A Circular Economy for Coffee Capsule Waste

A qualitative exploration of chemical recycling and advanced sorting of plastic aluminium coffee capsule waste and an analysis of the system barriers and potential interventions to transition to circularity.

by

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Executive Summary

In recent years, an increasing amount of plastic packaging waste has drawn attention from consumers, media and policymakers alike. To tackle this, the concept of a circular economy (CE) is well established in Europe through the implementation of the European Strategy for Plastics in the Circular Economy. The strategy places an importance on improving recycling to increase the amount of high-value materials in circular loops. An innovation intended to achieve this is chemical recycling, which provides an alternative to the current mechanical recycling system. Improvements in recycling are also being met with innovations in the sorting of the plastic packaging waste to improve overall recyclability.

One such packaging waste that can benefit from these innovations is composite plastic-aluminium packaging. The example taken in this report is that of single-use coffee capsules. These are incinerated due to their poor recyclability in current mechanical recycling systems, leading to a loss of materials, counteractive to the CE approach. This review outlines the end-of-life of such packaging and explores chemical recycling and sorting technologies that can help to realise a CE for the waste. The work also includes a qualitative exploration of the overall packaging waste system to analyse barriers towards a CE and propose interventions for the CE transition.

The work gathers information on different chemical recycling and sorting technologies through semi-structured interviews with practitioners and a review of scientific publications. In line with CE strategies, solvent dissolution is chosen as a potential chemical recycling technology for the coffee capsules. Subsequently, the collection and sorting of the capsules is outlined through flow diagrams, and a sorting protocol is drawn up for isolating a feedstock of the capsules for recycling with solvent dissolution. Two promising sorting technologies are highlighted here: NIR scanners with deep learning and packaging markers.

The overall packaging waste system of the coffee capsules is then explored in three main steps; (1) a mapping of stakeholders and flows of materials, money and influence, (2) semi-structured stakeholder interviews and (3) mapping of CE barriers along four key pillars: technological, regulatory, market and cultural. The results of the system study reveal a variety of interconnected barriers across different system levels. While key technological barriers exist in the form of limited industrial demonstration, several other barriers were found more insightful. These include a regulatory focus on material circularity, limited stakeholder awareness for the environmental impacts of different CE strategies, a lack of design guidelines for composite packaging waste, limited funding for industrial experimentation and a lack of consumer awareness of packaging sustainability and preference for convenience.

Following these findings, four system interventions are proposed to overcome the mentioned barriers and facilitate recycling of the coffee capsule. Overall, it is seen that any intervention requires significant further work and an understanding of the root causes, as the identified barriers are interconnected, and one may cause a chain reaction to others. The interventions proposed here should be taken as a guiding point of departure, and further work is needed to validate the interventions and their potential impact for change.

Abbreviations

CE – circular economy

CEFLEX – Circular Economy for Flexible Packaging

CLD – causal loop diagrams

CPA – Circular Plastics Alliance

DKR - Deutsche Gesellschaft für Kunststoffrecycling mbH

ECS – eddy current separator

EPRO – extended producer responsibility organisation

EU – European Union

HDPE – high density polyethylene

ISCC – International Sustainability and Carbon Certification

LCA – life cycle assessment

LDPE – low density polyethylene

NIR – near infrared

PA - polyamide

PBT – polybutylene terephthalate

PE – polyethylene

PET – polyethylene terephthalate

PP – polypropylene

PVC – polyvinyl chloride

SUP – single use plastic

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Chapter 1 – Introduction

1.1. The problem with plastic waste

Plastics are ubiquitous in our everyday lives. Ever since their development in the 20th century, synthetic polymers have transformed modern society. Plastics are lightweight, waterproof and chemically inert. For packaging food, beverages and household goods, they offer material and weight reductions, prevent product contamination and extend shelf lives. All of these qualities have made plastics the standard material of choice for packaging applications.

The same qualities that make plastics excellent for countless applications make them non-biodegradable, requiring management at their end-of-life. However, the amount of end-of-life plastic waste collected for treatment varies significantly from country to country. Varying local legislation, technology, and public behaviour determine how waste is disposed, collected, and sorted (Erkisi-Arici et al., 2021). In 2019 in the EU, only 32,5% of collected plastics re-entered the value chain through recycling, with 67,5% lost, either being incinerated for energy recovery (42,6%), or landfilled (24,9%) (PlasticsEurope, 2020). This is even worse for plastic packaging, where 32% of waste is never collected. With poor recycling rates of collected packaging, 95% of material value is lost after a very short use cycle (Ellen MacArthur Foundation, 2017).

The plastic waste that is not collected ends up accumulating on land, leaching chemicals into agricultural soils, collecting in rivers and freshwater reservoirs, and flowing into oceans. Here it acts as almost permanent pollution, impacting terrestrial, freshwater and marine ecosystems (Bläsing & Amelung, 2018; Jambeck et al., 2015; Li et al., 2016). Public awareness of these negative impacts is also growing, with an increasing perception of plastics as harmful to the environment and to human health and well-being (Ketelsen et al., 2020; Rhein & Schmid, 2020). Together, these factors, amongst others, are spurring public legislators and the private sector to take action.

1.2. A new plastics economy

In the last decade, the concept of the circular economy has emerged as an alternate way of doing business. It is defined in several ways by different scholars. Some focus on the optimization of waste and resources in loops (Geisendorf & Pietrulla, 2018) while others stress its importance as a means to an end, sustainability (Ghisellini et al., 2016; Kirchherr et al., 2017). The idea has been most popularised through the Ellen MacArthur Foundation, which defines the circular economy as

> *"…an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"* (Ellen MacArthur Foundation, 2013).

The Foundation stresses retaining resource value in a series of tight loops or circles and designing out waste. In the innermost loop, there is the least change required for a product before it can be returned to its original use, allowing savings in material, labour, energy and environmental externalities such as greenhouse gas emissions or toxicity. Diversifying use within the value chain is referred to as cascading, where plastic is first used in a beverage bottle and then melted and reused as secondary product packaging, substituting the need for virgin material in the value chain. The concept of a circular economy aims to maximise the number of these consecutive cycles, and at the least, ensure that uncontaminated materials are collected to close the cycle and increase material productivity (Ellen MacArthur Foundation, 2013). The concept of loops is illustrated for both technical and biological materials in Figure 1, showing material circulation in increasingly farther loops, from the innermost, maintenance, to the furthest, recycling.

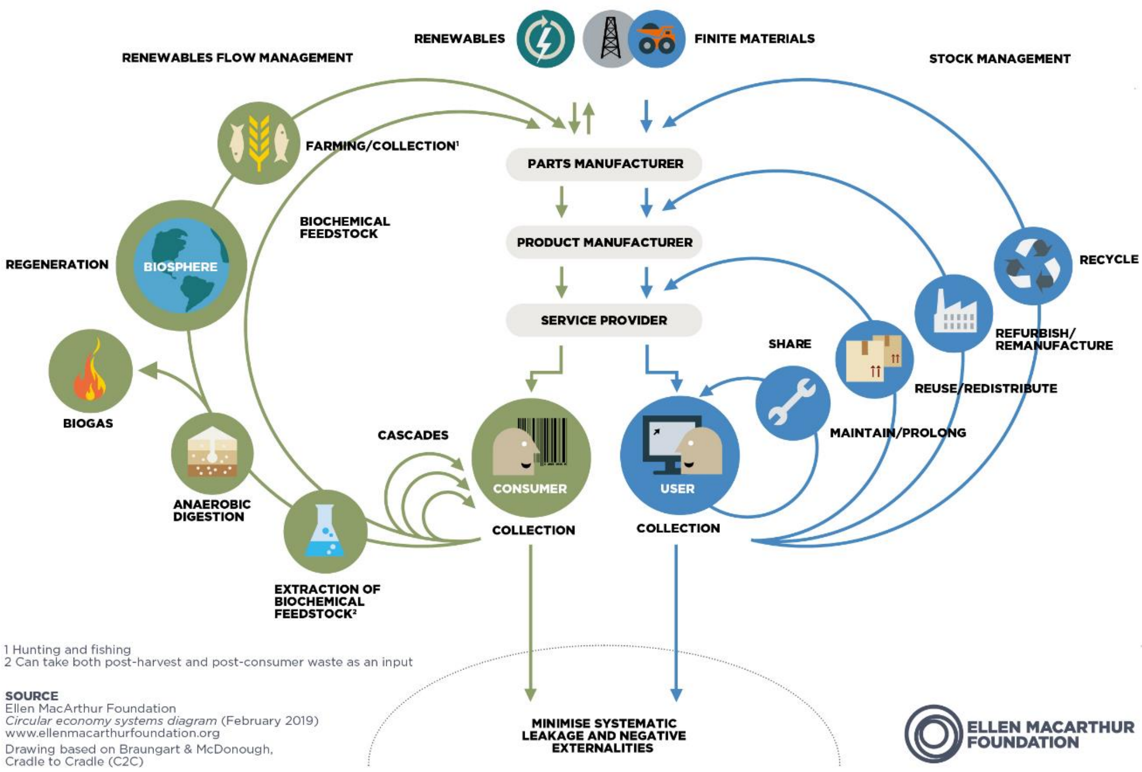

Figure 1: The circular economy butterfly diagram. (Ellen MacArthur Foundation, 2013)

In 2017, the Foundation published a report on The New Plastics Economy which stresses the importance of creating an effective after-use plastics economy by increasing the economics, quality and uptake of plastic recycling. These actions are intended to keep plastics in their value chain and avoid their leakage into the natural environment (Ellen MacArthur Foundation, 2017). In 2018, these ideas were formalised into a vision for the EU, in the European Strategy for Plastics in the Circular Economy (European Commission, 2018). The strategy outlines several key measures intended to improve plastics recycling. These are summarised in Table 1.

Table 1: Proposed measures as part of the EU Strategy for Plastics in a Circular Economy. (European Commission, 2018)

Measures
Improving the economics and quality of plastics recycling
Increasing design for recyclability
Boosting demand for recycled plastics
Better and more harmonised separate collection and sorting
Curbing plastic waste and littering
Preventing plastic waste in the environment
Establishing a framework for biodegradable plastics
Curbing the rising problem of microplastics

Driving innovation and investment towards circular solutions	
EU and private funding for research in innovative recycling and sorting solutions	
Harnessing global action	
EU external funding for improved waste prevention and management globally	
EU promotion and development of international standards	
EU certification schemes for recycling plants	

Although the Ellen MacArthur Foundation illustrates recycling as the furthest loop, the main measures of the European strategy revolve around increasing effective recycling. This is also seen in the EU's regulatory targets. The strategy sets a new goal for total plastics recycling of 55% by 2030 and establishes that all plastic packaging on the EU market must be reusable or recyclable in a cost-effective manner by then. Directive EU/2018/852 states that by 2030, at least 70% of all packaging waste is to be recycled (European Commission, 2018). The role of these recycling targets in a circular economy, and their relevance to the research question presented here are discussed in the following sections.

1.3. Current state of plastics recycling

With a strong focus on recycling in the legislative sphere, it is imperative to understand its current state. Currently, collected plastic packaging waste enters municipal solid waste flows at its end-of-life. This waste is composed mainly of five types of consumer plastics: low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) and polyethylene-terephthalate (PET) (Miandad et al., 2017). PE and PP have the highest share amongst this mix (PlasticsEurope, 2020). If the waste is not incinerated or landfilled, it can undergo two main types of recycling: mechanical or chemical (Niaounakis, 2020).

Almost all commercial recycling plants in the EU and elsewhere currently use mechanical recycling (Al-Salem et al., 2009; Hahladakis & Iacovidou, 2019; Jeswani et al., 2021; Qureshi et al., 2020). In this process, plastics are treated physically in a series of shredding, washing, drying, melting, and extrusion. This involves several technical challenges. Prior to the process, extensive sorting is necessary as a mix of polymers contaminate one another during the melt phase. While this may be overcome later by adding recompounding agents, a polymer blend typically displays worse mechanical properties than a pure plastic (Niaounakis, 2020). Washing is required as about 80% of mixed plastic waste is food contaminated, with contamination levels reaching up to 10 - 20% of the packaging weight (Niaounakis, 2020). Some municipal recyclers do not accept such waste at all, as contamination may persist in the polymer upon pellet extrusion, and such plastics are not acceptable for food-grade applications (Faraca & Astrup, 2019).

During melting and extrusion, rotating screws and heat are used to melt the plastic which is then forced through sections to produce extruded pellets. The thermal and shear stress on the plastic damage its polymer chains and weaken its mechanical properties (Schyns & Shaver, 2021). This step is also an issue for composite packaging waste. Packaging laminates containing aluminium are the main reason for the blockage of melt filters (Qureshi et al., 2020). These filters also plug when composite packaging contains a mix of other polymers with high melting temperatures such as PA and PET (Al Mahmood et al., 2019). The metal containing laminates also trigger metal-detecting equipment that is placed before sensitive equipment such as mills and extruders, which creates material losses (Qureshi et al., 2020).

Due to the above degradation of properties and high associated sorting costs, mechanically recycled plastics also fare worse in economic value. They compete directly with virgin plastics, which are superior in quality and favoured by current low crude oil prices (Schyns & Shaver, 2021). Therefore, there is limited incentive for the incorporation of recycled content in plastic production. This results in plastic waste disproportionately leaving the resource loop through incineration or cascading to a lower use upon degradation. (Sethi, 2017).

1.4. The case of coffee capsules

This work explores plastics recycling through the end-of-life of a specific type of plastic packaging waste; the single-serve coffee capsule. The format is a small capsule containing a measured amount of ground coffee first invented by engineers at Nestle in 1986 (Perfect Daily Grind, 2020). By popping it into a complimentary brewing machine, consumers can quickly and easily prepare a variety of café style drinks at their own convenience. Ever since, the coffee capsule business has expanded internationally, and capsules of endless variation are now sold by several global coffee brands. In Germany, in 2016, over 13% of consumers drank coffee from a single-serve brewer, and in 2018 in the UK, coffee capsule sales were 17% of the UK coffee market (Winther, 2018). According to market researchers, sales of these coffee capsule are only expected to grow (Mordor Intelligence, 2021).

Figure 2: Coffee capsules used with a complimentary brewing machine (Jacobs Douwe Egberts, n.d.).

In 2018, coffee brands produced 59 billion coffee capsules globally. Over 95% of these coffee capsules have a structure made of a composite of plastic and aluminium (Mordor Intelligence, 2021). Small amounts of coffee are contained in this composite capsule, which may also contain other ingredients such as dairy and chocolate. Espresso capsules may also contain a plastic or paper filter. The capsule design and materials are chosen to protect the product and allow capsule functionality with compatible brewers. The aluminium, for instance, serves as a gas, moisture and light barrier, but its material properties are also key during the machine brewing process, which involves perforating the capsules at an elevated temperature and pressure, an application that requires the structural integrity of the aluminium foil.

Figure 3: Mixed material coffee capsule waste. (Huntsdale, 2019).

While the materials are best suited for their use-phase, the capsules pose a significant challenge at their end-of-life. Other packaging that combines plastic and aluminium is also common in consumer products. Formats such as beverage cartons, flexible metallised films, standing metallised pouches and squeezable tubes are all examples of packaging where plastic is combined with aluminium in a composite packaging format.

In many cases, the aluminium is mechanically inseparable from the plastic, posing a greater recycling challenge than mono-material plastic packaging waste. Upon disposal, these capsules also contain residue of coffee grinds which persist after the waste is shredded and cause contamination in the recycling stream. This type of composite packaging waste is currently not mechanically recyclable in the EU (Visser & Dlamini, 2021). During sorting, such composite structures must be sorted out from other recyclable streams and sent for incineration (Al Mahmood et al., 2019; Faraca & Astrup, 2019; Georgiopoulou et al., 2021; Kaiser et al., 2018).

1.5. Relevance of chemical recycling as an alternative

An alternative to current mechanical recycling is chemical recycling. As the name suggests, it involves a change in the chemical makeup of the plastic polymer, or a chemical treatment of the polymer. Solvents, reactive agents or heat can also be used to yield monomers, oligomers or pure polymers which can be recovered for virgin-grade application. The idea is that chemical treatment is a means to produce pure polymer feedstock, free of the contamination and degradation that results with mechanical recycling and prevents in its high-value use. It also offers the potential to recover composite packaging such as the coffee capsules, which current mechanical recycling is unable to process. The different processes can be flexible as parameters such temperature, pressure, solvent, reactor and catalyst type can all be tuned to adjust the final yield or recovered material (Czajczyńska et al., 2017a; Qureshi et al., 2020; Sherwood, 2019; Walker et al., 2020). For this reason, feedstock for chemical recycling would, in theory, require less pre-sorting, offering labour and cost reductions and feedstock flexibility. The products of chemical recycling also do not compete with virgin feedstock for substitution, but themselves classify as virgin feedstock.

As mentioned in section 1.2, at the EU level, several targets have been set to eliminate non-recyclable packaging waste, either by designing out waste, or improving its high value collection, sorting and recycling. To support and enable these targets, the EU Strategy for Plastics highlights innovative solutions such as chemical recycling and advanced sorting as a key enabler for transforming the value chain and achieving the EU regulatory goals (see Table 1). The strategy also has an Annex III which calls for voluntary pledges from stakeholders to boost demand for recycled plastics (European Commission, 2018). Together, the pledgers commit to ten million tonnes of recycled plastics in new products by 2025. The stakeholders pledge to uphold that target provided that recycled plastics are available on the EU market in sufficient quantity, of a suitable quality and at competitive prices. Chemical recycling is mentioned here once again, this time by the pledgers as an upcoming game changer to reincorporate a wider variety of material streams and boost the availability of high value recycled content.

