recycler] swallows up materials that can be recycled mechanically very well, which are now lost. […] It must be given a chance, and that is why we have to run it on nicer materials for a* *few years than it is intended for. […] It will first be a competitor for mechanical recycling on the short term, so that is very disruptive. That depends on how big such a project is going to be. But if it absorbs too large flows, then of course not much is left for mechanical recycling.*"

RES states that does foresee some "*competition*" between mechanical land chemical recycling, but "*in a positive manner*". He states that the total supply will increase even more. This is underpinned by PAPRO, who states that there will be enough waste to recycle for both recycling methods.

Nevertheless, PAPRO explains that chemically recycled plastic is more similar to virgin material than mechanical recycled plastic. Chemical recycling offers a head start in the fact that the full waste flow can be thrown into the reactor. But awareness must be kept about the higher CO_2 impact of chemical recycling. In addition, PAPRO expects a price difference, due to the high investment costs for chemical recycling. Ultimately, all stakeholders prefer to see chemical recycling as complementary. PLPRO describes this as follows:

"*I guess that we need to be mindful of CO_2 impact. This is where mechanical recycling performs better. One solution does not fit all, it needs to be complementary. Look at it from different perspectives. We need to look at the full system of the product that is being packed. You need to have the full picture to define what is the best solution, but I think that it is not one solution.*"

RES, WREC and PAPRO state that chemical recycling might provide a solution for the institutional obstacle found in food safety regulation, which is discussed more when analysing the fourth theme about policy development and legislation. Despite the uproar about developments in the chemical recycling industry, it is still fairly quiet on the retailers' side of the value chain. RET states the following:

"*We talk to everyone and look at the developments in the packaging world, so we just follow what is possible. In the field of packaging for chemical recycling, that is not very much*."

The Ministry of Infrastructure and Water Management explains that many investments related to chemical recycling are planned (Ministerie van Infrastructuur en Waterstaat, 2021). The coming years up to 2025 will be characterized as an upscaling and testing phase and the hope is that chemical recycling will be a mature market by 2030. One of the main focus points of the first phase up to 2025 is the development of a weighting framework in which the choice for chemical and mechanical is used optimally (Ministerie van Infrastructuur en Waterstaat, 2021). Based on the Circular Economy implementation program 2019-2023, the chemical recycling action plan aims for at least 10%, relative to the entire market production, of plastics being chemically recycled in 2030. For this reason, in the high scenario gradual growth of this 10% towards 2030 is expected, leading to 5% of all plastic production in the Netherlands being chemically recycled in 2025. It is also assumed that this 5% is evenly distributed over all types of plastic. This means that 5% of the total flexible film production will also be chemically recycled in 2025. For the low scenario, it is assumed that chemical recycling will be put into practice mainly between 2025 and 2030. This is why the assumption for the low scenario is that only 2% of the total production will be chemically recycled in 2025, rather for experimenting.

Since chemical recycling is most applicable for contaminated waste flows, it will be a competitor to mechanical recycling. More specifically, it will compete for post-consumer and post-commercial waste streams, as post-industrial waste streams are considered to be too clean. Therefore, the chemically recycled content will, in the dynamic model, be extracted from the PCR rPE demand which is solely focussed on mechanically recycled rPE films for this study. Furthermore, the trends in both scenarios are assumed to develop gradually between 2020 and 2025. The assumption is these proportions are gradually growing, giving the following calculations:

$$\boldsymbol{Low\ Scenario}:$$
$$Chemicly\ recycled\ content\ in\ 2025 = Produced\ flexible\ films \times 1.02$$
$$Chemicly\ recycled\ content = Produced\ lexible\ films \times \sqrt[5]{1.02}^{Time}$$
$$Chemicly\ recycled\ content = Produced\ flexible\ films \times 1.004^{Time}$$
$$\boldsymbol{High\ Scenario}:$$
$$Chemicly\ recycled\ content\ in\ 2025 = Produced\ \ flexible\ films \times 1.05$$
$$Chemicly\ recycled\ content = Produced\ \ flexible\ films \times \sqrt[5]{1.05}^{Time}$$
$$Chemicly\ recycled\ content = Produced\ flexible\ films \times 1.0098^{Time}$$

This gives a growth rate for chemically recycled content relative to amount produced of around 0.40% for the low scenario and 1% for the high scenario.

Policy development and legislation

Differentiated rate of waste

In order to further stimulate the recyclability of packaging, the Packaging Waste Fund introduced a rate differentiation for rigid plastic packaging in 2019 (Afvalfonds Verpakkingen, 2019). For properly sortable and recyclable rigid plastic packaging with a positive market value, a lower rate of €0.38 instead of €0.64 per kilo plastic waste is currently applied (Afvalfonds Verpakkingen, 2019).

RET states that it would be helpful if such a tariff would also apply to foils, which is not the case yet. He emphasizes that "*the incentive for recycling HDPE does not exist for LDPE* [= flexible film[9]]" and that it is "*an interesting question* […] *why there is no such thing for foils*, […] *because recycling is more difficult for films*". Furthermore, RET also states that "*there is no incentive for companies like us* [retailers]. *There is no financial incentive behind it.*" RERES states that the differentiated rate is a good idea, but due to "*a lack of recyclability definitions*" it does not achieve its intended purpose. He also states that it "*just invites you to use virgin material*" and it pushes more to "*look at the current design than the use of recycled content*". WREC also points this out.

Since most stakeholders agree that this rather affects the design of products and packaging, it is accounted for with the factor 'Design for recycling' about technical components. Due to the uncertainty as to whether this policy will actually apply to flexible films in the next five years or thereafter, and the uncertainty about what the resulting effect would be on rPE demand, this factor has not been included within the theme *Policy and legislation*.

Single-use plastic ban

The single-use plastic (SUP) ban is a directive that covers the ten plastic products most commonly found on European beaches. The measures in this directive apply to all EU member states, including the Netherlands. The directive must be implemented in the regulations of all EU member states by July 2021 (Ministerie van Algemene Zaken, 2021).

[9] In the quote, the respondent speaks about LDPE, but he later indicates that he refers to flexible film.

WREC states that, due to this measure, he does observe a change in the waste streams that arrive at waste collection, but that this does not affect the flexible films. This ban does not focus on articles containing LDPE films, but rather on disposable products like straws and plastic plates. Therefore, this policy is not considered in this demand analysis.

EU plastic tax

As of January 1, 2021, the EU receives its own resources from a tax on non-recycled plastic packaging waste. This should encourage Member States to reduce the consumption of single-use plastics, promote recycling and boost the circular economy, in line with EU environmental goals. The new levy is calculated per Member State on the basis of the weight of non-recycled plastic packaging waste, with a call rate of € 0.80 per kilogram (European Council, 2020).

The actors acknowledge that this could provide an incentive for recycling, but it is currently unknown who is paying the price. RERES states that the tax could be effective "*if the bill ends up with the person who produces it*. […] *but that is currently not the case"*. WREC states that this is one of the issues with European legislation:

"*This plastic tax is imposed on governments. […] In the EU it ends up in the collective pot. It is not yet clear how this will be passed on at the national level. I think that at the moment this is at least an incentive for the government to invest heavily in recycling."*

PLPRO adds to this that every member state is doing something different with this fee. Also, producers are not producing for one market or country. PLPRO states:

"*We need to be harmonized within Europe. If we put in the market [that] it is this time for recyclability, there is an incentive that a certain amount should be recycled. This concept should be associated with the weight. […] It is not economically viable to do this on a country level.*"

PAPRO and RET both assume that the plastic tax will be passed on to the producer, according to the *polluter pays* principle. RET states that this will ultimately end up at the consumer, through increased products prices. Furthermore, "*a consequence could be that people switch to paper*", according to PAPRO, even though other materials are often not "*the best option*" when focussing on environmental performance. PAPRO already sees "*that supermarkets sometimes go to cardboard*".

For the low scenario, the assumption is that the EU plastic tax will not be passed on to the producer and, therefore, not affect the virgin plastic price. In the high scenario, the expectation is that the tax will be passed on to the producer and subsequently increase the price of virgin PE film. For this virgin plastic price, an average of €1950/ton is chosen (Nederlands Verpakkingscentrum, n.d.; 2021; Plastic Portal, 2021). With the EU plastic tax passed on, the assumption is that this price will increase with €0.80/kilogram. This means that €800 is added to the price per ton, resulting in a new virgin plastic market price of €2750/ton. The assumption for the high scenario is that this price increase will gradually develop over the coming 5 years, based on the following calculation:

$$Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$

$$Annual\ growthrate\ of\ virgin\ plastic\ price = \left(\frac{2750}{1950}\right)^{\frac{1}{5}} - 1$$
$$Annual\ growthrate\ of\ virgin\ plastic\ price = 0.0712$$
$$Annual\ growthrate\ of\ virgin\ plastic\ price = 7.12\%$$

The calculation above displays how the annual growth rate of the virgin plastic film price will increase with an annual growth rate of 7.12% if the Euplastic tax is transferred to producers. The assumption is that this will affect the rPE demand in the same way a change in oil price is assumed to, as explained before with the cross elasticity of demand. However, it is expected that a direct change in virgin plastic price has stronger effect on rPE demand than an indirect change in price due to rising oil prices. Therefore, the relationship with rPE demand is made a little bit stronger for this factor. Instead of the 0.18% increase in demand, a virgin plastic price increase of 1% will result in a 0.2% increase in rPE demand. It should be noted that this is a rough assumption.

Recycled content target

One of the targets of the European Plastic Pact is to increase the use of recycled plastics in new products and packaging by 2025. The recycled content target accompanied with this entails that plastics user companies must achieve an average of at least 30% recycled plastics (by weight) in their product and packaging range (European Plastics Pact, 2020). RERES states that he expects the most from this legislation. However, RERES also states the following:

"*This is one of those things that pops up very regularly and then vanishes again. […] If you look at how long this has been talked about, but nothing has happened. I hope it will happen. If it is going to happen, then the moment is within now and 2025. But I do not dare to say with 100% certainty that it will happen.*"

WREC explains that he thinks that this recycled content-incentive is needed to provide an incentive for recycling LDPE and using rLDPE. WREC states:

"*Despite all the plastic pacts and all the great stories, nothing is happening at all. Why not? We are waiting for each other*[10]*. The companies that are intrinsically motivated to improve this, that is very nice, but that is not going to happen because virgin is just cheaper. So, this is the incentive [needed]*"

RET thinks that this will probably be applied in the Netherlands, as it is already the case in the UK. According to PAPRO, such targets "*will be used more in the future*". He thinks that it could, however, at least take four years. WREC seems to have no doubts about this:

"*This [policy] will come. You can already see it in the UK. In order to achieve the goals of recycling, it must be able to be marketed. This is only possible by making this mandatory. It [the policy] is coming, 100%.*"

[10] Quote is corrected by the respondent afterwards. Original sentence in quote stated: "We have to wait for each other". This did, however, not indicate what the respondent meant, as it does now.