Due to the relevance of the topic in the regulatory sphere and to stakeholders alike, this work recognises a research gap in exploring the various chemical recycling technologies developing in the EU and their application for increasing high-value recycling of packaging waste. In this work, the topic is explored through the lens of a difficult-to-recycle packaging format, plastic-aluminium coffee capsules. By understanding the requirements and limitations of chemical recycling, the second stage of the research will look at the current collection and sorting infrastructure, including the use of innovative new sorting technologies to understand where change is necessary to allow for chemical recycling. Finally, the entire plastic packaging value chain will be viewed through a multistakeholder lens to identify existing barriers and propose interventions to enable a circular economy for such waste.

1.6. Research approach

To address the identified research gap, the main research question is defined as follows:

> How can innovations such as chemical recycling and advanced sorting create a circular economy for composite packaging such as coffee capsules?

The research will begin with characterizing the materials of a coffee capsule, followed by an identification and assessment of the chemical recycling technologies fit for processing it. The relevant sub-questions are:

1. What is the material and structure of the coffee capsule?
2. What chemical recycling technologies currently exist in the EU, ready to process composite packaging waste such as the coffee capsules?

The next phase will consist of assessing current municipal collection and sorting infrastructure and identifying new technologies and sorting schemes to enable the chemical recycling of coffee capsules and similar composite packaging waste. In sub-questions, these are:

3. How are coffee capsules currently collected and sorted for recycling at their end-of-life?
4. How can coffee capsules be collected and sorted to meet the feedstock requirements of chemical recycling technologies?

Finally, the work will focus on answering the main research question by evaluating the overall system, considering the identified innovations in chemical recycling and advanced sorting. The aim is to understand the system structure through its material, monetary and influence flows to pinpoint existing barriers towards the capsules' circularity. Lastly, potential interventions will be considered to help stakeholders and regulators in the transition to a circular economy.

5. What is the structure of the current capsules recycling value chain?
6. Where are the existing barriers towards circularity?
7. What interventions are necessary to transition the value chain towards circularity?

This work is divided across chapters, and the research approach is summarised visually in Figure 4.

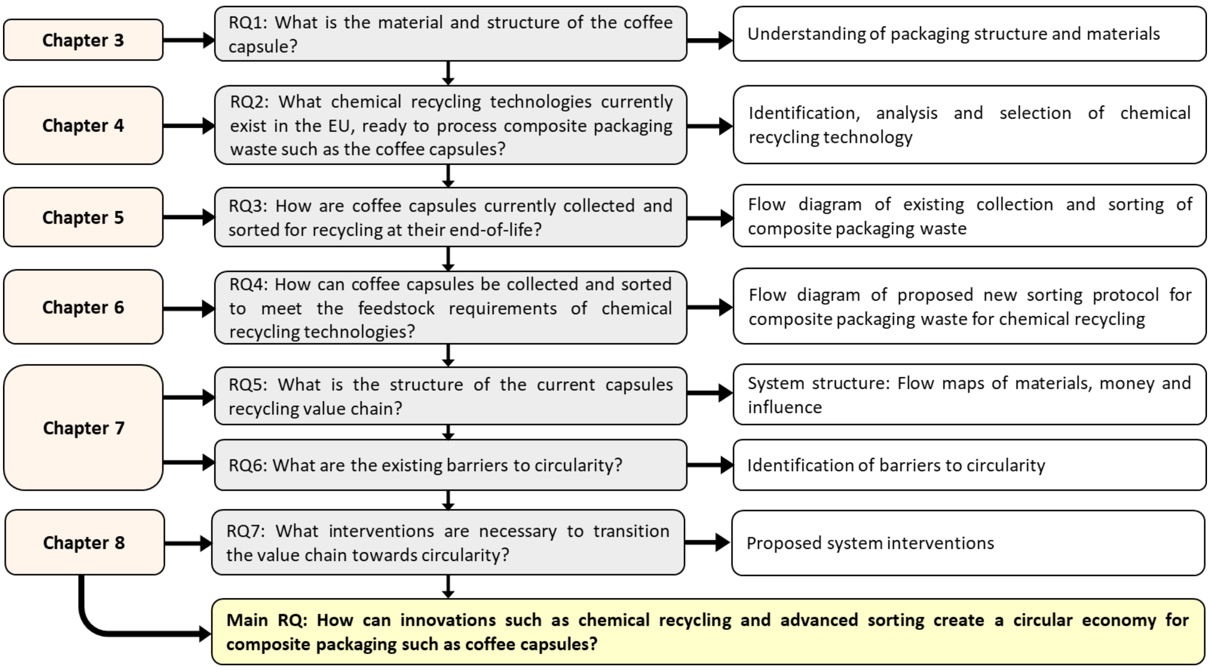

Figure 4: Research approach.

1.7. Relevance of research

This research topic was chosen because of its high social and environmental relevance. I began a Master study in circular economy because of a personal interest in the impact of the consumer goods sector. The sector involves a high daily turnover of materials through extensive value chains. Of this, only the final product is known and visible to the consumer. In this case study, the focus is on the packaging waste of an everyday consumer product, a coffee capsule. Such a product is part of the daily routine of many, and commonly available in home and professional settings, where it is disposed of after use without much concern. When disposed at scale, there are serious environmental impacts of such packaging waste. Increasing awareness of these impacts is now entering the public sphere, as seen by attention in the media, growing legislation around plastics and plastic packaging waste in the EU, as well as initiatives from brand owners seeking to increase consumer acceptance.

The emergence of new technologies for sorting and recycling aims to improve the circularity of this waste by reintroducing high-value materials back into the loop for consecutive use. It is of social and environmental relevance to assess the potential impact of these technologies and then determine how best they can be implemented, early in their innovation cycle.

To achieve this, the field of industrial ecology offers several tools. It is most known for the use of quantitative methods such as life cycle assessment and material flow analysis which are often used in tandem to assess the impacts of a technology or process (Kaufman, 2012). Both these methods however have their origins in the systems perspective of industrial ecology scholars. Garner and Keoleian (2006) express this as:

> *"Environmental problems are systemic and thus require a systems approach so that the connections between industrial practices/human activities and environmental/ ecological processes can be more readily recognized. A systems approach provides a holistic view of environmental problems, making them easier to identify and solve; it can highlight the need for and advantages of achieving sustainability."*

This work aims to employ a similar systems perspective of industrial ecology by gathering rich qualitative stakeholder data on the end-of-life solutions for composite packaging waste, and the potential of emerging technologies such as chemical recycling. The aim is to provide practitioners, researchers and policy makers with a point of reference for how these technologies can be implemented and what system barriers need to be considered when designing or proposing system interventions.

Chapter 2 – Research Methodology

The research is directed by a case study on coffee capsules to obtain granularity of the different stakeholders and processes in a product's end-of-life. In chapter 3, the material and structure of the coffee capsules is described in further detail, along with a comparison with other coffee capsules through a literature review. The Elsevier ScienceDirect search engine was used with terms such as "coffee capsule recycling" or "coffee pod recycling".

Chapter 4 and 5 were exploratory and completed through desk research with a review of scientific literature; as well as through semi-structured expert interviews with practitioners which also provided the bulk of content in chapter 6 and are described in detail below. The desk research for chapter 4 involved searching through Elsevier's ScienceDirect and Google with the terms "chemical recycling", "pyrolysis", "plastic packaging waste", "plastics recycling", "solvent dissolution" and the like. For chapter 5 the search terms were "packaging sorting", "plastic packaging material flows", "end-of-life pathways", "plastic packaging waste" and similar.

Once chapter 4 and 5 answered the first four research questions and provided a general overview, the research was concluded with a multistakeholder system approach in research questions 5, 6 and 7. The entire value chain was considered as a complex system where the identified technological developments intertwine with various stakeholders at multiple levels. A similarly broad research methodology was required to assess the potential for chemical recycling and advanced sorting to transform the plastics value chain into a more circular one.

For this, approaches from the field of innovation systems, systems change, and transition management were studied to select one best suited for guiding data collection and its subsequent assessment. Hekkert et al. define their concept of an innovation system as "*a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology*" (2007). A transition or change in such a system can be described as "*an intentional process designed to alter the status quo by shifting and realigning the form and function of a targeted system*" (Foster-Fishman et al., 2007; Loorbach, 2010)

Transition management provides a governance approach for systems change. It stresses the complexity of social actors of multiple levels such as businesses, researchers and governments which overlap in interests, forming networks based on mutual benefit, where decisions are made that eventually bring about the system change (Halbe and Pahl-Wostl, 2019; Loorbach, 2010). Transition management frameworks aim to proactively steer transformations by assessing the system structure and dynamics in light of their complex, multi-level nature.

Without becoming too prescriptive, the frameworks put forth by Hekkert et al. (2007), Halbe and Pahl-Wostl (2019), Foster-Fishman et al. (2007) and Loorbach (2010) were distilled into a simplified methodology for answering questions 5, 6 and 7. It can be described in four steps:

1. System structuring and flow mapping (materials, knowledge and influence)
2. Semi-structured stakeholder interviews (also used in chapters 4 and 5)
3. Mapping CE barriers
4. Mapping possible interventions

Each step is elaborated as follows:

1. System structuring and flow mapping (materials, knowledge and influence)

A visual representation of the capsules' value chain was drawn up and each stakeholder's role in the process was identified. A description of each type of stakeholder is available in Appendix A. Material, monetary and influence flows were mapped between these stakeholders to understand the complex inter-relations. This process was iterative with step 2, as further interviews revealed previously unconsidered relations and flows. Initially it was intended to also provide relative magnitudes of the important flows. During the process, it became clear this data was challenging to collect in the limited research timeframe. Much of it also varied greatly as the stakeholder network grew. It was therefore not included in this report, and instead the flow directions allow a qualitative discussion on the system to reveal barriers and opportunities for circularity.

2. Semi-structured stakeholder interviews

Semi-structured interviews provided most of the data in this research. Chapters 4, 5 and 6 were furnished with information from these expert interviews, as well as all of the analysis in chapter 7. It was important to gain insights across the entire system but given that this research was constrained for time and resources, I attempted to interview at least one of each the stakeholder groups, aiming for more wherever possible. Access to interview participants was greatly facilitated through my role as an intern in a multi-national beverage company, as part of the R&D packaging sustainability team. Stakeholders were approached through cold emails and cold calls, as well as through networking in industry webinars. For some stakeholder groups, multiple interviews were conducted. For example the chemical recyclers were approached for at least two interviews, the first of which discussed the technologies, and the second discussed the packaging waste system as a whole.

The viewpoints of the regulatory stakeholders such as the EU and the federal German government, as well as industry organisations such as CEFLEX were obtained from governmental communications and proposals, regulations, directives and publicly published reports. It was also not possible to interview one group, the petrochemical industries. However, during the research, other participants were asked about the role that these industries play in the system, and where they raise barriers or provide opportunities for circularity. I also attended several webinars arranged by the petrochemical industries and held informal conversations with their representatives.

All interviews were conducted via video calls. The topics were prepared beforehand, and the parties were guided through them with both closed and open-ended questions encouraging free elaboration. The parties were first asked about the role of their organisation in the value chain. They were then briefed on the challenge of recycling the composite material coffee capsules and their current end-of-life pathways. Next, they were asked to consider the causes of these challenges through iterative interrogation, asking "why" a problem would occur. This allowed identification of the barriers towards circularity. Finally, each participant was asked to visualise what could be an intervention for the barrier that steers the system towards circularity. This was also prompted through the use of guiding "what-if" questions, asking participants to imagine different scenarios for circularity, and how they would impact the current system. The interviews were transcribed and revisited to identify unconsidered flows, barriers and opportunities. Findings from the interviews are referenced throughout the report as (Stakeholder). Appendix B provides a list of all stakeholder interviews and the topics discussed within.

3. Mapping barriers and opportunities

To recognise barriers and opportunities from the interviews in section 7.2, the coding framework provided by Kirchherr et al. (2018) was used to group the findings. Kirchherr et al. built on previous work and conducted the first study of its scale on the barriers towards a circular economy, utilising desk research, stakeholder interviews and a survey. Their large number of findings were coded to identify and categorise the barriers that academics and practitioners cited in the transition to a circular economy. Their coding framework is presented in Table 2. This was used to organise the interview findings by identified barriers in section 7.2.

Table 2: Barriers to a circular economy. (Kirchherr et al., 2018)

Barrier	Description
Technological	Lack of data/proof on technologies and their impacts in implementing a CE
Market	Lacking economic viability of circular business models
Regulatory	Unsupportive policies for a CE
Cultural	Lack of awareness or willingness to engage with CE

Finally, after mapping the flows of material, money and influence, and identifying the barriers towards a circular system, Chapter 8 argues for potential interventions that can guide stakeholders and regulators towards increased recycling in a circular economy. In their framework for designing transition processes, Halbe and Pahl-Wostl (2019) invite interview participants to construct structured causal loop diagrams (CLDs). CLD construction begins with the stakeholder defining the problem as a start variable. The participants are then asked to find root causes and identify feedback loops. Lastly, these are linked with potential solutions for the system. The CLDs allow structured analysis of the interviews and reveal case-specific problems and solutions based on local knowledge (Halbe & Pahl-Wostl, 2019).

Although initially a similar framework was to be adopted to propose interventions in chapter 8; towards the completion of the work, the work faced a serious constraint of time. Therefore, the interventions presented in chapter 8 are based upon my own analysis of the system problems, the interconnectedness of barriers and stakeholders, and potentially impactful solutions for change.

Chapter 3 - Characterisation of Coffee Capsules

1. What is the material and structure of the coffee capsule?

Several coffee brands offer their own capsules, and for each, they are compatible with complimentary brewing machines manufactured in partnership with appliance makers. Nespresso machines are made by Krups and DeLonghi, Tassimo machines are made by Bosch, Philips produces the machines for L'Or capsules, and so on. The materials used for each capsule are chosen to best suit the operating mechanism of each machine. Each system utilises different brewing temperatures, pressures, capsule perforation and drink preparation mechanisms, and the materials of the capsules are tailored specifically to this. This also makes any capsule or material redesign harder to standardise, as the new variation must be compatible with existing coffee machines, which are already present in the homes and offices of consumers, acting as a technological lock-in. That provides further incentive for brand owners to prioritise recycling of their existing product design over any redesign measures, when faced with pressure over their products being unrecyclable in the existing collection and recycling networks.

This research was completed as part of an internship with a multi-national beverage brand owner. The coffee capsule in focus is a composite structure manufactured by the brand owner. In a literature review of scientific publications, four other studies looking at lab scale material recycling of common coffee capsule waste were found. A brief summary of their description is provided in Table 3 alongside that of the capsules from this study.

Table 3: Summary of coffee capsules found in the literature review and studied in this research.

Image	Source	Description of capsule and materials	Contents
	This research	• Flat 3D capsule shape • Rigid injection moulded internal structure to regulate liquid flow • PP capsule body • Organic fibre coffee filter (internal) • PP/aluminium laminated lid • Acrylic ink barcode on lid for machine to read drink recipe	• Roast and ground coffee • Soluble instant coffee • Dairy • Chocolate
	De Bomfin et al. (2019) Domingues et al. (2021)	• Hollow 3D capsule shape • PET/PP laminated lid • PP capsule body • PP coffee filter (internal) • Aluminium foil sheet (internal)	• Roast and ground coffee • Soluble instant coffee • Dairy • Chocolate

	Al Mahmood et al. (2019)	• Flat circular disc • Three layered laminate of PET, aluminium and PP	• Roast and ground coffee
	Al Mahmood et al. (2020)	• 3D capsule shape • Three layered composite of PVC, aluminium and PBT (FP1) and PP, aluminium and PCTFE (FP2) • Acrylic ink barcode on lid for machine to read drink recipe	• Roast and ground coffee • Dairy • Soluble instant coffee • Chocolate

The capsules in this study differ slightly from the others presented in Table 3. The body of the capsule is not a hollow capsule or a laminate, but a rigid injection moulded polypropylene structure. The capsules also contain organic fibres as a coffee filter. The aluminium foil is present as a lid, greater in thickness than other capsules where aluminium is used either a filter inside the capsule or in a laminate as part of the capsule structure. The aluminium lid is extruded with a layer of polypropylene that is heated to seal the lid to the capsule body.

Such capsules are representative of the problem of a mixed material structures unrecyclable with current mechanical recycling (Niaounakis, 2020). This issue is well known, and the consumption of coffee in capsules was banned in public agencies in the German city of Hamburg due to the difficulty in recycling the waste (Domingues et al., 2021). After consumer use, the aluminium foil is not peelable from the disc. It remains sealed to the polypropylene upon shredding, leaving composite flakes that cannot be sorted in any single material stream without causing contamination. The trapped coffee grind residue sticks onto flakes after shredding, creating further organic contamination. Therefore, during sorting, these structures are sorted out for incineration at municipal waste sorting facilities.

The challenge in recycling such a product is to either find an effective way to separate the laminated layers from each other, which can be done by the consumer or through the recycling process. Given that the packaging format is developed for customer convenience and single-use disposal, expectations that consumers will separate capsule components and dispose them in separate recyclable streams are low, and this is confirmed in consumer research by the brand owner. Another alternative is to redesign the capsules minimising the use of multiple composite materials to allow efficient recycling all in one material stream. As pointed out at the start of this chapter, brands are hesitant to redesign capsules as it means significant investment in changing design, production and manufacturing of not just the capsules, but also the complimentary brewing appliances.

Another option of interest to brands is to explore a recycling technology capable of processing such composite packaging without any pre-separation required. The technology must also be capable of dealing with organic contamination such as the coffee grinds and filter paper fibres. The following chapters will explore new innovations in chemical recycling technologies and the supporting sorting and collection infrastructure needed to improve value retention of coffee capsules in a circular economy.

Chapter 4 - Chemical Recycling Opportunities for Coffee Capsules

2. What chemical recycling technologies currently exist in the EU, ready to process composite packaging waste such as the coffee capsules?

At their end-of-life, plastics are often collected in a comingled stream and then sorted into separate polymer bales, to be sold to companies that process them for recycling. This recycling can be characterised by two main types: mechanical and chemical. Currently, almost all waste processing facilities around the world recycle plastics mechanically, producing extruded granulates of a lower quality than the original plastic waste (Dogu et al., 2021; Gala et al., 2020; Qureshi et al., 2020). Chemical recycling, the focus of this research, can be further divided into different types, depending on its output. This chapter describes the technical principles of each, in the context of its relevance for processing post-consumer coffee capsules. This is done through a combination of literature reviews and semi-structured interviews with experts and technology owners.

4.1. Solvent-based recycling or dissolution

Chemical recycling has been used in literature to define a process in which polymers are broken down into monomers to be used as feedstock to produce new plastics and petrochemicals (Al-Salem et al., 2009; Coates & Getzler, 2020; Niaounakis, 2020). The term ‘chemical’ is used as the process involves a change in the chemical structure of the polymer. However, many industry and commercial researchers consider the term to also include solvent-based dissolution processes due to their use of chemical solvents to recover target polymers (Eunomia, 2020; Thoden van Velzen et al., 2020; WRAP UK, 2019). Although, as the technology is described below, it does not include a change in the polymer’s chemical structure.

Solvent-based recycling involves immersing a waste stream in a solvent bath where a target polymer is selectively dissolved, and other components of the feed remain as solid residue and can be filtered off. Zhao et al. (2018) provide a comprehensive summary of solvents reported in literature for recovering different target polymers. The target polymer is contained in the solution phase and then recovered either through the use of a non-solvent to reprecipitate the resin, or through flash distillation (Kannan et al., 2017; Walker et al., 2020). The process yields pure polymer in a form ready for reprocessing, either as a powder or grain (Achilias et al., 2009). An advantage of polymers recovered this way is limited degradation of key properties such as tensile strain and molecular weight, which is common for mechanically recycled plastics (Sherwood, 2019). This allows recycled polymers to be quality competitive with virgin grades (Achilias et al., 2009; Sherwood, 2019; Walker et al., 2020) . The feedstock that is input to the solvent bath also requires less complex sorting, as multi-material packaging does not need to be separated into homogenous mono-material fractions before processing (Kaiser et al., 2018).

The technology has been studied for decades, and the dissolution recovery of polyolefins from co-mingled plastics streams has been demonstrated at the lab and pilot industrial scale (Achilias et al., 2009; Kannan et al., 2017; Niaounakis, 2020; Pappa et al., 2001). Lab scale treatment of plastic-metal laminates used in consumer packaging has also been reported in published literature. Yousef et al. (2018) use solvents to separate plastic-aluminium packaging such as crisps, biscuits and coffee packs, and cite material recoveries of over 99%, with aluminium recovered in flakes for powder metallurgy applications, and mixed plastics recovered with a potential use in lightweight applications. Nieminen et al. (2020) use solvents to separate aluminium-plastic pharmaceutical blisters, and call for further investigation on the recovered aluminium fraction which shows corrosion losses in their work due to the use of harsh solvents. Walker et al. (2020) deconstruct multi-layered polymer films into constituent resins with nearly 100% material efficiency.

In desk research, solvent dissolution shows promise in the separation of composite packaging waste such as coffee capsules, and was thus explored further for its industrial application through semi-structured expert interviews with commercial recyclers (Sherwood, 2019).

In the EU, solvent dissolution is under development by several companies. APK AG in Germany (APK AG, n.d.) separates PE/PA multi-layer films to recover separated PE and PA for reuse as flexible packaging for non-food contact applications, and plan to scale-up to processing post-consumer comingled plastic streams. Fraunhofer IVV in Germany have developed the CreaSolv process for recovery of contaminated post-consumer plastic waste (Fraunhofer IVV, n.d.). The process is available for commercial licensing, and has been licensed by Unilever in Indonesia to recover PE from multi-material single-use sachets, where the polyethylene layers make up over 60% of the weight of the structure (Unilever, n.d.).

Figure 5: Lab-scale solvent dissolution of (A) three-layer PP/PA/PE film to remove (B) insoluble adhesives, inks and PA layer and recover (C) PP and PE flakes (Roelands, 2021).

In the Netherlands, Obbotec BV has developed their selective plastic extraction technology to recover high purity PP and PE from streams of contaminated heterogenous mixed plastics (Obbotec BV, n.d.). Dutch research institute TNO has also developed a selective dissolution process for recovering polymers, named the Möbius dissolution process. The research is however still in the phase of lab demonstration, working with samples at the scale of hundreds of grams. Saperatec GmBH in Germany has developed a solvent-based process for separating metal-plastic laminates. The process involves immersing the laminates in a pre-selected solvent that targets the adhesive layer between the two materials, causing a swelling which breaks apart the laminate into its individual layers, allowing for their separate recovery (Saperatec GmBH, n.d.).

During the research, all the above-mentioned recyclers were interviewed to obtain a preliminary proof of concept of recycling the coffee capsules using solvent dissolution. Each recycler confirmed that the technology is well suited for recovering the spent capsules. By choosing a suitable solvent, the rigid PP of the capsule can be dissolved, while valuable aluminium remains an inert solid, together with the contaminating coffee grounds and filter paper. The PP can then be recovered as pure polymer grains, while the residue can be filtered off, and the aluminium washed and separated from coffee and paper residue for recovery. As the process can be scaled up to selectively dissolve all of the target polymer in the feed, the recovery rate is thus limited by the amount of target polymer in the feed. Recyclers cite recovered PP purities 99% suitable for food-grade applications, however this is yet to be confirmed. Throughout the research, no empirical reports of the industrial material efficiency of the technology were publicly available, and similarly no data was provided on the environmental impact of the technology as opposed to mechanical recycling or other chemical recycling alternatives.

4.2. Chemical depolymerisation

Chemical depolymerization is a process through which a polymer is broken down into its monomer building blocks using chemically reactive agents. The main type of depolymerisation with a commercial application is solvolysis, which involves the addition of water or solvents such as methanol or glycols together with use of a catalyst (Thiounn & Smith, 2020). These processes are suited for the recycling of condensation polymers such as polyesters and polyamides (Niaounakis, 2020). PET, the most widely produced polyester (Li-Na, 2013), is formed through a polycondensation reaction between ethylene glycol and terephthalic acid. In its chemical depolymerisation, the polymer chain is targeted at its monomer bonds to yield products that can be refined and used for repolymerisation of virgin PET. For polyolefins such as polypropylene, the polymer used in the coffee capsules, no technology currently exists to chemically depolymerise its long, repeating hydrocarbon chains (Dogu et al., 2021; Niaounakis, 2020). Therefore, chemical recycling with this process was not considered further due to inapplicability for the materials in the case study.

4.3. Thermal depolymerisation

Thermal depolymerisation or thermolysis is when polymers are decomposed into shorter chain molecules at high temperatures and in the absence of oxygen (Sharuddin et al., 2016). The products of plastic depolymerisation are mainly hydrocarbon oils, gases and waxes. The oils and gases can be further processed to produce new monomer feedstock which can be used to reform the original polymers with virgin properties, thus essentially closing the polymer material loop (Dogu et al., 2021).

Unlike solvent dissolution and chemical depolymerisation through solvolysis or hydrolysis, which both involve targeted chemical reactions, thermal depolymerisation is a random thermal degradation of the hydrocarbon polymer chains. The carbon-carbon bonds undergo random scission at temperatures ranging between 400 - 600°C (Miandad et al., 2019; Shangwa et al., 2020), resulting in a mixture of shorter chain hydrocarbons which form the output gases, oils and waxes. As the process involves a random scission of hydrocarbons, the feedstock can be a heterogenous mixture of different polyolefins, theoretically providing an economic advantage over other recycling methods if fewer feedstock pre-treatment steps are required (Dogu et al., 2021). The preferred plastic feedstock for thermal depolymerisation is polyolefins such as PE and PP, and these plastics also make up the largest share of household consumer packaging waste (PlasticsEurope, 2020).

The most common form of thermal depolymerisation is pyrolysis, an industrially established technique. Several studies have been carried out on its potential for recycling different types of household plastic waste streams. Shahruddin et al. (2016) provide a review of these studies and show that recovery of PP and PE streams is usually in the range of 80 – 85% conversion to oils, with the remainder being waxes and gases. The share of oils, gases and waxes in the output can be fine-tuned by changing the process parameters, and this is summarised in several publications (Czajczyńska et al., 2017; Dogu et al., 2021; Meys et al., 2020; Miandad et al., 2017; Qureshi et al., 2020).

Recently, multiple companies have emerged in the EU recycling plastics through thermal depolymerisation by maximizing the oil output, in a form of pyrolysis termed as "plastics-to-oil" recycling. Obbotec B.V. in the Netherlands, Renew ELP and Plastic Energy in the UK, Carboliq GmbH and Biofabrik in Germany, and Quantafuel in Denmark are all examples of this, working with household plastic waste streams and converting them to liquid chemicals and fuel oils (Carboliq GmbH, n.d.; Obbotec BV, n.d.; Plastic Energy, n.d.; Quantafuel, n.d.; ReNew ELP, n.d.). While this type of depolymerisation is suitable for streams of mono and mixed plastics, it is not for streams which contain inorganic contaminants such as aluminium found in composite packaging (Al Mahmood et al., 2020; Ludlow-Palafox & Chase, 2001; Qureshi et al., 2020).

Recycling composite packaging requires a slightly different form of thermal depolymerisation so the aluminium can be recovered in its solid state (Al Mahmood et al., 2020; Qureshi et al., 2020). While the principle of thermal disintegration of the polymers is similar, recovering solid aluminium requires different types of reactors, catalysts and process operating conditions. Al Mahmood et al. (2020), Qureshi et al. (2020), and Shahruddin et al. (2016) highlight microwave pyrolysis which has been demonstrated by Ludlow-Palafox and Chase (2001) to process PE and aluminium laminated toothpaste tubes. Microwave pyrolysis involves the use of a reactor bed containing carbon which, when exposed to a microwave field, can reach temperatures up to 1000°C in a few minutes (Ludlow-Palafox & Chase, 2001). The polymers are disintegrated and solid aluminium residue can be sieved from the reactor bed. In their study on recycling the toothpaste tubes, Ludlow-Palafox and Chase report a 100% material recovery of the laminated aluminium, and an 81.1% recovery of the plastic hydrocarbons into oils and waxes, with the remainder being gas that is burnt to energetically self-sustain the process. Their work has been commercialised at the European level. Enval Limited in the UK operates the microwave pyrolysis process specifically targeting the recycling of plastic aluminium laminates. The output from the process is solid aluminium, pyrolysis oils used as chemical feedstock or fuel, and hydrocarbon gas that is burnt onsite to sustain the process' energy requirements (Enval Limited, n.d.).

Further studies on the recycling of plastic aluminium composites were found to be scarce in the reviewed literature. Apart from pyrolysis, Al Mahmood et al. (2019, 2020) demonstrate the recycling of aluminium via thermal disengagement of plastics from plastic-aluminium laminates. However, this was not considered further as the plastics are not recovered but instead gasified in the process. As stated by Kaiser et al. (2018), in the case of composite packaging where aluminium makes up 10-20% and the plastic makes up the remainder, the overall recycling rate will be at maximum 10-20%, and usually lower due to oxidative losses of aluminium.

4.4. Technology selection

Of the chemical recycling technologies detailed above, one was selected to proceed with the next steps of the research. Initially this work intended to provide quantitative data such as process operating parameters, feedstock requirements, process outputs, material recovery rates, an indication of environmental impacts, and the current and future scale of these technologies. However, very little empirical data was found on the industrial scale performance of these technologies in scientific literature. This has also been highlighted by other researchers (Rollinson & Oladejo, 2019). Even less is available publicly from the companies still developing these technologies due to competitive concerns. The companies are briefly summarised in Table 4.

Considering the absence of such quantitative data, a decision on the most suitable technology was made guided by the principles of efficient and high value material retention in a circular economy. As detailed in the circular economy diagram (Figure 1) of the EllenMacArthur Foundation, as well as in the CE concepts put forth by other scholars (Korhonen et al., 2018) there is a hierarchy of circular loops, each with a different level of value retention. Recycling is placed on the outermost loop, just before energy recovery or disposal, indicating the lowest value retention. However, even within recycling, different types of recycling result in different levels of material efficiency and value retention. Two different distinctions can be made in the type of recycling system: either open loop or closed loop. Closed loop recycling refers to when a material is reverted back to an earlier process in the same product system, directly replacing its input from primary production (Morseletto, 2020). Open loop recycling refers to when at least a share of the recycled materials enters another product system (Morseletto, 2020). While the preference of one over another depends on several factors such as product use, process economics and material losses (Geyer et al., 2016), closed loops are generally regarded in industrial ecology as preferable to open loops due to the avoidance of additional collection and transport emissions and additional processing steps (Geyer et al., 2016; Morseletto, 2020).

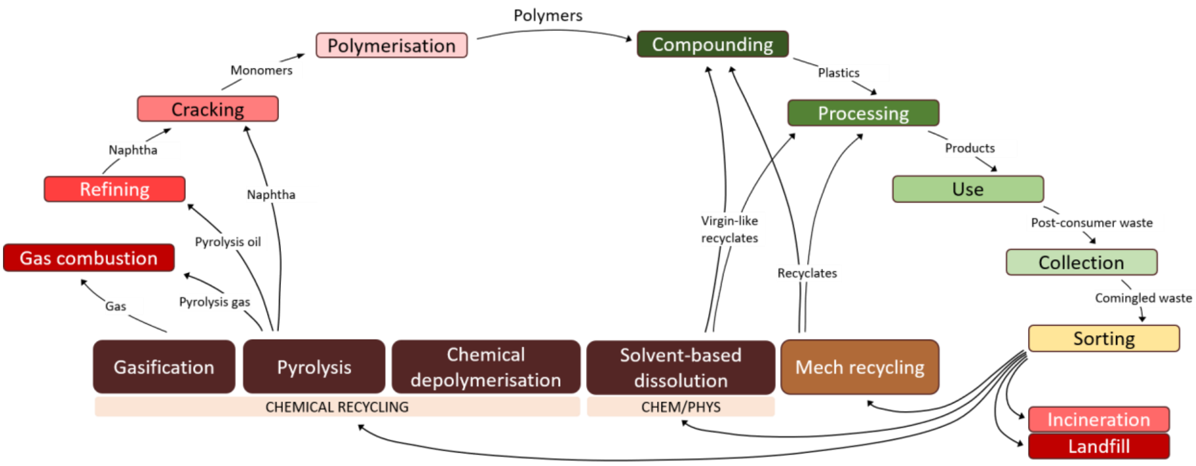

Figure 6: Plastics recycling value chain and end of life recycling pathways. Own illustration.

Considering the above, the plastics value chain and end-of-life recycling pathways with different forms of chemical recycling are presented in Figure 6. From the technologies discussed in this chapter, the two that apply to composite plastic aluminium waste are solvent dissolution and thermal depolymerisation via microwave pyrolysis. Of the plastic portion of the waste, pyrolysis yields hydrocarbon oils and gases, from which the gas is burnt to sustain the process energy requirements. There are two issues with this. The first is that recovery of materials for energy is not considered as recycling, under the EU Directive 2018/852 (European Parliament, 2018). Therefore, the portion of plastics converted to gas and burnt for energy is lost and not recycled. Second, while the remainder of the plastic portion, about 80 – 85% as reported in literature (Ludlow-Palafox & Chase, 2001; Sharuddin et al., 2016), is converted to oils for feedstock recycling, there are no reports on its final plastic-to-plastic conversion. Assuming the oil is used for plastic conversion, further petrochemical refining is still necessary before the oils can be used as plastic feedstock (Qureshi et al., 2020). This increases the number of steps required to return to the material's original use, expending more emissions and increasing material losses due to multiplicative process conversion inefficiencies along the way. On this point, Rollinson and Oladejo (2019) provide a strongly critical review of the thermodynamic inefficiency of waste pyrolysis technologies, and conclude them as environmentally unsuitable. Another point to note is that if the oils are used instead as feedstock for the production of other chemicals, the recycling becomes open-loop, and the materials are lost to another product system.