Furthermore, PLPRO explains the following about this regulation in relation to circularity:

"*Having this legislation is the way that will oblige us to move to there. But we need to be conscious as well. what are the consequences on food safety? There are applications where you cannot do it. The industry will evolve if you have the legislation. All industries will move faster.*"

For both the low and the high scenario, it is assumed that this regulation will be enforced in the coming years. Nonetheless, it is not expected that the 30% target will already be reached in 2025. Therefore, in the high scenario, 20% recycled content is reached in 2025. Therefore, a gradual trend is adapted in the model. In the MFA models, the recycled content was around 9.5%. The increase towards a 25% recycled content is assumed to gradually be reached, for which the following calculation is provided:

$$Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$

$$Annual\ growthrate\ of\ recycled\ content = \left(\frac{20}{9.5}\right)^{\frac{1}{5}} - 1$$

$$Annual\ growthrate\ ofrecycled\ content = 0.17$$

$$Annual\ growthrate\ of\ recycled\ content = 16.05\%$$

The calculation above displays that, in the high scenario, the recycled content proportion of the total amount of flexible films on the market - currently 9.50% - will increase each year with 16.05%.

Also, for the low scenario, the assumption is that this target will be enforced by the government. Nevertheless, for the low scenario it is assumed that this target is not so well regulated, controlled and complied with. This is why it is expected for the low scenario that only 15% recycled content for flexible films will be achieved in 2025. This gives the following calculation:

$$Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$

$$Annual\ growthrate\ of\ recycled\ content = \left(\frac{15}{9.5}\right)^{\frac{1}{5}} - 1$$

$$Annual\ growthrate\ ofrecycled\ content = 0.0956$$

$$Annual\ growthrate\ of\ recycled\ content = 9.56\%$$

The calculation above displays that, in the low scenario, the recycled content proportion of the total amount of flexible films on the market, will increase with an annual growth rate of 9.56%

Extension food grade regulation

The interviewees mention food grade regulations as one of the big obstacles in legislation affecting the demand of rPE. The food grade regulation entails that for the use of recycled material in plastic food packaging, a number of requirements apply, in addition to the migration limits that apply to all food-contact materials (KIDV, n.d.). The first requirement, the entry requirement, states that 95% of the plastic that is recycled, must have been already food approved in its earlier life. This means that 95% of the packaging that enters the recycling process should have already been used as packaging for food before. This is often already the case for PET packaging. This entry requirement is, however, more difficult for packaging made of PE and PP, because many of these packaging plastics are used for both food and non-food products. Therefore, it is difficult to guarantee that 95% of the recycled material comes from food packaging. The applicability of recycled PE and PP is therefore limited to non-food products for the time being (KIDV, n.d.).

This regulation might form an obstacle for rPE. PAPRO explains how flexible films are initially for two-thirds present in food packaging and the remainder in non-food packaging. WREC acknowledges that, because of this, full circularity is not feasible for flexible films. WREC states that much attention is paid to whether something does not come "*in contact with food*", which is a "*major obstacle*". Nevertheless, this does not mean that there are no other options. WREC explains the following about recycling options:

"*It is a kind of pyramid when you look at qualities. There are thick-walled articles at the bottom. At the top of that pyramid is food-contact […]. We have to want to go up one or two levels. From industrial waste flows, we can make consumer packaging. Which means that the consumer packaging we make [from post-consumer waste], can also go up one level.*"

WREC further states that for food-contact packaging "*chemical recycling comes into play*". RES explains that with chemical recycling, "*an artificial oil*" is created "*which may eventually end up in the food category*". PAPRO also sees a possibility in the application of chemical recycling for food-contact packaging. Furthermore, he explains how food safety regulation, for plastic specifically, is quite strict compared to other materials:

"*Everything that comes into contact with food must be safe, safely produced. There is also separate legislation for all kinds of materials. There is very little in it for cardboard. For plastic it says [that] there must be specific migrations, limits and overall migration tests under different circumstances. The legislation is very well put together for plastic [in context of] food safety, but not for other materials*."

WREC states, when asked how recycling into food-contact packaging is, contrary to PE films, possible for PET waste, that "*PET is […] more recyclable. Foil is more difficult than PET. You can come a long way with certification, but it just takes time*".

The relatively high molecular contamination of rPE makes food-grade applications unlikely within the coming decades (Thoden van Velzen, Brouwer & Smeding, 2019). Various studies are trying to identify the contaminants present, determine their origin and design effective countermeasures. Research about this topic is still in an early stage. Although food grade rPE is not to be expected in the coming decades, the recycling of this packaging into non-food packaging and consumables will increase and become more visible to the general public (Thoden van Velzen et al., 2019).

Looking at the value pyramid for recycled plastics, given in Figure 2.2, PCR rPE is applied partly in the third market segment - low consumer products -, partly in the fourth market segment - bulky and logistical products - and partly in the last segment - through incineration for energy recovery and as fuel for cement kilns. As explained by the interviewed stakeholders, the strict food grade regulation makes it difficult to apply PCR recycled content in not only the food grade market segment, but also in higher quality consumer goods. RIVM (2019) explains that over the years it will be important to monitor whether technologies and exceptions to legal frameworks become available that make other recycled polymers suitable for food contact. However, it is not expected that rPE will be applied in food grade products before 2025. Nevertheless, for the high scenario, an extension of the food grade regulation is expected, in combination with technical qualitative developments, resulting in PCR rPE being allowed within the high consumer products market. For the low scenario, no extension of the food regulation is expected in the coming 5 years.