On the other hand, the polymer product from solvent dissolution is reported to be in a grain or powder form (see Figure 5) free of contaminants and suitable for recompounding and subsequent plastic production (Achilias et al., 2009; Kaiser et al., 2018; Sherwood, 2019; Zhao et al., 2018). Referring to Figure 6, this puts the output of solvent dissolution much closer to the original product form. Without any empirical information on the process environmental impacts, in this research, I assume that a lower number of processing steps in the middle will point to a more environmentally sound form of recycling, as proposed by CE scholars (Korhonen et al., 2018). For the sake of completeness, it must be mentioned that this is in no way conclusive. Quantitative data is needed on the potential negative impacts of the solvents used as well as process energy demand if large amounts of solvent are flashed for recovery.

However, considering the higher material efficiencies reported for solvent dissolution compared to thermal depolymerisation, as well as the position of its product outputs in the overall recycling value chain, solvent dissolution is selected in this research as the chemical recycling technology for recycling composite packaging waste. The next section reviews the collection and sorting infrastructure and explores how it must be adapted to meet the requirements of recycling composite packaging via solvent dissolution.

Table 4: Summary of technology providers able to process composite coffee capsule waste

Technology	Technology provider	Type of feedstock	Current capacity	Output	Yield	Location	Status
Solvent dissolution	Fraunhofer IVV	Mixed plastics Plastic aluminium composites	3kT	Targeted polymers (PE, PP) from mixed plastics Solid aluminium	>99% of PP 100% of aluminium	Germany	Online (Indonesia)
Solvent dissolution	Obbotec B.V.	Mixed plastics Plastic aluminium composites	2kT	Targeted polymers (PE, PP) from mixed plastics Solid aluminium	>95% of PP 100% of aluminium	Netherlands	Online
Solvent dissolution	Saperatec GmbH	Mixed plastics Plastic aluminium composites	18kT	Targeted polymers (PE, PP) from mixed plastics Solid aluminium	100% of PP 100% of aluminium	Germany	Online
Microwave pyrolysis	Enval Ltd.	Plastic aluminium laminates and rigid composites	2kT modular scaleable units	Hydrocarbon oils and gases Solid aluminium	100% of aluminium 81.1% of plastics as oil (remainder burnt as process fuel)	UK	Online

Chapter 5 – Collection and Sorting of Coffee Capsules

In this chapter, it was explored how feedstock ready for chemical recycling could be sourced through the existing waste collection system. From the moment a consumer disposes of a coffee capsule to the point it can reach the chemical recycler as suitable feedstock, two main steps take place: collection and sorting. It is therefore important to understand these in detail before determining the potential pathway for the capsules. The sub-question to be answered first in this chapter is thus:

3. How are coffee capsules currently collected and sorted for recycling at their end-of-life?

This work starts by looking through the different pathways for post-consumer packaging waste in Europe, with a focus on Germany. Germany was chosen as it has consistently ranked as a leader among the EU27 countries with regards to its plastic packaging recycling rate (Plastics Europe, 2019; PlasticsEurope, 2020). It was also the first country in Europe to develop and implement an industry-funded extended producer responsibility (EPR) system for the collection of consumer packaging, called the Green Dot scheme. After its success, the system was rolled out across the other European countries (Der Grüne Punkt, n.d.). Due to the maturity of its packaging recycling industry and well-established waste management legislation, the country serves as a good benchmark for possibilities for the coffee capsules' end-of-life.

In Germany, the national Packaging Act, the Verpackunggesetz or VerpackG, interprets the European Packaging Directive into German law (Bundesregierung Deutschland, 2017). It requires all manufacturers who place products on the market to pay a contribution fee towards a national EPR organisation that ensures the separate collection and recycling of consumer packaging waste. After the founding of the Green Dot scheme in 1990, several EPR organisations emerged in Germany to offer manufacturers the services needed to comply to the VerpackG. Currently, there are eight such EPR organisations in place in the country. Each is responsible for arranging the collection and sorting of EPR registered packaging from households of a certain German region. For this, they engage the private waste management companies which build and operate the sorting facilities and waste collection services. The manufacturers of the coffee capsules similarly pay a licencing fee towards the EPR schemes for the collection and recycling of their capsules, and hence their end-of-life pathway follows that of all other EPR registered packaging in Germany. The details of this pathway are discussed in the following sections.

5.1. Collection

After a consumer disposes the coffee capsules, the first step in their end-of-life is collection. Waste collection can have several arrangements, and these can be categorised based on two main parameters: collection method and collection portfolio (Thoden van Velzen et al., 2018). The collection method refers to the way consumers deposit waste into the collection system. There are two widespread methods for this: drop-off or kerbside (Hahladakis et al., 2018). In kerbside collection, consumers have access to collection bins at a short distance from their doorstep. In a drop-off system, collection bins are available in strategic, high-traffic areas where consumers can bring their waste and recyclables for drop-off (Hahladakis et al., 2018). Depending on regional differences, a mixture of both methods can be employed across a country. In Germany, a majority of the public has access to kerbside collection for plastic packaging waste (Netherlands Institute for Sustainable Packaging, 2017; Picuno et al., 2021).

The collection portfolio dictates the types of materials collected commingled with each other in both kerbside and drop-off systems. In Europe, most countries operate a separate collection of recyclables such as plastic packaging, paper, glass and metals from non-recyclable household or organic waste, which is directly sent for incineration (Brouwer et al., 2019; Cimpan et al., 2015; Netherlands Institute for Sustainable Packaging, 2017; Thoden van Velzen et al., 2018). While initially the focus of separate collection was to channel recyclables away from landfill or incineration, in recent years as the concept of a circular economy has taken hold, the focus has shifted towards maximising material recovery from separately collected streams (Thoden van Velzen et al., 2018). This separate collection of recyclables is divided into different collection portfolios. While an assessment of the most suitable collection portfolio is out of the scope of this work, comparisons between different portfolios are available in published literature (Brouwer et al., 2019; Hahladakis et al., 2018). A summary of the separate collection portfolio in Germany is adapted from Cimpan et al. (2015) as follows:

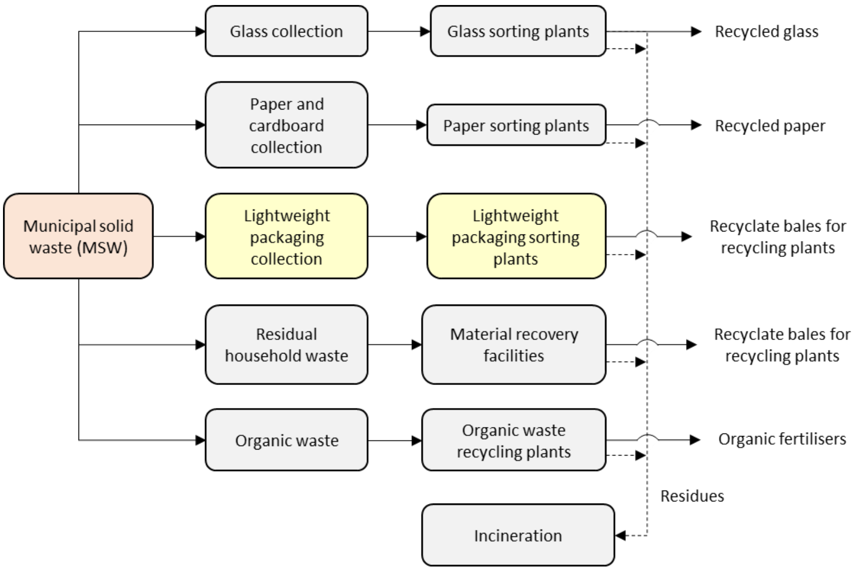

Figure 7: German waste collection portfolio, own illustration adapted from Cimpan et al. (2015). Collection of coffee capsules highlighted in yellow.

Packaging waste such as the coffee capsules is registered with an EPR organisation and collected separately alongside residual household waste in yellow kerbside bins or bags (Picuno et al., 2021). There are also separate streams for paper and card, and glass, as they each flow subsequently to separate reprocessing routes. In some regions glass is not collected kerbside but at drop-off sites, in which case the typical kerbside arrangement is shown in Figure 8 as follows:

Figure 8: Yellow bin for collecting registered packaging waste under the German EPR scheme, alongside separately collected residual waste (black), organic waste (brown) and paper (blue).

After collection, waste from the yellow bins is transported to sorting facilities where it is sorted into different material fractions for reprocessing. Sorting plants for packaging waste differ from plants handling other waste streams such as residual waste, or organic fractions. They process the feedstock into sorted bales which is traded to recyclers. The bales have standard specifications set by the Deutsche Gesellschaft fur Kunststoff-Recycling (DKR) which mandates required compositions of the sorted bales for recycling. A typical sorting plant produces about 12 to 13 fractions, and these are shown in Figure 9 which also summarises the collection and sorting arrangement in Germany. The full DKR specifications for the sorted fractions are available in Appendix C.

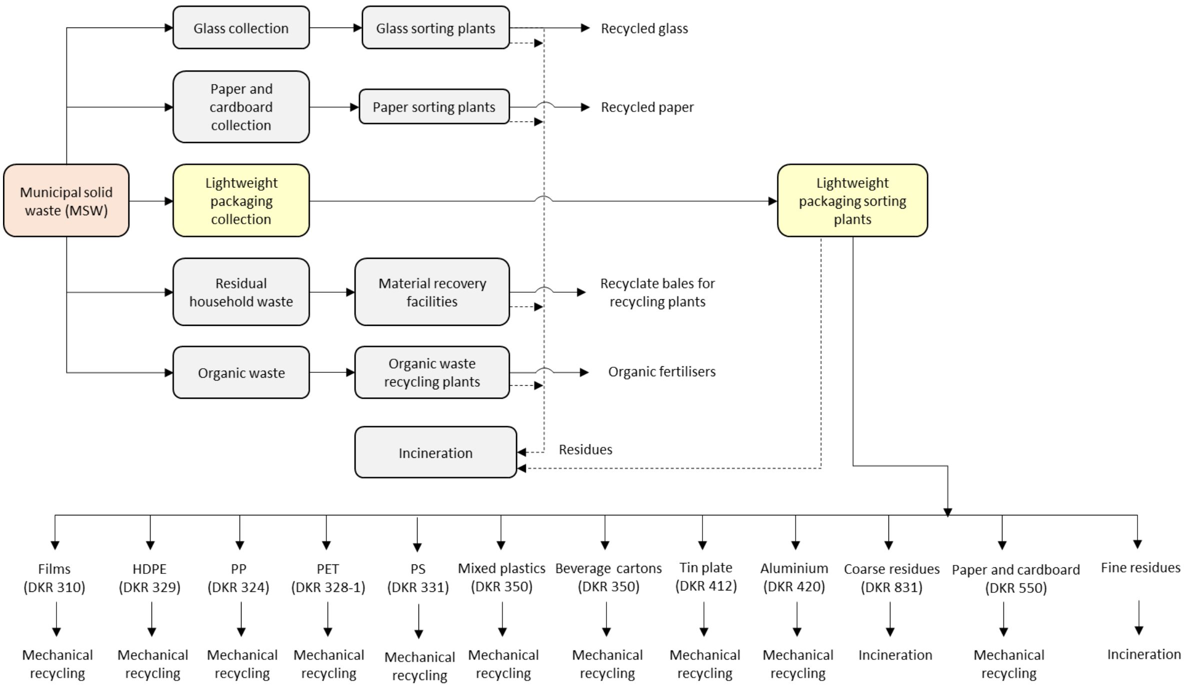

Figure 9: Summary of collection and sorting arrangement of German packaging waste. Adapted from Picuno et al. (2021).

5.2. Sorting

To understand how a complex composite packaging such as coffee capsules perform at a packaging sorting facility after collection, the best route would be conducting a sorting trial in a sorting facility. However, due to the limitations of the research, this stage involved developing a map of state-of-the-art German packaging plants through a literature review of the German waste management system, publicly available literature, and a sorting test commissioned by the brand owner. The works of Cimpan et al. (2015), Jansen et al. (2015) and Kaiser et al. (2018) provide flow diagrams of German lightweight packaging plants, which were furnished with additional information from the material flow analyses of Dutch packaging recycling systems done by Brouwer et al. (2019; 2018) and a compositional analyses of Dutch plastic packaging waste conducted by van Velzen et al. (2018). As pointed out by Picuno et al. (2021) and Jansen et al. (2015), the Dutch packaging recycling system is largely similar to the German one, and adopts the same German DKR standards for recyclate bales produced at sorting plants. Reviewing the above, a sorting protocol for the coffee capsules was developed. It is presented in Figure 10 and described below.

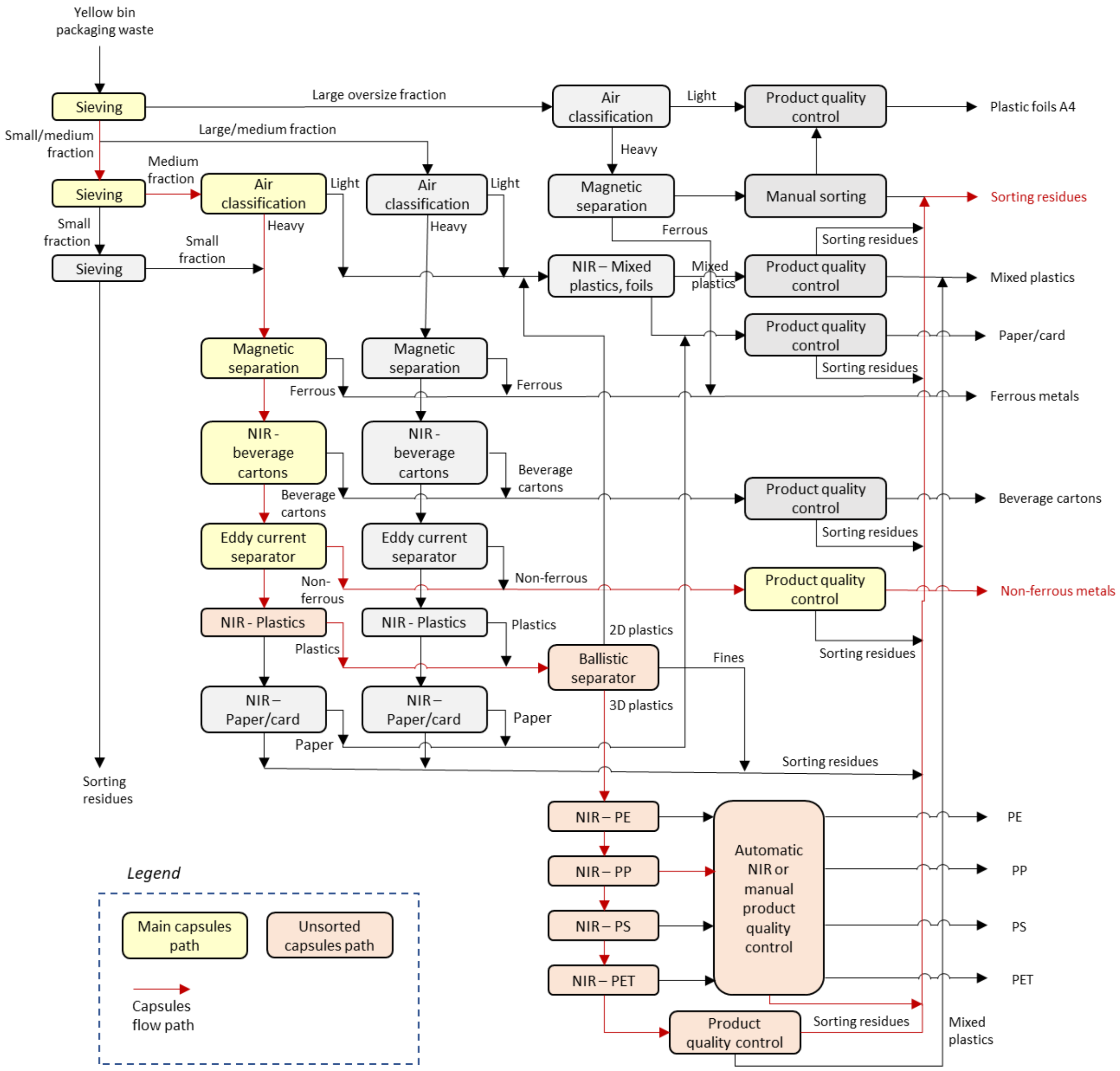

Figure 10: Sorting protocol for coffee capsule waste. Own illustration.

The feedstock to a sorting plant is packaging waste in the yellow bins. It arrives at the plants and is first sieved into size ranges. The largest oversized fraction is sent for air classification, where large 2D plastic films are recovered, and the rest is sent for incineration as residue after extracting ferrous metals. Of the remaining sizes, further sieving separates them into three or four fractions. Middle fractions are sorted on parallel lines in a series of sorting steps. The smallest size fraction is sent for incineration as sorting residue. This cut off size for incineration can be high in older plants, where costs for recovering materials from fine fractions are high, and the recovered materials pose little economic value (Sorting plant A; B).

The coffee capsules fall into a medium size fraction and proceed to the subsequent sorting steps. An air classifier removes light, two-dimensional packaging such as mixed plastic films and plastic foils. What remains is a mix of heavier three-dimensional packaging, rigid or flexible. The next step is magnetic separation to recover ferrous metals. This is followed by an NIR scanner detecting beverage cartons, which produce a unique signal at the scanners due to the co-lamination of paper, aluminium and polyethylene (Sorting plant B). These are removed from the stream into the DKR-510 bale.