Roughly two-thirds of the packaging comes into direct contact with food (Krebbekx, Duivenvoorde & Haffman, 2017). For the high scenario, it is therefore assumed that 33% of the (in the Netherlands produced) packaging market becomes available for PCR rPE films. Nevertheless, since it is not expected that this full market segment will directly apply PCR rPE in their consumer packaging, the assumption is that 50% of this market will adapt and demand PCR rPE in their packaging in addition to the fraction of this market that already applies rPE PCR in garbage bags. A gradual growth over the coming 5 years is expected, resulting in the following calculation:

$$High\ consumer\ product\ aplicability\ in\ 2025 = Packaging\ market \times 0.33$$

$$High\ consumer\ product\ demand\ in\ 2025 = Packaging\ market \times 0.33 \times 0.50$$

$$High\ consumer\ product\ demand\ in\ 2025 = Packaging\ market \times 0.165$$

$$High\ consumer\ product\ demand = \left(Consumer\ packaging\ market \times \sqrt[5]{1.165}^{Time}\right) - Consumer\ packaging\ market$$

$$High\ consumer\ product = (\ Consumer\ packaging\ market \times 1.0310^{Time}) - Consumer\ packaging\ market$$

This means that in the high consumer product demand in the packaging market for PCR rPE has an annual growth rate of 3.10%.

Technical Components

The grain and its properties

WREC explains how there are several technical issues at play. Those issues consider the colour and smell of the re-granulates. Especially the smell is a big issue, according to RERES, RES and PAPRO. RES states about this:

“*I do know that the people who work in that fragrance day in and day out, have an opinion about it. [...] That is something to take into account*.”

The remaining quality properties link back to the fact that rPE cannot (yet) match the quality of virgin flexible films and the costumer and retailer requirements from the second theme about rPE market trends. For example, the technical issue with the grains, is not an issue occurring with virgin flexible films. Also, the consumer and retailer demand for a certain colour and the printing of labels are also linked to the qualitative properties of the rPE. RES explains this pressure to the recycle process:

"*Smell, appearance, mechanical functionality, strength. [But] I think if the consumer goes along with the awareness... a black [plastic] bottom of a tray was very luxurious [but not properly sortable], but you hardly see that anymore. If we make everything [in the first cycle] transparent, it will be more functional.*"

WREC indicates that they are "*really still searching*" in context of the quality properties of the grain. they are investigating the question whether "*you* […] [can] *deliver substantial improvements with additives*". They are currently working on antioxidants, stabilizers and whether the degree of PP and pollution can be improved. He states that "*is that going to improve? 100%. But there is time pressure*". PLPRO states that "*technically, everything is possible, but it costs money and who is going to do it?*".

When interviewing the different actors, another technical component came to light. The idea was that the degradation of the quality of PE per cycle also plays a role in the development of a circular value chain. Various amounts were mentioned by the different actors about the number of cycles that a PE fibre could survive from virgin production. PLPRO states that virgin plastic now lasts for two cycles, while WREC says this is "*very dependent on the life cycle*" of the product and the exposure to UV. PAPRO, on the other hand, estimates that PE can last 5 to 10 cycles. Based on this, it seems that there is not enough clarity about the amount of cycles a virgin PE fibre can survive. RES reassures a little by indicating that research is being done on repairing degraded fibres:

"*You will probably have to boost something every time, an improvement step. There will always be degradation, just of a different nature: [PE] chains [getting] shorter. Some sort of average strategy will have to be unrolled. I think that eventually x% additive A and y% additive B [will] have to be added, [in a] standardized [manner]. But what and how much, that is a point for research*."

RERES also indicates that there are solutions for this problem:

"*[...] Chain scission is the breaking up of [polymer] chains. You can do something about that with antioxidants. Then it still has good protection. The techniques are there for PE to prevent that failure. Then you make [PE] chains that have become shorter a bit longer again. But of course, every step costs money, that is always the case. So, to what extent people are willing to do so? That is the question. Anyway, it is technically possible*."

This section focuses only on technical components and thus the technical feasibility, developments and possibilities. The respondents mainly indicate that a great deal of technical development is possible and feasible, but that institutional development, social adoption and market structures determine whether this technology can also develop. Therefore, the estimate for the technical components is that they will develop positively enough in both scenarios to ensure market establishment, for both PIR rPE and PCR rPE. The main question here is which market segment the products end up in, in order to know the relationship to demand. However, this is more dependent on institutional factors, specifically about food regulation.

In itself, there is therefore no specific relationship between quality of rPE and rPE demand established in this analysis. Rather, the starting point is merely that the quality in both the low and the high scenario is assumed to be sufficient for market implementation. PCR rPE is already implemented in the low consumer product and bulky and logistical market segments, but is assumed to be technically suited for the high consumer product market segment in 2022 and onwards for the high scenario.

Design-for-recycling (DFR)

One of the other technical obstacles discovered in the literature review is about multi-layered packaging. In particular multilayer films, consisting of PE and other plastics, since these films cannot yet be properly recycled (Bergsma & Bijleveld, 2017; RVO, 2016; Verrips et al., 2017; Thiounn & Smith, 2020). When asked about multi-layered plastic packaging, WREC states the following:

"*Multi-material is what we don't want. Nowadays, the DKR 310 stream still contains multi-materials. We are still trying to filter these out. But sometimes that does not work, and it still ends up in the DKR 310 stream*."

The use of multi-material packaging has a lot to do with the design phase. When we asked PLPRO if they see development in designs suitable for recycling, she stated:

"*Yes, absolutely. I think the development is ongoing. […] [but] I don't know if they are on the scale that is needed for 2025*"

WREC states that he does hear a lot of development in this area. But "*seeing and hearing are two different things*". About design for recycling through mono-material in packaging, WREC does notice some difference in the arriving PCR waste streams:

"*What we do see is that, for example, packaging of PE [mixed with] PET has not been around for a while, because that combination is very unpleasant. If I have a PE packaging, or a combination of PE and PP, that is a bit better. 100% [flexible] PP packaging is great. […] [However] that PE packaging turns into a thick-walled article [because] the flow is just too small. [It] is not collected separately. We already see that trend a bit [to sort PP separately], but there is mainly a lot of talk about it*."

Based on the above, it is assumed that design for recycling rather affects rPE supply, through easing the recycling process. Brouwer et al. (2020) estimated that, if all packages would be designed for recycling, the post-consumer plastic packaging waste net recycling rate would increase by 7%. This means that an increase of DFR of 1%, results in an increase of the overall recycling rate (from sorting to recycling) of 0.07%. From the plastic pact, the first objective is to achieve 100% recyclability in plastic products and packaging in 2025. They measured that currently, the proportion of packaging designed for recycling is 16%. Also, WREC acknowledges that a trend is visible in DFR in the waste collected. For the high scenario, the expectation therefore is that 100% of the market being designed for recycling in 2025. This provides the following calculation:

$$Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$

$$Annual\ growthrate\ of\ DFR\ proportion\ on\ the\ total\ market$$
$$= \left(\frac{100}{16}\right)^{\frac{1}{5}} - 1$$

$$Annual\ growthrate\ of\ DFR\ proportion\ on\ the\ total\ market = 0.4427$$

$$Annual\ growthrate\ of\ DFR\ proportion\ on\ the\ total\ market = 44.27\%$$

As estimated above, the annual growth rate of DFR proportion on the total market in the high scenario is 44.27%. For the low scenario, it is not expected that all plastic packaging will be designed for recycling in

2025. Therefore, 50% of the market is assumed to be designed for recycling in 2025 in the low scenario. Again, this trend is assumed to develop gradually:

$$Annual\ growthrate = \left(\frac{Future}{Present}\right)^{\frac{1}{n}} - 1$$

$$Annual\ growthrate\ of\ DFR\ proportion\ on\ the\ total\ market = \left(\frac{50}{16}\right)^{\frac{1}{5}} - 1$$

$$Annual\ growthrate\ of\ DFR\ proportion\ on\ the\ total\ market = 0.2559$$

$$Annual\ growthrate\ of\ DFR\ proportion\ on\ the\ total\ market = 25.59\%$$

As estimated above, the annual growth rate of the DFR proportion on the total market in the low scenario increases each year with 25.59%. Since this is the net recycling rate, we assume sorting and recycling efficiency to increase by that proportion in the model.

C.2. Relevant calculations behind Vensim PLE model

1. Flexible films on the Dutch market:

a. All scenarios

➔ $FF\ on\ the\ Dutch\ market = (683917 \times FF\ market\ growth\ rate^{(Time-2020)}) \times (1 + Percentage\ less\ plastic\ use\ through\ plastic\ pact)$

➔ $FF\ market\ growth\ rate = 1.018$

b. Low & high scenario without Plastic Pact

➔ $Percentage\ less\ plastic\ use\ through\ plastic\ pact = 0$

c. Low Scenario with Plastic Pact & High Scenario with Plastic Pact

➔ $Percentage\ less\ plastic\ use\ through\ plastic\ pact = (-0.0436475 + 1)^{(Time-2020)} - 1$

2. Consumer source collection efficiency (including beverage cartons):

a. All scenarios

➔ $FF\ Consumer\ source\ collection\ efficiency = 0.65 \times (1 + Consumer\ source\ collection\ efficiency\ increase)$

➔ $Beverage\ cartons\ source\ collection\ efficiency = 0.65 \times (1 + Consumer\ source\ collection\ efficiency\ increase)$

b. High scenario (with and without plastic pact)

➔ $Consumer\ source\ collection\ efficiency\ increase = 1.0317632^{(Time-2020)} - 1$

c. Low Scenario (with and without plastic pact)

➔ $Consumer\ source\ collection\ efficiency\ increase = 1.023486^{(Time-2020)} - 1$

3. Commercial source collection efficiency:

a. All scenarios

➔ $Commercial\ collection\ efficienc = 0.57 \times (1 + Commercial\ source\ collection\ efficiency\ increase)$

b. High scenario (with and without plastic pact)

➔ $Commercial\ source\ collection\ efficiency\ increase\ =\ (0.0202184 + 1)^{(Time-2020)} - 1$

c. Low Scenario (with and without plastic pact)

➔ $Commercial\ source\ collection\ efficiency\ increase\ =\ (0.0103115 + 1)^{(Time-2020)} - 1$

4. Increase of commercial waste going to post-separation:

a. High scenario (with and without plastic pact)

➔ $Commercial\ FF\ waste\ to\ postseparation\ =\ (5.00797)^{(Time-2020)} - 1$

b. Low Scenario (with and without plastic pact)

➔ $Commercial\ FF\ waste\ to\ postseparation =\ (4.78176)^{Time-2020} - 1$

5. Design-for-recycling

a. All Scenarios

➔ $Effect\ DFR\ increase\ =\ (Percentage\ DFR\ increase \times 0.0007) + 1$

➔ $Percentage\ DFR\ increase\ =\ (16 \times Annual\ growth\ rate\ DFR^{(Time-2020)}) - 16$

b. High scenario (with and without plastic pact)

➔ $Annual\ growth\ rate\ DFR\ =\ 1.4427$

c. Low Scenario (with and without plastic pact)

➔ $Annual\ growth\ rate\ DFR\ =\ 1.2559$

6. Consumer source separated sorting efficiency

a. All scenarios

Consumer packaging

➔ $Source\ separated\ sorting\ efficiency\ (consumer)\ =\ 0.4866 \times Source\ seperated\ sorting\ efficiency\ increase \times Effect\ DFR\ increase$