The next step is an eddy-current separator (ECS) which detects all packaging containing non-ferrous metals. While in municipal solid waste, non-ferrous metals may include copper, zinc and lead from household electronic waste, the main non-ferrous metal present in packaging waste is aluminium (Sorting plant B). This is an important step for the capsules and is described here in further detail.

The ECS applies a magnetic field over the material stream. This induces an electrical charge in a non-ferrous metal such as aluminium, and packaging containing it is ejected off the belt with a trajectory proportional to its aluminium content. The sorting plants do not differentiate between the different trajectory paths, and hence the aluminium content of different packaging (Sorting plant A; B). All aluminium containing packaging ejected by the ECS is collected in one bale, the DKR-420. This means that the capsules containing less than 10% aluminium by weight would be sorted in the same bale as an aluminium beverage can, which may contain 80 – 98% aluminium by weight, and this bale would also contain other aluminium containing packaging such as laminated foils, food pouches and menu trays. In a pilot-scale sorting test conducted by the capsule brand owner, 80% of the stream of capsules was detected by the ECS and sorted into the bale. Across Germany, the DKR-420 bales are sent for aluminium recovery via pyrolysis, where the polymer and paper fraction of a bale is lost as heat energy (Sorting plant A, sorting plant B).

The capsules that fail to be sorted correctly into the non-ferrous metals stream proceed to the subsequent sorting stages, where NIR scanners are used to detect plastics, paper and card. When plastics are removed, the stream arrives at the plastics sorting block, where a cascade of NIRs recover streams of target mono-plastics, commonly PET, PE, PP and PS. Depending on how the capsule lays on the belt and if the PP is facing upwards towards the NIR detector, it will be sorted into the PP bale, DKR-350. If the aluminium lid faces the NIR detector instead, the capsules proceed through the cascade of NIRs unsorted and are incinerated as residual waste.

In each sorting facility, a final step involves product quality checks to ensure the sorted bales comply with the DKR specifications. If contaminants are found to be too high, the materials are rejected from the bale, and the sorting machine settings adjusted to improve composition. In the case of the few capsules that are sorted into the PP bale, the DKR standard enforces a maximum contamination limit of 10% by weight. Hence, if the product quality checks detect such a material in the bales, it is rejected from the bale to limit contamination.

Therefore, of all outgoing bales produced at the sorting facilities, the capsules can be sorted in two possibilities. The majority of capsules fall into the DKR-420 bale for non-ferrous metals, which largely contains aluminium containing consumer packaging. The other option for the capsules is sorting as residues, in which case the packaging is incinerated. In the next chapter, it is explored how to divert this composite packaging waste towards chemical recycling, and what changes are necessary in the sorting infrastructure to enable this.

Chapter 6 – A New Sorting Protocol for Composite Waste

4. How can coffee capsules be collected and sorted to meet the feedstock requirements of chemical recycling technologies?

As the majority of the capsules are sorted into the non-ferrous metals fraction, it was investigated how the capsules could be recovered with other valuable materials from the DKR-420 bale as reliable feedstock for the chemical recycler. For this, interviews were conducted with sorting plant A and B, sorting equipment providers A, B and C, chemical recyclers A, B and C, aluminium recycler A and aluminium foil roller A. This was coupled with a literature review, and a potential sorting scheme was developed to recover feedstock suitable for chemical recycling via selective plastic dissolution.

The chemical recyclers are interested in a feedstock that maximises the content of high-value consumer plastics such as polyolefins PE and PP as well as clean washed aluminium (Chemical recycler A; B and C). Although the composite packaging also includes paper and card, the stakeholders expressed low interest in recovering this fraction chemically, due to the current absence of a technical solution for damaged paper fibres during the pre-shredding, washing and drying steps.

6.1. Classification of packaging in a DKR 420 bale

As the capsules fall mainly into the DKR-420 fraction which also contains other composite packaging waste, the first step was to investigate the actual composition of the bale to determine the fraction of different materials present. An interview with Chemical recycler A allowed access to a lab scale study determining the material classification of a DKR-420 bale. The waste is described in Table 5 and reported in Figure 11.

Table 5: Classification of types of packaging waste found in DKR-420 bales (Chemical recycler A).

Aluminium-rich packaging High aluminium weight content, may include composites with other materials.	**Polymer-rich packaging** Composites of polymer and aluminium with a high polymer weight content.	**Paper-rich packaging** Composites of paper/card and aluminium with a high paper/card weight content than aluminium.
Beverage cans, food cans, aerosol spray cans, tubes, bottle screw caps, food trays	Flexible food and drink pouches, flexible laminate packaging, laminated pharmaceutical blisters, rigid packaging	Alu-foil lined sachets, cartons, potato crisp tubes, wrappings (butter, chocolate etc.)

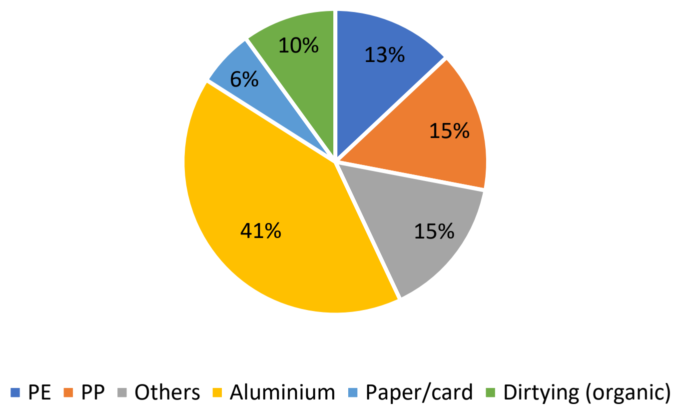

Figure 11: Material composition of DKR-420 bale from sorting plants. (Chemical recycler A).

6.2. Sorting protocol for DKR 420 waste

From the packaging classification presented in section 6.1, stakeholder interviews allowed identification of a target feedstock for chemical recycling via dissolution. A sorting scheme to enable feedstock recovery is proposed in Figure 12 and described below.

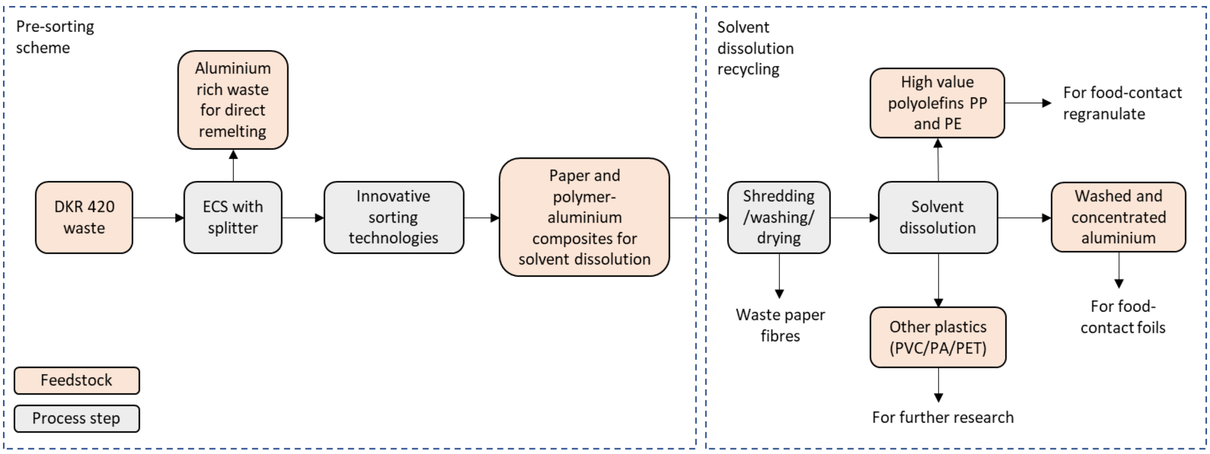

Figure 12: Proposed post-sorting solution for obtaining capsule feedstock. Own illustration.

Although Germany has a separate deposit system for aluminium cans (Gesamtverband der Aluminiumindustrie e.V., 2020), consumers still dispose of aluminium drink cans in the yellow bins for lightweight packaging (Sorting plant A; B), and these together with packaging such as aerosol cans, food menu trays and aluminium tubes make up the largest aluminium rich fraction of the DKR 420 bale.

Aluminium rich waste for direct remelting

According to sorting plants A and B, the first step in isolating composite packaging is to remove all aluminium rich packaging from the bale for its direct remelting into scrap aluminium. This is technically "low hanging fruit" as it can be achieved with existing eddy-current separators with a splitter in their collection hood (Smith et al., 2019; STEINERT GmbH, n.d.). Objects with a higher aluminium content are ejected at a further distance than composite packaging with a lower aluminium content. Optimising splitter settings allows precise separation of fractions by dividing them based on the distance of their ejection pathways (Sorting plant A; B; Smith et al., 2019).

The benefits of this first step are two-fold. First, this allows recovery of a higher grade of aluminium from DKR 420 waste. As previously stated, DKR 420 bales are currently incinerated, and aluminium is recovered from remelting its flakes sieved from bottom ash. Gökelma et al. (2021) review the recyclability of aluminium from bottom ash after the incineration of composite packaging waste. Aluminium is prone to oxidation losses, and this is exacerbated by the type of incinerators used for composite waste, and the high amount of foreign material in the feedstock (Capuzzi & Timelli, 2018). Dirty mixed scrap requires the use of a rotary furnace, which negatively impacts the material recovery efficiency. R. Bunge (2016) report oxidisation of up to a third by weight of used beverage cans incinerated this way.

Secondly, separating a stream of high aluminium content allows its exploration for direct scrap remelting. Gökelma et al. (2021) find that the re-melting metal yield increases with larger particle sizes due to a decreasing ratio of oxide formation/metal. This yield refers to the portion of scrap that becomes useable metal after remelting. Concentrating aluminium packaging scrap for direct remelting will result in higher metal yields as opposed to remelting the aluminium particles sieved from incinerator bottom ash (Capuzzi & Timelli, 2018; Gökelma et al., 2021). Capuzzi & Timelli (2018) report average aluminium yields of 94% when a clean feedstock of aluminium beverage cans is remelted with a limit on foreign material of 5.2%. Apart from increased material recovery efficiency, remelting direct scrap can realise more emissions savings relative to primary production of aluminium, when compared with its incineration.

Innovative sorting technologies

The next step in this sorting scheme involves the use of new innovations in sorting to detect composite packaging on the belt from other residue or non-recyclables that are present in the bale. Currently, the state-of-the-art in identifying and sorting plastic packaging is focused on material optical spectroscopic properties, mainly near-infrared (NIR) sorting as the standard in sorting plants (Zhu et al., 2019). Light is shone onto packaging materials on the moving sorting belt, and a unique radiation reflection curve is received at the detector and used to identify the polymer. The technique has widespread use as it allows for fast, on-the-line detection of polymers with accuracy and does not require any surface pre-treatment of the packaging (Zhu et al., 2019). But it is not without limitations. When it comes to reading the complete make-up of composite packaging on the belt, NIR faces challenges (Woidasky et al., 2020). Sorting plant A and B state:

> "…NIR cannot read the full picture of a composite. It all depends on what material is facing the scanner. That's all that is detected, and the packaging can be sorted incorrectly because of it…"

Chen et al. (2021) demonstrate this in their study using NIR to detect the composition of flexible multilayer plastic packaging on a sorting conveyor belt. They report that the presence of aluminium, even as just a metallised layer, prevents any radiation from passing through, and any materials below the aluminium are not detected by the NIR scanner. Araujo-andrade et al. (2021) conduct a review on the techniques available for monitoring the on-line composition of multi-material waste and find:

> "…In view of the appearance of such emerging recycling solutions (selective polymer dissolution), there is a need to develop finer identification techniques for multimaterial waste plastics […] a number of complementary technologies are required in order to obtain a full fingerprint of all

> organic (e.g., polymer matrix, coating or paper) and inorganic (e.g., fibres, fillers or metals) materials involved…"

As mentioned, the focus for chemical recyclers is concentrating the share of three valuable materials from the composites bale: PP, PE and aluminium. From expert interviews and desk research, two types of sorting innovations were identified, and these are described further as follows:

NIR equipped with deep learning

This work proposes an add-on to existing NIR technology, seen as a promising innovation from the expert interviews. Combining high-resolution cameras with NIR technology and deep learning algorithms can help train automated sorting machines to accurately detect the composition of multi-layered materials, and overcome the presence of noise or gaps in the NIR spectra of composite packaging (Araujo-andrade et al., 2021; Wilts et al., 2021). The sorting protocol is built by feeding large amounts of high-resolution images, sensor data and accompanying NIR spectra, allowing the automatic recognition of specific forms and textures of packaging. All additional equipment can be retrofitted over existing sorting belts, and the technique remains non-invasive and requires no surface treatment of the packaging (Araujo-andrade et al., 2021; STEINERT GmbH, n.d.; TOMRA, n.d.; Wilts et al., 2021; ZenRobotics, n.d.).

In the EU, TOMRA, a Norwegian multi-national supplier of sensor-based sorting solutions has developed proprietary GAIN Intelligence, a deep learning-based add-on to their existing sorting lines (TOMRA, n.d.). ZenRobotics, based in Finland, are supplying on-line sorting equipment with automated deep learning robots to increase the efficiency of sorting mixed consumer waste (ZenRobotics, n.d.). In Germany, STEINERT GmbH, a leading sorting equipment supplier has similarly developed and tested deep learning cameras as an add-on to NIR spectroscopy to determine composite packaging with further precision (STEINERT GmbH, n.d.).

While the expert interviews reveal nascent commercial development of the technology, publications demonstrating the efficiency or potential of the technology are limited. Wilts et al. (2021) tested and evaluated automated sorting by equipping NIR detectors with high-resolution cameras. The study was conducted at an existing waste sorting plant on real heterogenous household waste, and the results allow very early conclusions to be drawn on the efficiency of the technology. Apart from their publication, this research finds little to no empirical data on how deep learning can enable accurate sorting of composite waste such as the coffee capsules. Nonetheless, the technology is promising for identifying composites, and further work on its industrial demonstration will be an important enabler for chemical recycling of composites.

Packaging markers for sorting

Another innovation in sorting that can unlock a reliable feedstock for chemical recyclers is the use of chemical tracers or digital watermarks on packaging. Chemical tracers involve a special ink used to print information onto the packaging, which is illuminated and read at the sorting plant through optical spectroscopy. A watermark is a small code applied directly onto the packaging either as a physical embossing or optical stamp (Ellen MacArthur Foundation, n.d.). Differences in the code can be read by scanners fitted onto existing lines at sorting plants. The key advantage for these markers is that their reading is independent of the material's physical or optical properties. The marker is also able to store details about the packaging such as its manufacturer, material composition, and its content and purpose, either food or non-food (Woidasky et al., 2020).

In the EU, this technology is emerging with several actors coordinating to bring it to market. The most notable effort is Project Holygrail under the European Brands Association. The project involves the entire packaging value chain, with over 85 material and packaging converters, brand owners, waste management companies and chemical recyclers. The technology has undergone proof of concept testing on test sorting lines but has yet to arrive on the market. In its current stage, brand owners are modifying packaging with the markers to upscale to industrial testing by introducing the watermarked packaging into test markets (European Brands Association, n.d.).

Apart from the EU, publicly funded research in the UK has developed PRISM, an invisible fluorescent marker-based sorting system that can be read by existing optical sorting systems in UK sorting plants with minimal modifications (UK Research and Innovation, n.d.).

If implemented correctly, packaging markers have the potential to enable a tailored feedstock specific for chemical recycling via solvent dissolution. For composite packaging like the coffee capsules, this could also allow marking of the material combination and instruct sorting for a special chemical recycling route (Gasde et al., 2021).

This section concludes with the presentation of a sorting protocol for composite packaging to enable feedstock for solvent dissolution. In the following chapter, this work discusses how these innovations in chemical recycling and sorting can help to transition the coffee capsule life cycle towards circularity.

Chapter 7 – The Transition to a CE for Coffee Capsules

7.1. System structuring and flow mapping

5. What is the structure of the current capsules recycling value chain?

7.1.1. Material flows

While conducting the literature review and expert interviews for the previous chapters, it was evident that the system in which the life cycle of the capsules takes place is a complex socio-technological system involving a wide variety of stakeholders. In order to achieve a circular economy for such waste, research must think beyond just technical capabilities, and employ a multi-stakeholder systems perspective. To understand how technological innovations such as chemical recycling and advanced sorting would impact the system, it was necessary to first structure the stakeholders and map key flows. These stakeholders were identified and then interviewed. These stakeholders are mapped in Figure 13 which also details the interflow of materials in the system. As seen in chapter 5, the capsules largely fall into the DKR-420 bale. However, the end-of-life pathway for mono-plastics such as PP was also included in this diagram. This is because many stakeholders along the mono plastics chain also impact the end-of-life of composite capsules directly, and a side-by-side comparison allows recognition of implicit flows or barriers which are detailed further in Table 6.