Beverage cartons

➔ $Source\ seperated\ beverage\ cartons\ sorting\ efficiency =\ 0.73 \times Effect\ DFR\ increase \times (1 + Beverage\ cartons\ source\ seperated\ sorting\ efficiency\ increase)$

b. High scenario (with and without plastic pact)

Consumer packaging

➔ $Source\ seperated\ sorting\ efficiency\ increase\ =\ 1.09755^{(Time-2020)}$

Beverage cartons

➔ $Beverage\ cartons\ source\ seperated\ sorting\ efficiency\ increase\ =\ 1.01204^{(Time-2020)}$

c. Low Scenario (with and without plastic pact)

Consumer packaging

➔ $Source\ seperated\ sorting\ efficiency\ increase\ =\ 1.08301^{(Time-2020)}$

Beverage cartons

➔ $Beverage\ cartons\ source\ seperated\ sorting\ efficiency\ increase\ =\ 0$

7. Post-separated sorting efficiency (consumer & commercial)

a. All scenarios

➔ $Post\ separated\ waste\ sorting\ efficiency\ =\ 0.1065 \times ("Post - seperated\ sorting\ efficiency\ increase") \times Effect\ DFR\ increase$

b. High scenario (with and without plastic pact)

➔ $Post\ separated\ sorting\ efficiency\ increase\ = 1.38868^{(Time-2020)}$

c. Low Scenario (with and without plastic pact)

➔ $Post\ separated\ sorting\ efficiency\ increase\ = 1.334050945^{(Time-2020)}$

8. Recycling efficiency of household waste and of the post-separated commercial waste

a. All Scenarios

➔ $DKR\ 310\ Post\ seperated\ recycling\ efficiency\ =\ 0.61 \times Effect\ DFR\ increase \times (1 + DKR310\ and\ postseperated\ commercial\ recycling\ efficiency\ increasse)$

➔ $DKR\ 310\ Source\ separated\ recycling\ efficiency\ =\ 0.61 \times (1 + DKR310\ and\ postseperated\ commercial\ recycling\ efficiency\ increasse) \times Effect\ DFR\ increase$

➔ $Commercial\ plastic\ waste\ recycling\ efficiency\ (post\ separated)\ =\ 0.61 \times (1 + DKR310\ and\ postseperated\ commercial\ recycling\ efficiency\ increasse) \times Effect\ DFR\ increase$

b. High Scenario (with and without plastic pact)

➔ $DKR310\ and\ postseperated\ commercial\ recycling\ efficiency\ increasse\ = 1.02046^{(Time-2020)} - 1$

c. Low Scenario (with and without plastic pact)

➔ $DKR310\ and\ postseperated\ commercial\ recycling\ efficiency\ increasse\ = 1.00487036^{(Time-2020)}$

9. Price of oil

a. All Scenarios

➔ $Effect\ price\ increase\ of\ oil\ =\ (Annual\ price\ increase\ of\ oil \times 100) \times 0.0018$

b. High Scenario (with and without plastic pact)

➔ $Annual\ price\ increase\ of\ oil\ =\ 1.0187^{(Time-2020)} - 1$

c. Low Scenario (with and without plastic pact)

➔ $Annual\ price\ increase\ of\ oil\ =\ (1 - 0.02015)^{(Time-2020)} - 1$

10. Retailer and Consumer behaviour

a. All Scenarios

➔ $Retailer\ \&\ Consumer\ behavior\ =\ (0.0404 + 1)^{(Time-2020)} - 1$

11. Biobased plastic

a. All Scenarios

➔ $Biobased\ plastics\ effect\ =\ 0.0006 \times Biobased\ plastics\ annual\ growth\ rate$

b. High Scenario (with and without plastic pact)

➔ $Biobased\ plastics\ annual\ growth\ rate\ =\ 1.162^{(Time-2020)}$

c. Low Scenario (with and without plastic pact)

➔ $Biobased\ plastics\ annual\ growth\ rate\ =\ 1.2^{(Time-2020)}$

12. Biodegradable plastics

a. All Scenarios

➔ $Biodegradable\ plastics\ effect\ =\ 0.0043 \times Biodegradable\ plastics\ annual\ growth\ rate$

➔ $Biodegradable\ plastics\ annual\ growth\ rate\ =\ 1.1182^{(Time-2020)}$

13. Chemical Recycling

a. High Scenario (with and without plastic pact)

➔ $Chemical\ recycling\ demand = Produced\ FF \times ((0.004 + 1)^{Time-2020} - 1)$

b. Low Scenario (with and without plastic pact)

➔ $Chemical\ recycling\ demand = Produced\ FF \times ((0.01 + 1)^{Time-2020} - 1)$

14. EU Plastic Tax

a. All Scenarios

➔ $Effect\ virgin\ plastic\ price\ increase =\ 1 +$
$("Virgin\ plastic\ annual\ price\ increase\ (EU\ plastic\ tax)" \times 0.002)$

b. High Scenario (with and without plastic pact)

➔ $"Virgin\ plastic\ annual\ price\ increase\ (EU\ plastic\ tax)" =\ 1.0821^{(Time-2020)} - 1$

c. Low Scenario (with and without plastic pact)

➔ $"Virgin\ plastic\ annual\ price\ increase\ (EU\ plastic\ tax)" =\ 0$

15. Recycled Content Target

a. All Scenarios

➔ $Recycled\ proportion = 0.095 \times Increase\ rate\ recycled\ content$

b. High Scenario (with and without plastic pact)

➔ $Increase\ rate\ recycled\ content = 1.1605^{(Time-2020)}$

c. Low Scenario (with and without plastic pact)