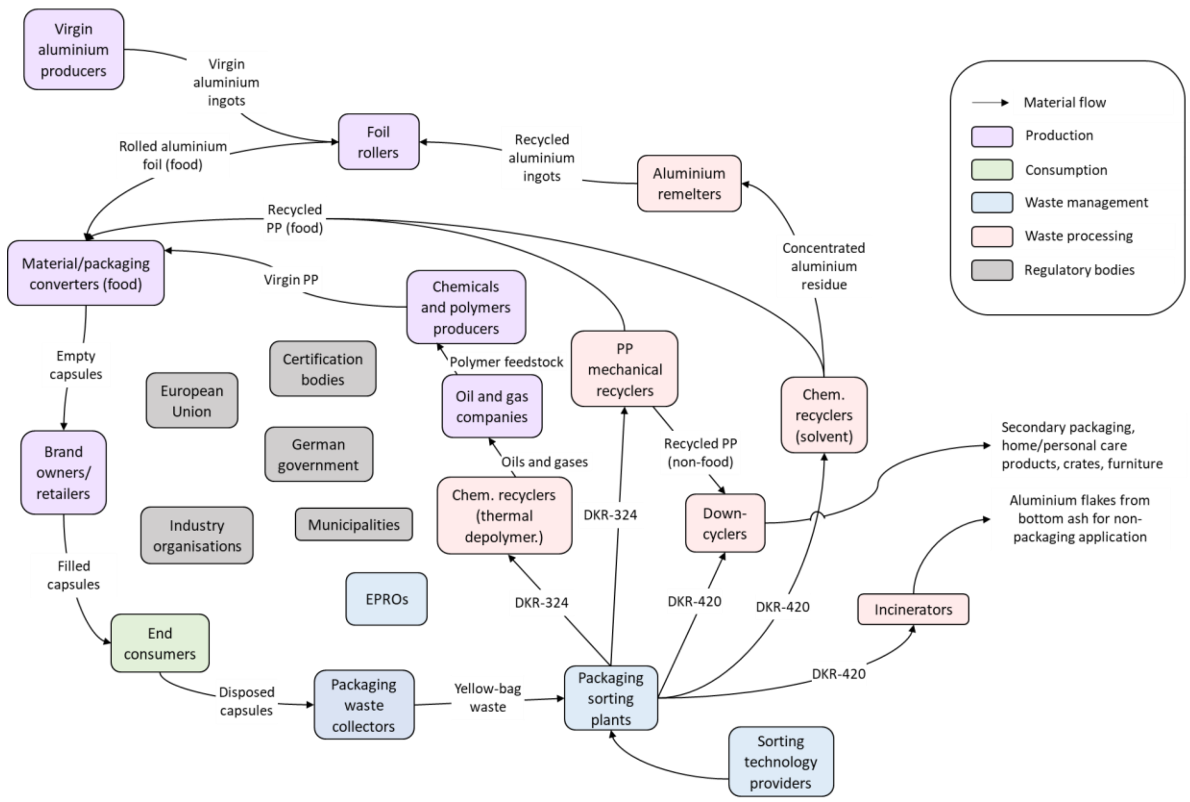

Figure 13: System structuring and flows of materials.

Table 6: Description of system material flows.

From production to disposal	
Stakeholders Involved	Description
Material/packaging converters Brand owners/retailers End consumers	• Material and packaging converters use virgin and recycled raw materials to produce the coffee capsules. • The capsules are sold to brand owners and retailers to be filled and placed on the market. • Consumers purchase, use and dispose of the capsules in the dedicated yellow bins for packaging waste collection.
From collection to sorting of the coffee capsules	
EPROs Waste collection Sorting plants Sorting technology providers	• Brand owners/retailers licence packaging waste with EPROs. EPROs manage the collection and sorting of packaging waste by tendering contracts with waste management companies. • Yellow bag waste is transported by collectors to packaging waste sorting plants. • Sorting plants separate the waste into various material bales for recycling, specified by the DKR standards (Duales System Deutschland GmbH, 2018). • Sorting technology providers produce and sell the equipment necessary to the sorting plants.
Processing of DKR-420 fraction	
Stakeholders Involved	Description
Sorting plants Incinerators	• All DKR-420 bales are sent for incineration (Sorting plant A & B; Aluminium recycler A; EPRO A, B, C) • As shown in Figure 11, only 30-40% of the DKR-420 bale is composed of aluminium-rich packaging. The remainder is composite packaging such as the coffee capsules, which includes materials such as plastics, papers, and organic residue. • This fraction of the bale is lost as heat during incineration and is not considered recyclable. (Sorting plant A; Chemical recycler A) • The recovered aluminium is used as scrap in other industries such as paints, automotive and industrial equipment (Šyc et al. (2020), Sorting plant A & B)
Downcycling of DKR-420 fraction	
Stakeholders Involved	Description
Sorting plants Downcyclers	• Niche recyclers working with composite waste were discovered in the interview process. • They use proprietary grinding techniques to produce polymer-aluminium (poly-al) regranulate which can be used in thick-walled products such as garden furniture, crates and flowerpots. • Poly-al composites also found to be a challenge for beverage cartons which contain poly-al laminates essential for preserving beverages. (Downcycler A) • *'…our method of recycling is better than pyrolysing it, which is right now the only other option…'* (Downcycler A)
Chemical recycling of DKR-420 fraction	

<table>
<tr><th>Stakeholders Involved</th><th>Description</th></tr>
<tr><td>Sorting plants

Chemical recyclers (solvent based)

Material and packaging converters

Aluminium remelters

Foil rollers</td><td>The DKR-420 bale can be processed by chemical recyclers who dissolve the polymers using selective dissolution.
For the coffee capsules, the process separates the base polymer from the aluminium and other additives and residue (Chemical recycler A; B; C).
Recovered polymer can be regranulated for reuse in food-contact applications.
Recovered aluminium from the process can be melted, rolled and reused to produce food-contact packaging foils (Aluminium recycler A, aluminium foil roller B).
This pathway has yet to be demonstrated on a commercial scale.</td></tr>
<tr><td colspan="2">Mechanical recycling of DKR 324 and other mono and mixed plastic streams</td></tr>
<tr><td>Sorting plants

Mechanical recyclers

Material/packaging converters</td><td>Bales with the largest volumes at sorting centres are rigid mixed plastics (DKR 350) and light mixed plastic films (DKR 310). These are followed by mono PP (DKR 324), mono PET (DKR 328) and mono HDPE (DKR 329) (Picuno et al., 2021)
Mechanical recycling is currently the dominant end-of-life pathway but faces challenges in reusing plastics for food-contact applications.
Most plastics end up in lower value applications such as home and personal care products.
With highly efficient sorting, mechanical recycling of mono and mixed plastic streams for food contact applications is emerging.
"…chemical recycling is energy intensive and has multiple demands, making it hard to consider as sustainable. Mechanical recycling with improved sorting will continue to play a large role in recycling plastics and even providing food-grade plastics in the future…" (Mechanical recycler A).</td></tr>
<tr><td colspan="2">Chemical recycling of DKR 324 and other mono and mixed plastic streams</td></tr>
<tr><td>Chemical recyclers (thermal depolymerisation)

Oil and gas companies

Chemicals and polymers producers</td><td>Mono plastic streams of DKR 324 (PP) and DKR 329 (HDPE) as well as DKR 350 (rigid mixed plastics) and DKR 310 (light mixed plastic films) are valuable hydrocarbon feedstocks for chemical recycling via thermal depolymerisation (Chemical recycler D, E, F).
These streams are the largest in volume at sorting plants.
The streams require further pre-sorting to remove PET, PA, PVC and aluminium which cause issues in the depolymerisation process (Chemical recycler D, E, F).
The output are oils and gases which are sent for processing by oil and gas companies and further to chemical companies for production of virgin plastic feedstocks or other chemicals (Chemical recycler D, E, F).</td></tr>
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7.1.2. Monetary flow directions

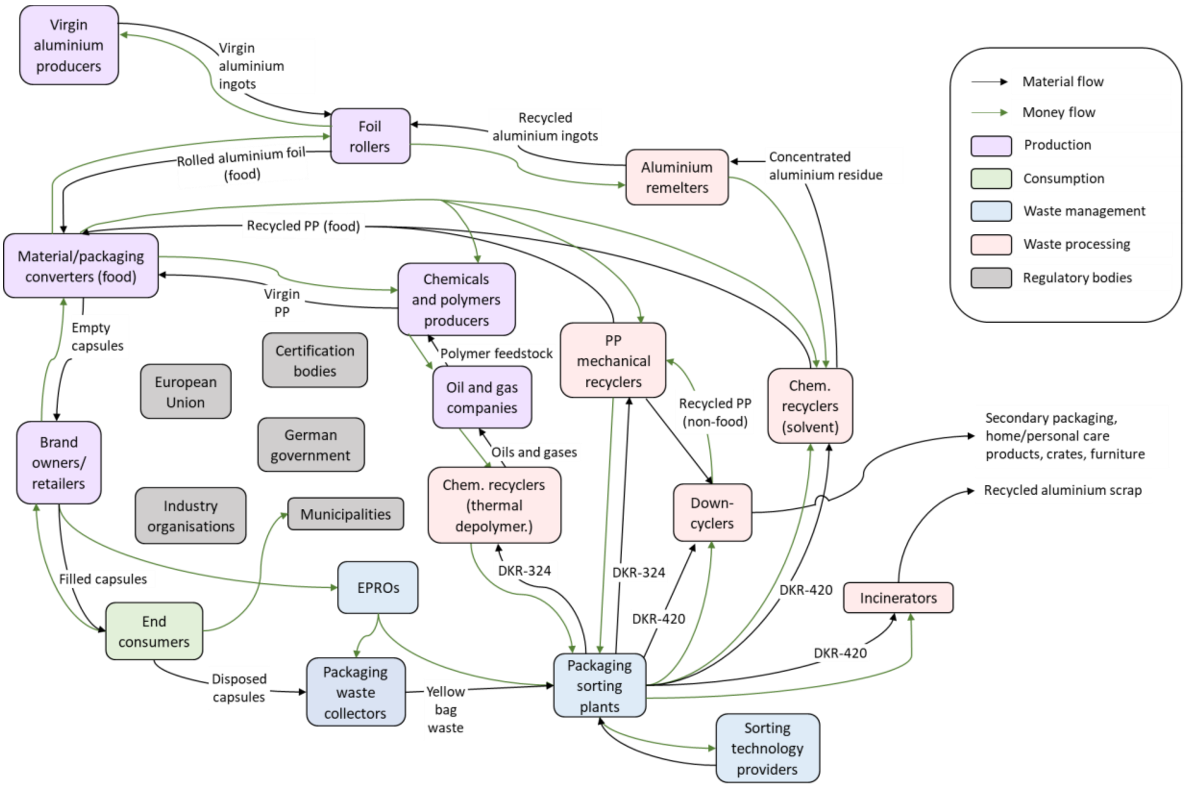

Figure 14: System structuring and flows of materials and money

In Figure 14, the green arrows indicate the flow direction of money along with materials (indicated in black). On the left side of the diagram, money flows are positive, and money is exchanged for finished goods at each step along the value chain. After the capsules are disposed, the main monetary driver for the activities becomes the EPROs. They receive packaging licencing fees from brand owners for the volumes of packaging waste placed on the market. Every three years, all German municipalities are divided up amongst the EPROs, who must then reconciliate local packaging waste collection and sorting. For this, the EPROs tender the services of waste management companies that operate collection logistics and sorting plants (EPRO A, B, C and D). EPROs fund all these activities with licencing payments from brand owners and retailers.

The contracts between the EPROs and the sorting facilities may be set up in two ways. EPROs either contract the sorters for "service-only", in which case the sorted bales remain under the ownership of the EPRO. Or, the EPROs can have an "all-in" agreement with the sorters where they purchase the waste from the EPROs and are free to trade it after sorting in the recyclate market. During the interviews, the latter contract types were more common when it came to high value recyclates such as mono and mixed plastics streams, and the former was used for lower value wastes such as DKR 420.

In the diagram, the monetary flow for DKR 324 waste is positive, and sorters are able to sell the mono and mixed plastics to recyclers, both mechanical and chemical. Sorting plant A mentions *"…there is a lot of demand for sorted plastics such as PP, HDPE and PET. This demand has been there* *for a while. The only recent time when prices were negative was during the Covid-19 pandemic in 2020. We are now also opening a new sorting facility for recovering these plastics from mixed plastics streams. We are not alone on new ventures like this either….”*.

The situation is opposite for the DKR 420 waste. Currently sorting plants must pay recyclers a "gate fee" to process the sorted bales. The waste is not considered valuable by the recyclers which incinerate it to recover bottom ash. Sorting plant B mentions *"…DKR 420 bale processing is very expensive, and there is not a lot of high value aluminium waste in that bale…"*. Sorting plant A remarks *"…we make money from the waste we can sell. For waste we have to pay to clear, we make a loss, since we are required to sort it due to increasing material recovery quotas for sorting plants. It would be better for us if brand owners stopped using such packaging and shifted to mono material structures instead…"*.

Chemical recycling of this bale on the other hand is very new. Currently no commercial trading of this bale to chemical recyclers is happening. As developments grow, it would be interesting to see how increasing demand for this feedstock shapes the monetary flow direction. An interesting remark by Chemical Recycler C is *"…licensing one tonne of composite waste currently costs brand owners around EUR 1000. As the material recycling quotas at sorting plants increase and the costs of recovering these materials increase further, composite packaging will end up being abandoned to due licensing costs. In Belgium the licencing cost for composite waste is already at EUR 2000 per tonne. If we can commercialise chemical recycling for this waste, we bring a lot of value to brands which still need composite packaging for their products…"*.

7.1.3. Influence flows

Mapping the flow of influence through the system revealed some noteworthy results. These are visualised in Figure 15 and described in Table 7 below.

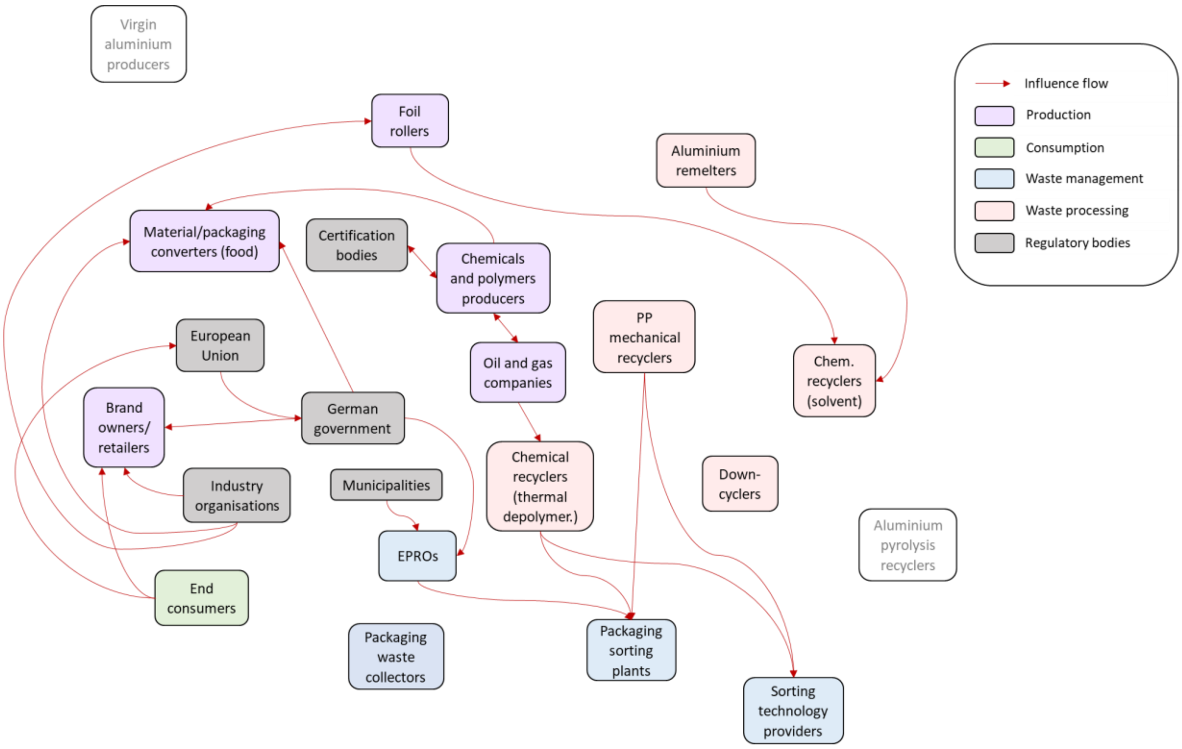

Figure 15: Noteworthy flows of influence between stakeholders.

Table 7: Description of noteworthy flows of influence.