➔ $Increase\ rate\ recycled\ content = 1.0956^{(Time-2020)}$

16. Extension food grade regulation
(starts after 1 year in 2021)

a. All Scenarios

➔ $PCR\ high\ consumer\ pr\ demand = DELAY\ FIXED$(High Consumer pr opening market , 1 , 0)

➔ High Consumer pr opening market =
$Annual\ growth\ rate\ opening\ market\ high\ consumer\ pr * FF\ to\ Packaging$

➔ *"FF to Packaging"* adapted from the MFA 2020 model.

b. High Scenario (with and without plastic pact)

➔ $Annual\ growth\ rate\ opening\ market\ high\ consumer\ pr = 1.031^{(Time-2020)} - 1$

c. Low Scenario (with and without plastic pact)

➔ Annual growth rate opening market high consumer pr = 0

17. rPE Demand

a. All Scenarios

$$\begin{aligned} rPE\ Demand = {} & ((FF\ on\ the\ Dutch\ market) \\ & \times Recycled\ proportion) \times (1 \\ & + Effect\ price\ increase\ of\ oil) \times (1 \\ & + \text{"}Retailer\ \&\ Consumer\ behaviour\text{"}) \\ & \times (Effect\ virgin\ plastic\ price\ increase) \times (1 \\ & - Biobased\ plastics\ effect + 0.0006) \times (1 \\ & - Biodegradeable\ plastics\ effect + 0.0043) \\ & + \text{"}PCR\ NFC - LC\ demand\text{"} \end{aligned}$$

18. PCR rPE Demand

a. All scenarios

➔ $PCR\ rPE\ Demand = rPE\ Demand \times Percentage\ PCR\ rPE\ demand - Chemical\ recycling\ demand$

➔ $Percentage\ PCR\ rPE\ demand = 0.93$

19. PIR rPE Demand

a. All scenarios

➔ $PIR\ rPE\ Demand = (rPE\ Demand \times Percentage\ PIR\ rPE\ demand)$

➔ $Percentage\ PIR\ rPE\ demand = 0.07$

C.3. Results for comparing PCR rPE supply and demand from 2020 up until 2025

This table displays the estimated post-consumer and post-commercial demand and supply from 2020 until 2025. The difference in value between those variables determines whether there is a positive (green) or a negative (red) business case for flexible film recycling.

			Time					
Scenario	**Factor**		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
High	**PCR rPE Demand**		**60424.1**	**72931**	**97728.3**	**126539**	**160166**	**199581**
	PCR rPE Supply	Post-consumer rPE supply	28415.8	33644	40501.9	49017	59774.9	73684.2
		Post-commercial rPE supply	81606	84500.2	88222.7	92354	97124.9	103512
		Total PCR rPE Supply	**110021.8**	**118144.2**	**128724.6**	**141371**	**156899.8**	**177196.2**
	Balance		***-49597.7***	***-45213.2***	***-30996.3***	***-14832***	***3266.2***	***22384.8***
High - with Plastic Pact	**PCR rPE Demand**		**60424.1**	**69747.7**	**89758.7**	**111387**	**134965**	**160875**
	PCR rPE Supply	Post-consumer rPE supply	28415.8	32175.5	37064.5	42921.1	50079.7	59061.8
		Post-commercial rPE supply	81606	80812	80713.4	80830.4	81341.5	83142.8
		Total PCR rPE Supply	**110021.8**	**112987.5**	**117777.9**	**123751.5**	**131421.2**	**142204.6**
	Balance		***-49597.7***	***-43239.8***	***-28019.2***	***-12364.5***	***3543.8***	***18670.4***
Low	**PCR rPE Demand**		**60424.1**	**65899**	**72781.9**	**81327.3**	**91831.5**	**104639**
	PCR rPE Supply	Post-consumer rPE supply	28415.8	32207.7	36557.2	41568.4	47373.3	54142
		Post-commercial rPE supply	81606	83448.8	85399.6	87488.9	89806.9	92803.6
		Total PCR rPE Supply	**110021.8**	**115656.5**	**121956.8**	**129057.3**	**137180.2**	**146945.6**
	Balance		***-49597.7***	***-49757.5***	***-49174.9***	***-47730***	***-45348.7***	***-42306.6***
Low – With Plastic Pact	**PCR rPE Demand**		**60424.1**	**63022.7**	**66567**	**71136.1**	**76818.1**	**83711.1**
	PCR rPE Supply	Post-consumer rPE supply	28415.8	30801.9	33435.6	36359.4	39628.3	43313.6
		Post-commercial rPE supply	81606	79806.5	78107.6	76527.7	75141.8	74380.4
		Total PCR rPE Supply	**110021.8**	**110608.4**	**111543.2**	**112887.1**	**114770.1**	**117694**
	Balance		***-49597.7***	***-47585.7***	***-44976.2***	***-41751***	***-37952***	***-33982.9***

C.4. Results for the proportions of the Linearly processed, circularly processed, incinerated and reapplied (and reused) content

This table displays the linearly processed, circularly processed, incinerated and reapplied (and reused) proportion relative to 3 references from 2020 up until 2025. The ratios shown are relative to (1) the flexible films produced in the Netherlands, (2) the total amount of flexible films on the Dutch market and (3) the total amount of processed flexible film waste that actually arrives at the waste processors.

Processing category / Destination	Unit	Scenario	Time 2020	2021	2022	2023	2024	2025
Flexible films produced in the Netherlands (excluding flexible films imported)	Tons	**Low - with Plastic Pact**	3.90E+05	3.75E+05	3.59E+05	3.43E+05	3.26E+05	3.10E+05
		Low	3.90E+05	3.92E+05	3.92E+05	3.92E+05	3.90E+05	3.87E+05
		High	3.90E+05	3.89E+05	3.79E+05	3.66E+05	3.51E+05	3.32E+05
		High- with Plastic Pact	3.90E+05	3.72E+05	3.46E+05	3.20E+05	2.93E+05	2.65E+05
Linearly processed	%	**Low - with Plastic Pact**	91.47	96.56	96.22	95.91	95.60	95.25
		Low	91.47	92.35	92.02	91.72	91.43	91.09
		High	91.47	93.10	95.16	97.84	100.87	104.17
		High- with Plastic Pact	91.47	97.35	99.57	102.48	105.73	109.28
Circularly processed (reused, reapplied and unused)	%	**Low - with Plastic Pact**	38.25	41.75	44.57	47.71	51.26	55.34
		Low	38.25	40.76	43.59	46.75	50.32	54.43
		High	38.25	42.39	49.49	55.37	62.92	72.99
		High- with Plastic Pact	38.25	43.38	50.60	56.34	63.74	73.62
Incinerated	%	**Low - with Plastic Pact**	89.07	94.05	93.66	93.28	92.90	92.45
		Low	89.07	89.95	89.57	89.21	88.84	88.42
		High	89.07	90.68	92.59	95.07	97.84	100.81
		High- with Plastic Pact	89.07	94.82	96.88	99.57	102.56	105.75
Reused and reapplied	%	**Low - with Plastic Pact**	17.06	19.68	22.63	26.09	30.19	35.06
		Low	17.06	19.65	22.60	26.07	30.17	35.04
		High	17.06	21.11	29.12	38.96	51.34	67.39
		High- with Plastic Pact	17.06	21.13	29.28	39.27	51.84	68.10
Flexible films brought on the Dutch market	Tons	**Low - with Plastic Pact**	6.84E+05	6.66E+05	6.48E+05	6.31E+05	6.14E+05	5.98E+05
		Low	6.84E+05	6.96E+05	7.09E+05	7.22E+05	7.35E+05	7.48E+05
		High	6.84E+05	6.66E+05	6.48E+05	6.31E+05	6.14E+05	5.98E+05
		High- with Plastic Pact	6.84E+05	6.96E+05	7.09E+05	7.22E+05	7.35E+05	7.48E+05
Linearly processed	%	**Low - with Plastic Pact**	52.21	54.33	53.26	52.09	50.79	49.33
		Low	52.21	51.96	50.94	49.82	48.58	47.18

		High	52.21	54.33	55.59	56.78	57.59	57.77
		High- with Plastic Pact	52.21	51.96	48.62	45.43	42.15	38.66
Circularly processed	%	**Low - with Plastic Pact**	21.83	23.49	24.67	25.91	27.24	28.66
		Low	21.83	22.94	24.13	25.39	26.74	28.19
		High	21.83	24.74	28.91	32.13	35.93	40.48
		High- with Plastic Pact	21.83	23.16	24.71	24.98	25.41	26.05
Incinerated	%	**Low - with Plastic Pact**	50.84	52.92	51.84	50.66	49.36	47.88
		Low	50.84	50.61	49.58	48.45	47.20	45.79
		High	50.84	52.92	54.09	55.17	55.86	55.90
		High- with Plastic Pact	50.84	50.61	47.31	44.14	40.88	37.42
Reused and reapplied	%	**Low - with Plastic Pact**	9.74	11.07	12.52	14.17	16.04	18.16
		Low	9.74	11.06	12.51	14.16	16.03	18.15
		High	9.74	12.32	17.01	22.61	29.31	37.37
		High- with Plastic Pact	9.74	11.28	14.30	17.41	20.66	24.10
Total Processed Flexible film waste	Tons	**Low - with Plastic Pact**	5.06E+05	5.18E+05	5.05E+05	4.92E+05	4.79E+05	4.67E+05
		Low	5.06E+05	5.21E+05	5.32E+05	5.43E+05	5.53E+05	5.64E+05
		High	5.06E+05	5.26E+05	5.48E+05	5.61E+05	5.75E+05	5.88E+05
		High- with Plastic Pact	5.06E+05	5.23E+05	5.20E+05	5.08E+05	4.96E+05	4.84E+05
Linearly processed	%	**Low - with Plastic Pact**	70.52	69.81	68.34	66.78	65.09	63.25
		Low	70.52	69.38	67.86	66.24	64.50	62.60
		High	70.52	68.71	65.78	63.86	61.58	58.80
		High- with Plastic Pact	70.52	69.17	66.31	64.52	62.39	59.75
Circularly processed	%	**Low - with Plastic Pact**	29.48	30.19	31.66	33.22	34.91	36.75
		Low	29.48	30.62	32.14	33.76	35.50	37.40
		High	29.48	31.29	34.22	36.14	38.42	41.20
		High- with Plastic Pact	29.48	30.83	33.69	35.48	37.61	40.25
Incinerated	%	**Low - with Plastic Pact**	68.67	68.00	66.52	64.95	63.25	61.39
		Low	68.67	67.58	66.05	64.42	62.67	60.76
		High	68.67	66.93	64.01	62.05	59.73	56.90
		High- with Plastic Pact	68.67	67.38	64.52	62.69	60.52	57.82
Reused and reapplied	%	**Low - with Plastic Pact**	13.15	14.23	16.07	18.17	20.56	23.28
		Low	13.15	14.77	16.67	18.83	21.28	24.08
		High	13.15	15.58	20.13	25.43	31.35	38.04
		High- with Plastic Pact	13.15	15.01	19.50	24.73	30.59	37.24