Regulatory Influence

Stakeholders	Description
European Union German government Brand owners/retailers EPROs Sorting plants Material/packaging converters	• Directives set by the EU and implemented into the national packaging waste laws were cited by multiple actors as triggers for action. (EPRO A, B, C; Material/packaging converter A; Sorting plant B) • Directive EU/2018/852 states that by 2025 end, at least 65% weight of all packaging waste is recycled, and 70% by 2030 end (European Parliament, 2018) • To meet this Directive, German national packaging law, VerpackG, sets material recycling quotas for different materials in packaging waste. Sorting plants must recover 63% of plastics and 90% of aluminium by 2022 (Bundesregierung Deutschland, 2017). • *"…there is not enough high-value waste to meet these quotas with the existing recycling technologies..."* (EPRO D) • Quotas on recycled content in single-use plastic (SUP) bottles are in place, requiring 25% weight by 2025, and 30% by 2030. Several other SUP sales have been banned (European Parliament, 2019) • EU Strategy for Plastics in a Circular Economy (EU SPCE) established the Circular Plastic Alliance (CPA) which collected pledges for using recycled material content. • Industry stakeholders that make up the CPA have committed 10 million tonnes of recycled plastic materials being reused in EU products (European Commission, 2018). • *"…we only expect these to increase in the future…"* (EPRO A & Material/packaging converter A) - On minimum material recycling quotas and minimum required recycled content quotas

Influence from petrochemical industries

Stakeholders	Description
Oil and gas industries Chemicals and polymer producers Chemical recyclers Material/packaging converters	• Regulatory pressure to move away from fossil fuel and an increasing market demand for recycled plastic is driving petrochemical industries such as oil and gas and chemicals production to innovate their recycled plastic offerings. • *"…nobody wants to miss out on their potential to sell a product, the giants (petrochemical industries) want the same, they will develop their own recycled content for the changing market…"* (EPRO B) • They are focused on converting hydrocarbons in plastic packaging waste to oils and gases as chemical feedstock for their processes (Chemical recycler D, E, F). • Thermal depolymerisation has failed to commercialise in the past but is now undergoing a revival. • "Plastics-to-oil" pyrolysis and other variations on pyrolysis including plasma or microwave-assisted pyrolysis have emerged with significant industrial support. • Petrochemical industries are working closely with emerging chemical recyclers, offering investment and R&D to ensure recycling outputs match feedstock for downstream chemicals processing (Chemical recycler D, E, F). • In return, petrochemical industries secure rights to offtake output products to market their own virgin chemicals as sustainably sourced from plastic waste (Chemical recycler D, E, F). • Petrochemical industries also partner with material and packaging converters to develop offerings for brand owners made of their chemically recycled virgin feedstocks (Material/packaging converter A, Chemical recycler E)

Partnerships between mechanical/chemical recyclers, sorting plants and sorting technology providers

Stakeholders	Description
Mechanical/ chemical recyclers Sorting plants Sorting solution providers	• Involvement of petrochemical industries to ensure a secure supply chain of chemically recycled plastic feedstock has increased demand of clean, sorted mixed polyolefin fractions (Chemical recycler D, E, F). • Increasing regulatory quotas on recycled plastic content have also increased demand of clean, sorted mono plastic streams for high-purity food-grade mechanical recycling (Sorting plant A; Mechanical recycler A; Material/packaging converter A) • Recyclers, both chemical and mechanical, are partnering with sorting facilities and engaging sorting solution providers to develop clean, sorted mono and mixed plastics fractions (Sorting plant A & B, material/packaging converter A) • Sorting facilities have growing incentives to provide higher quality bales of both mixed plastics (for chemical recycling), and mono plastics (for mechanical recycling) (Sorting plant A & B). • Sorting plants and equipment providers are incentivised to develop new sorting schemes to unlock purer bales of mono and mixed plastics. • Increasingly, these stakeholders are partnering up to test and build their own sorting and recycling chains (Material/packaging converter A, sorting equipment provider A, sorting plant B)

Influence from Industry Organisations

Stakeholders	Description
Industry organisations Brand owners/retailers	• Industry organisations such as CEFLEX (Circular Economy for Flexible Packaging) have emerged which involve multiple stakeholders from across the value chain collaborating on strategies for a circular plastics recycling value chain (CEFLEX, n.d.). • The first deliverable of CEFLEX established the Design Guidelines for a Circular Economy, focusing on mono-material structures of PE and PP for flexibles and phasing out multi-material structures to improve recyclability (CEFLEX, 2020). • Mono-material structures being widely adopted by brand owners and packaging converters to allow improved mechanical and chemical recycling of mono and mixed plastics streams (Brand owner A). • Multi-material composites are increasingly being phased out by brand owners across their product portfolios (Brand owner A). • The above are both stimulating the demand for sorted mono plastic waste streams by mechanical recyclers, and mixed plastics waste streams by chemical recyclers focused on mixed polyolefins to oil/gas (Sorting plant B; EPRO B & C).

Influence of Aluminium Foil Industry

Stakeholders	Description
Aluminium remelters Foil rollers	• CEFLEX design guidelines have encouraged industrial shift away from multi-material packaging containing aluminium, creating an issue for the aluminium foil industry which sees a losing market in food and beverage packaging applications (Aluminium foil roller A; Aluminium recycler A) • *"…in phase 1, they introduced the design guidelines for mono-materials, and now everyone is switching to that, even though functionality is not there. Functionality is the first requirement for packaging. When they come to the formats that really*

	need multi-materials, they will understand why mono is not always the answer…" (Aluminium foil roller A) • Aluminium industry has an incentive to demonstrate effective chemical recycling of aluminium and polymer/paper composites to ensure their market longevity. • Aluminium industry also faces pressure to reduce carbon emissions (Aluminium foil roller A; Aluminium recycler A) • *"…recycling aluminium from packaging is not our core business as foil producers, but if it also demonstrates lower carbon emissions, it can help us with another main pressure point in the aluminium industry which is transitioning to net zero carbon. So we are willing to invest…"* (Aluminium foil roller A). • Aluminium industry is influencing joint collaboration between chemical recyclers (solvent/delamination based) to demonstrate technical, economic and sustainable efficiency of recovering the multi-material DKR 420 waste (Aluminium foil roller A)

Influence from consumers on market actors and regulators

Stakeholders	Description
End consumers Brand owners European Union	• Consumer trends and knowledge on sustainability are a main driver behind product design and material considerations by brand owners (Boz et al., 2020; Rhein & Schmid, 2020) • *"We know these products are a sustainability problem. But […] they started leading our business growth. And you cannot just kill that off as a business owner…"* – Brand owner A • Regulators are also driven by the perception of the general public. As stated by EPRO D *"…The SUP ban was driven by public perception of plastic waste on beaches. The recycled content quotas are driven by public perception of sustainable packaging. I cannot say if striving for material circularity is really sustainable…"*

7.2. Barriers towards a circular economy for coffee capsules

6. What are the existing barriers towards circularity?

The interview findings helped to build the system structure and identify flows of materials, money and influence. They also revealed important findings on the current barriers towards a circular economy for the coffee capsules, and for similar plastic aluminium composite packaging waste. Their discussion is structured in the framework presented by Kirchherr et al. (2018), as described in Chapter 2. This discussion is summarised in Table 8, 10, 11 and 12.

7.2.1. Technological

Availability of the right technologies is a key prerequisite when speaking of the transition to a circular economy (Kirchherr et al., 2018). For the coffee capsules, this means the development of chemical recycling and advanced sorting to a degree where technical bottlenecks are no longer a transitional barrier. When applied in the coding framework for the interviews, the technological barriers were identified as stakeholders citing a limited ability to deliver high-quality products, limited availability of industrial demonstrations, and an unavailability of data on the environmental impacts of a study, as identified by Kirchherr et al. (2018). The last barrier also hinted at the participants' understanding of a circular economy, and their main motivation behind realising a circular plastics system.

The most common barrier identified throughout the interview process was the participants' limited awareness of the measured environmental impacts of new technologies. Almost all stakeholders expressed interest in industrial trials to demonstrate technical or economic feasibility of the new technologies, but few had any quantitative data on the environmental impacts. Some also expressed that measuring the impacts of one type of system over another can become too complicated, and that targets such as recycled content were easier to work towards and communicate.

Another identified barrier was that not all chemical recycling is equal. Different processes require different types of feedstocks, which means different types of pre-sorting. These sorting technologies are still under development, and ongoing industrial demonstration is needed to optimize the types of pre-sorting best suited for each recycling technology. The pre-sorting must be able to deal with variations in the waste stream and produce consistent feedstocks free of contamination, as well as integrate with existing state-of-the-art sorting systems.

Lastly, all chemical recycling technologies are not yet fully matured. For example, when speaking with Chemical Recycler C (solvent delamination), it was noted that the resulting aluminium and polyolefin flakes after processing the mixed composite waste still pose a challenge. The aluminium flakes can be too thin to smelt effectively, and the PE and PP flakes can be impossible to sort from each other, to obtain clean mono streams for mechanical recycling.

Table 8: Identified technological system barriers

Barriers	Examples from interviews
Lack of empirical quantitative data on the environmental impacts of chemical recycling technologies Stakeholders find environmental impacts of new chemical recycling technologies difficult to measure, studies are underfunded and not prioritized.	• *"…I have funding for my techno-economic industrial pilots, but an LCA will cost about 15.000 Euros. No one has funded that yet. I can build my business case in detail, but we don't have detailed data on the environmental impacts, just a really good bet that we are better…"* – Chemical recycler C (solvent dissolution) • *"…We are converting the plastic waste into useful materials. We are conserving materials and preventing waste. It is very difficult to measure the overall system, and what would be the way to measure that sustainability? An LCA can be very subjective and very costly, but not reveal everything…"* – Material/packaging converter A • *"…at our scale it is difficult to determine the sustainability of the overall system. The regulatory quota is on amounts of recycled content. That is an easier metric to measure and demonstrate…"* – Chemical recycler E (thermal depolymerisation)
Chemical recycling is still under development and needs larger industrial scale trials to fix technical barriers and establish business cases.	• *"…aluminium in this waste can be under 10um thick. When you recover this chemically, the flakes you get are too thin to smelt and burn right away. We are working on compacting them into bricks we can actually smelt. Without this, the recovery for aluminium is just around 30-40%, too low for anything to make sense…"* – Aluminium recycler A • *"…we still need larger trials with more post-consumer waste to understand things. We have data on working with post-industrial waste, but that is not the real picture yet…"* – Chemical recycler C
Chemical recycling requires innovation in sorting, which is still under development.	• *"…chemical recycling will not solve everything. It is a process that needs the right feedstock. PA, PET, PVC, these are all present in the input streams and create problems in the reactor. Collection and correct sorting will always be relevant for any type of recycling…"* – Chemical recycler E (thermal depolymerization) • *"…DKR 420 contains many things. We are trying to see what sorting works best to get a stream out for our [recycling] process. Many options are possible, but we need to find the optimum…"* Chemical recycler C (solvent delamination) • *"…should we sort at the sorting plant, or do a pre-sorting on our site before recycling? Should we separate the streams using a robot arm […] use NIRs […] or density separation? We are still trying to figure out the right combination to get out the feedstock we want, and this needs effort and investment…"* Aluminium foil roller A

7.2.2. Regulatory

Regulatory barriers in this research referred to obstructing regulation, or regulation causing confusion and consensus in how to achieve a circular economy (Kirchherr et al., 2018). Regulation here includes the EU directives and communications on plastics and plastic packaging waste, transposed national packaging waste legislation and industry design-for-recycling guidelines, although they are not regulatory measures, but guide the actions of brand owners and material/packaging producers similarly.

The interviews revealed that several stakeholders cite this increasing regulation as a key driver for research and innovation efforts. Current regulation at the EU level has clear and measurable targets for material circularity by weight. Directive 2008/98/EC states:

- By 2025, 55% of municipal waste is prepared for re-use/recycling.
- By 2030, 60% of municipal waste is prepared for re-use/recycling.

Directive EU/2018/852 states that:

- By December 31st 2025, at least 65% weight of all packaging waste is recycled.
- By December 31st 2030, at least 70% weight of all packaging waste is recycled.

Directive EU 2019/904 on Single Use Plastics (SUPs) bans 10 common SUPs and introduces targets on PET bottles such that:

- From 2025, all PET bottles up to three litres must contain at least 25% recycled plastic.
- From 2030, all PET bottles up to three litres must contain at least 25% recycled plastic.

The national German Packaging Act sets its own national targets to achieve the required EU targets. All EPROs arranging collection and sorting are required to reach minimum annual average rates for their contracted packaging weight in preparation for recycling and reuse. They in turn, require all contracted sorters and collectors to fulfil them. The quotas are given in Table 9.

Table 9: Minimum annual material quotas for preparation for recycling and reuse by EPROs (Bundesregierung Deutschland, 2017).

Material	In 2019	Starting from 2022
Glass	80%	90%
Paper and cardboard	85%	90%
Ferrous metals	80%	90%
Aluminium	80%	90%
Beverage cartons	75%	80%
Composite packaging	55%	70%
Plastics (combined material recycling)	58,5%	63%

Table 10: Identified regulatory system barriers

Barriers	Examples from interviews
Regulators are focused on material recycling quotas by weight which are not necessarily sustainable.	• *"…through mass balance approaches we have a good indication of material circularity in the system. That is the target everyone in the value chain is working to meet…"* – Chemical recycler E • *"…our customers are increasingly required to include recycled content, and we will innovate to meet that demand…"* – Material/packaging converter A
No consensus on design-for-recycling guidelines for packaging, or their consideration in product design requirements	• *"…the industry is shifting to mono-material streams (referring to CEFLEX D4CE guidelines), but at the regulatory level, there is no rule around designing packaging for recycling. For food safety, materials can be banned from packaging. Just like that, there should be better guidelines on designing packaging for recycling…"* – EPRO D • *"…the industry together is trying to design out aluminium barrier packaging. Why? Because it is evil and cannot be recycled at all? That's not true. We can recycle it (referring to chemical recycling) and we must recycle it, because it has a very important packaging function. Packaging must first be designed for its functionality. This should be the priority in any design guideline…"* – Aluminium foil roller A • *"…material converters can add something in the plastic that is very difficult to remove, for example they add 50ppm of chlorine. We are expected to produce oils with only a maximum of 1ppm chlorine. How is this realistic?..."* – Chemical recycler D (thermal depolymerisation)
Regulators continue increasing quotas but directly affected actors do not have the incentives to innovate.	• *"…we earn from the bales we sell minus the bales we pay a gate fee for recycling. If the regulators keep increasing material recycling quotas, we have to sort more low-value waste to meet that. This increases our sorting costs and the fees we pay to recyclers…"* – Sorting plant A • *"…there is not enough high-value packaging waste to meet the increasing material recovery quotas. To improve this, regulators should fund recycling and sorting first, before enforcing higher quotas…"* – EPRO C and D

7.2.3. Market

Kirchherr et al. (2018) identify market barriers from literature mainly as lower prices of competing virgin materials, uneconomic circular production relative to linear, and high upfront investment costs. The presence of such barriers in the composite packaging waste recycling system is summarised in Table 11.

Table 11: Identified market system barriers

Barriers	Examples from interviews
Low or no demonstrated economic value of DKR 420 mixed composite waste for sorting plants.	• *"…right now we pay recyclers a gate fees to take away the sorted bales of DKR 420 […] if there was a demand for this waste, like the mono-plastics, then it could be something worth further sorting…"* – Sorting plant A
Large investments required to demonstrate chemical recycling and sorting technologies at scale	• *"…what I need for an industrial trial is probably nothing for a large brand owner, but for me, it is a large amount. We need the right investments before we can demonstrate anything…"* – Chemical recycler D
Recycling of multi-material structures competes with large focus on mono and mixed plastics recycling	• *"…the industry is moving in one direction. There is a lot of vested interest in mono and mixed plastics. It can be that it's enough to kick out multi material packaging, if no one wants to design with it any longer…"* – Material/packaging converter A

7.2.4. Cultural

Cultural barriers mainly refer to the behaviour of consumers and the culture of decision makers along the value chain (Kirchherr et al., 2018). It was a barrier cited frequently in the interviews, and the findings are summarised in Table 12.

Table 12: Identified cultural system barriers.

Barriers	Examples from interviews
Consumers demand convenience and single serve portioned coffee	• *"…as people started working from home more, sales of single-serve products has gone up. We know these products are a sustainability problem. But all of a sudden, they started leading our business growth. And you cannot just kill that off as a business owner…"* – Brand owner A
Consumer behaviour around correct packaging disposal limits design considerations by brand owners	• *"…we can try to make these capsules peelable, so the consumer separates the foil from the cup. But we have data that shows the majority of them will not do that. They don't purchase convenience packaging and then work to separate it before throwing it away…" – Brand owner A*
Consumers lack a proper understanding of the waste hierarchies	• *"Most of the regulation and company behaviour is built around public perception. Consumers think plastic waste is evil, and if you advertise that recycling plastics saves plastic waste, you get happier consumers. It's all about the public perception. And the public won't know which recycling is better than the other"* – EPRO D

Smaller brand owners are culturally hesitant to make the first move, partially tied to high upfront investment costs	• *"…we are not pioneers. We don't have the resources to make those investments. We will wait and see what emerges in the recycling world. A lot of people talk about some new solution, but not everything gets adopted. So we wait and see until something rolls out on the large scale…"* – Brand owner A (referring to supporting chemical recycling trials)
Economic considerations are of higher importance to decision makers than environmental ones	• *"…I pitched the (recycling) proposal to them (material/product converters) myself. But at the executive level, the only thing that matters is the money. These guys are on the board for 2 years, maybe 3, before someone else comes in. In that time, their only goal is to create business growth…"* – Aluminium recycler A

7.3. Discussion of system structure and barriers

The tables detailed in sections 7.1. and 7.2. above reveal several interesting findings which are briefly reflected upon here. First, in the mapping of material flows, it was challenging to trace the actual composition and amount of materials in the streams. This was also expressed by the stakeholders as waste streams are inherently variable in composition, with seasonal changes in material flows. Aluminium foil roller A remarks *"…Waste composition is dynamic. It's different in each place, and even for the day of the week. If it's hot, kids will drink more juice, then you'll have more juice pouches and drink cans in the bale, so more aluminium. It is not static…".* The way off-take contracts are arranged amongst sorting plants and recyclers can also vary depending on the prevailing price of the recyclate traded on the market. This influences material flows, with increased down-cycling when the economics of high-value recycling are poor due to low prices of virgin plastic feedstock (Sorting plant B).

Following the flows of money with the flows of materials uncovered two things. First, the demand for sorted mono and mixed plastic packaging waste is increasing at recyclers, stimulated by interest from the petrochemical industries for such a feedstock, as well as increasing implementation of mono-material design guidelines. Composite packaging waste continues to have a negative monetary value at sorting plants. However, there is potential if demand can be stimulated through the emergence of chemical recyclers that recover this waste. As mentioned by sorting plant B, in the past, DKR-420 waste had a positive value due to a high demand for aluminium scrap from the automotive industry, which has since waned.

Lastly, in the mapping of influence flows, it was interesting to see how the system was interconnected at all three levels: micro, meso and macro. Several stakeholders cited macro-level regulatory measures as the main motivator for innovation. The direction from the regulatory sphere strongly shaped their circularity strategies. Therefore, I would like to highlight a CE barrier that the stakeholders cited as stemming from the regulatory sphere. Throughout the system, there is a focus on all stakeholder levels on *material* circularity, and limited knowledge or concern for the reductions in environmental impact, which should be the aim of a CE (Kirchherr et al., 2017; Korhonen et al., 2018). Regulators have focused on maximising recycling as a repeated and main target. Recycling is a low-value circularity strategy, just above material recovery where materials are incinerated to recover a product's energy. This is illustrated in several CE strategy frameworks, the most comprehensive of which is the 9R framework for circularity strategies provided by Potting et al. (2017), shown in Figure 16 below.

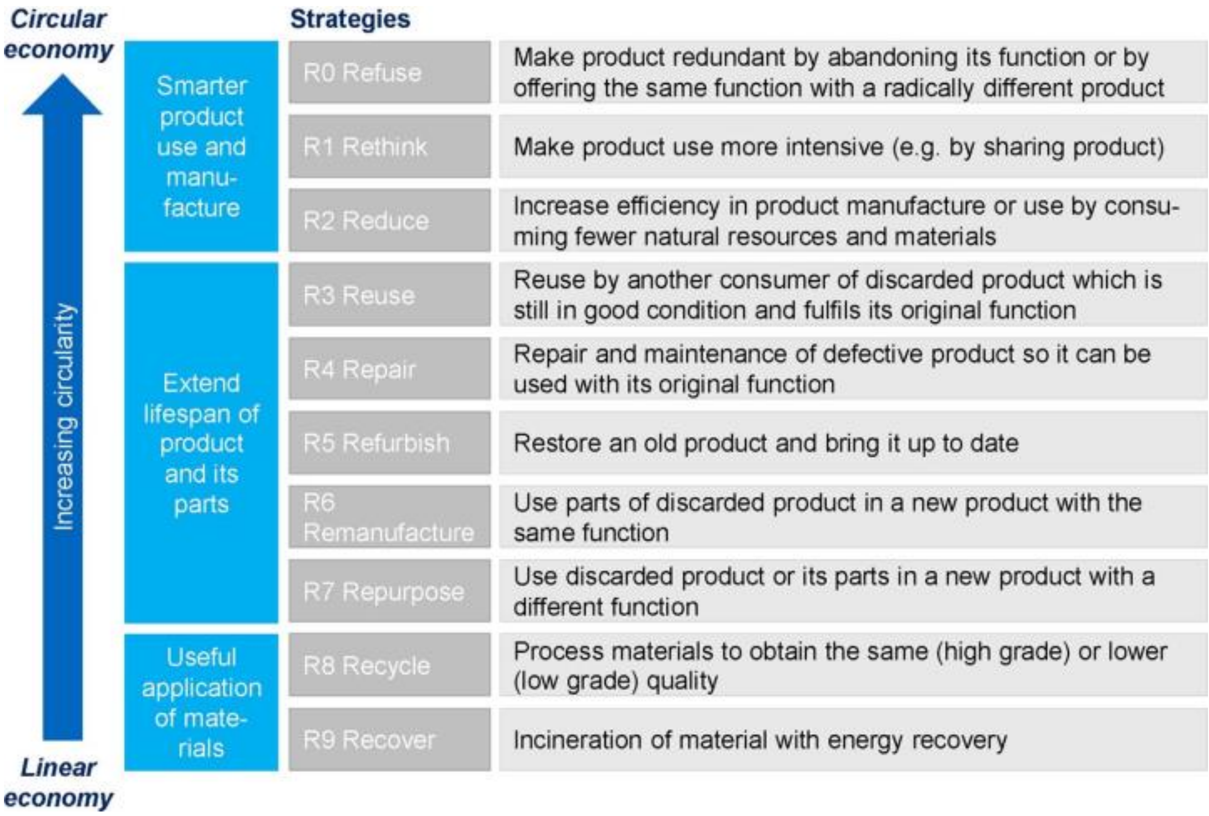

Figure 16: 9R circularity strategies adapted by Kirchherr et al. (2017) *from Potting et al.* (2017).

Although almost all stakeholders are informed of the need for a CE for plastic and composite packaging waste, awareness for higher level circularity strategies that look at product circularity were not observed. Although it can be argued that the path towards a CE for such waste must start somewhere, even if that means a regulatory push towards increasing high-value recycling from a current status quo of not recycling. However, the risk of this approach is that it may lead to a new system environment locked-in on material circularity, which will require significant effort to transition away from once again. This prevalence of regulatory barriers for a CE is also confirmed by other researchers (Kirchherr et al., 2018).

In the interviews, the regulatory measures were sometimes cited to be driven by micro-level influence from the individual consumers that make up the general public. If this is indeed a root cause or triggering barrier, it is important to discuss the role of the consumer and consumer awareness in the system. As brand owner A points out, businesses are pushed into knowingly making sustainably poor decisions due to consumer demand for such convenience products. Therefore, the question arises if a business can sustainably compete in high-value markets such as single-use coffee capsules while also making environmentally sound decisions. As it is within the nature of a business to maximise customer satisfaction and firm profits (Coase, 1937), consumer awareness around sustainable packaging choice can be a potential lever for regulators to influence business decisions around sustainability.

While not explicitly outlined in section 7.2., several other barriers were also interconnected with one another. For example, the technological barrier of a lack of empirical quantitative data on environmental impacts can be linked to the macro-level regulatory barrier where regulators are focused on material weight recycling quotas alone. Similarly, the market barrier of a large investment requirement for chemical recycling and sorting technologies can be linked with the cultural barrier where system decision makers place a higher importance on economic considerations than environmental ones.

Multiple levels are also involved in one barrier. For example, at the macro level, regulators continue to increase quotas of materials that must be recovered for recycling at sorting plants. While this provides sorting technology providers and chemical recyclers with an opportunity to fill the gap with high value recyclate, stakeholders expressed that measures to stimulate these innovations should be put in place before the sorting quotas are introduced. The burden to meet these quotas otherwise falls on sorting plants in the micro-level who incur higher costs to sort lower quality waste, while they do not possess direct control over the innovation needed to meet these quotas.

The interconnectedness of the material, money and influence flows presented in this chapter, as well as the interconnection of the identified barriers across the system point towards how a multi-level, multi-stakeholder perspective is necessary to implement a difficult concept like circular economy. Several interventions are proposed and discussed in the following section as a solution to these challenges.

Chapter 8 – Potential Interventions to the System

7. What interventions are necessary to transition the value chain towards circularity?

This section aims to identify and discuss interventions that would shift the system structured in Chapter 7 into a more circular one. From the findings in Chapter 7, it is evident that most of the stakeholders in the system view a circular system as one focused on material circularity. Therefore, the first intervention covers the most concerning issue in the value chain, which is circularity purely for circularity's sake.

8.1. System Intervention 1: Developing a new standard for assessing packaging sustainability

Effective recycling of materials was cited as the main target when speaking of circular economy ambitions. Any innovation that stems from this ambition might as well be environmentally suboptimal, as stakeholders displayed little knowledge or concern for quantifiable reductions in environmental impacts.

An example is the intended plastics-to-plastics conversion by chemical recyclers working with thermal depolymerisation. SABIC Innovative Plastics B.V. is a plastics recycling facility in the Netherlands, an arm of the leading global petrochemicals manufacturer SABIC based in Saudi Arabia (SABIC, n.d.). The plant processes mixed plastic waste into pyrolysis oil used for manufacturing virgin food-grade plastics. On the company website, SABIC states:

> *"When examining the direct impact of advanced recycling, our study indicates that this route has a higher carbon footprint of between 6-8% compared to the more traditional fossil feedstock route for producing polymers. The two can therefore be considered to have a comparable direct carbon footprint, allowing for a margin of error. However, it is important to note that there is potential to improve the energetics of pyrolysis technology for advanced recycling, which could make the carbon footprint of this route more favorable."* (SABIC, n.d.).

Despite limited evidence of environmental impact reduction, such plants are awarded certification by the International Sustainability and Carbon Certification (ISCC) for the circularity of their processes. The ISCC certifications for waste plastics recycling plants only provide validation that the input feedstock into a process is from waste origins. If the value chain of a product can be verified on a mass balance basis, the output product is labelled a circular material (ISCC, n.d.).

If regulation continues to focus solely on material weight circularity, it is possible that environmentally suboptimal technologies such as pyrolysis will gain increasing validation and get "locked-in". This research proposes a new way of incentivising the value chain towards environmental sustainability, by focusing on a potentially new metric: greenhouse gas emissions measured as a carbon footprint. This measure is used in life cycle assessment (LCA), an environmental management tool which translates the environmental sustainability of product, process or service into a quantitative measure (Azapagic, 2017). The tool is now standardised by ISO 14040 and 14044 (2006a, 2006b) and widely used to measure and compare the impacts of new products. LCA was historically first developed by the Coca Cola Company in 1969, to select the environmentally superior option between two formats of packaging (Levy, 2017). A similar standard should be considered for current packaging systems, and work is needed to determine what that standard would look like. This intervention is summarised in Table 13.

Table 13: System intervention 1.

Developing a new standard for assessing packaging sustainability	
Barriers addressed	• Stakeholders find environmental impacts of new chemical recycling technologies difficult to measure, studies are underfunded and not prioritized • Lack of empirical quantitative data on the environmental impacts of chemical recycling technologies • Regulators are focused on material recycling quotas by weight which are not necessarily sustainable
Potential feasibility	• Key stakeholders are aware of the pitfall of focusing on material circularity alone. Through collaborative standard setting along the entire value chain, new regulation can be introduced that requires a demonstrated reduction in the environmental impact of a packaging system
Intended effect	• To incentivise stakeholders to measure and manage environmental sustainability when developing new circular packaging systems
Potential setbacks	• Drafting a new industry standard requires extensive research, a collaborative technical assessment and stakeholder agreement • Measuring carbon can limit the consideration of system impacts to only be optimized for carbon reduction and leave out other key impacts such as ecotoxicity, damage to human health, or others

8.2. System Intervention 2: Establishing design guidelines for composite packaging

The interviews revealed that composite material packaging will continue to play an important role in food and beverage applications due to its functional properties. At the same time, design-for-recycling guidelines are directing packaging design away from these structures. CEFLEX design guidelines for polyolefin-based packaging already prohibit the use of metal or paper layers which obstruct current mechanical recycling processes. Apart from this, the Circular Plastics Alliance set up under the European Strategy for Plastics (2018) have a work plan for the design-for-recycling guidelines of 19 “first-wave” plastic products to help achieve regulatory recycled content targets. Reviewing this work plan, the first-wave products prioritised from the packaging industry are listed in Table 14.

Table 14: First-wave priority products (packaging) in the CPA workplan for design-for-recycling guidelines (Circular Plastics Alliance, 2020)

Product	Polymer
Flexible packaging	LDPE
Beverage bottles	PET
Necked bottles for milk and detergents	HDPE
Food containers, caps and closures	PP
Trays	PET
Cups, trays, dairy packaging	PS
Insulation, protective	EPS

The list above does not include composite structures such as the coffee capsules. The Alliance highlights that through joint research, a second wave of priority products will be chosen for developing design-for-recycling guidelines (Circular Plastics Alliance, 2020). These products will be chosen by identifying material flows that still require research and development to realise their improved collection and recycling. As pointed out in the interviews:

"…the material recycling quotas keep increasing. There isn't enough high-value packaging waste at sorting plants to keep meeting them. Eventually, something will have to change…" – EPRO D

"…if brands tried to harmonise, things would look a lot better at this plant. There's so many types of coffee capsules on the market, and each one is a different design. Do we need 10 types of capsules that all sort and recycle differently?..." – Sorting Plant A

Therefore, this work suggests that the second wave of products include a focus on design-for-recycling of composite packaging. These guidelines should be developed keeping in mind the potential and remaining limitations of new chemical recycling technologies. While technologies such as solvent dissolution will unlock a larger variety of material combinations that can be efficiently recycled, guidelines should recognise where obstacles remain, such as limits on the thickness of aluminium layers or combinations with selected types of paper fibres or polymers which hamper the recycling processes. These should then be a further point for research and development efforts. This intervention is summarised in Table 15.

Table 15: System intervention 2.

Introducing design-for-recycling guidelines for composite packaging	
Barriers addressed	• No consensus on design-for-recycling guidelines for packaging, or their consideration in product design requirements • Recycling of multi-material structures competes with priority interest in mono and mixed plastics recycling
Potential feasibility	• Research efforts are ongoing at the regulatory level to continuously assess and update design-for-recycling guidelines • There is potential to harmonise the design of composite packaging, keeping in line with new developments in chemical recycling • If a decision is made collaboratively, it is possible to have consensus and shared implementation, such as the CEFLEX guidelines (2020)
Intended effect	• A closer look at the design of composite packaging can unlock a larger share of high-value packaging waste to meet regulatory quotas
Potential setbacks	• Drafting a new industry design guideline requires extensive technical research and agreement amongst all stakeholder interests. • Brands use composite materials to create attractive packaging for marketing purposes. EPRO D expresses pushback against increasing guidelines as *"…there needs to be a balance between recycling and a free market. Brands want to do the right thing but also market as they like…"*

8.3. System Intervention 3: Financial stimulation for industrially demonstrating sorting technologies

Chapter 5 of this research explored the path that post-consumer plastic waste takes from households to recycling facilities. It was seen how important the collection and sorting scheme is in ensuring the right waste composition is available for the recycling step, and how new sorting technologies are being developed to enable different types of chemical recycling. In the interviews, the lack of industrial pilots and data on these sorting technologies was highlighted as a bottleneck for the system transition towards increased chemical recycling and higher-value recycling outputs. Stakeholders require experimentation between different types of sorting schemes and recycling processes to determine the optimum feedstock and output.

Therefore, as an intervention, this work proposes increasing financial stimulation for developing and experimenting with sorting techniques. Kircherr et al. (2018) point to how financial support is already a commonly employed policy instrument in the EU, particularly in the agricultural sector. The EU Strategy for Plastics supports this point, however with an explicit focus on financial investment from the private sector. The strategy stresses the importance of developing robust extended producer responsibility schemes to create a private fund for investment in these technologies (European Commission, 2018).

> “ Innovative solutions for advanced sorting, chemical recycling and improved polymer design can have a powerful effect. For instance, scaling up new technological solutions such as digital watermarking could allow much better sorting and traceability of materials, with few retrofitting costs. […] While the EU can play an enabling role, European businesses need to invest in the future and affirm their leadership in the modernisation of the plastics value chain. ”

Despite a call for the private sector to lead investment, stakeholders still cite difficulty in accessing funding for experimentation. This work suggests that additional EU support be given to EPR organisations, research institutes and developers of sorting technologies to distribute funding for demonstrating these technologies at an industrial scale. At the time of writing, just two publications on sorting techniques were identified in scientific literature, that of Wilts et al. (2021) and Gasde et al. (2021). This intervention is intended to change that and is summarised in Table 16.

Table 16: System intervention 3.

Increasing EU investment in demonstration of sorting technologies	
Barriers addressed	• Chemical recycling requires innovation in sorting, which is still under technical development • Large investments required to demonstrate chemical recycling and sorting technologies at scale
Potential feasibility	• Value chain collaboration is already observed on this topic, with brand owners and material/packaging converters seeing the need and collaboratively investing in sorting technologies to trial their own sorting schemes
Intended effect	• Further industrial demonstration of sorting and chemical recycling will result in critical empirical data needed for decision making on the feasibility and implementation of these innovations and reduce uncertainty for investors

Potential setbacks	• It can be difficult to get sufficient collaboration in the value chain to agree on shared funding and its allocation

8.4. System Intervention 4: Raising consumer awareness

The last intervention proposed aims to tackle the cultural barrier when considering a circular system for coffee capsules. As identified in section 6.2, consumer behaviour around convenience packaging, disposal of composite packaging and their knowledge on recyclability of composites strongly shape the decisions market actors make around product design. Market actors respond to increased demands from consumers for sustainable packaging, and invest large amounts of resources and capital, all with the expectation of increased consumer satisfaction and market share (Ketelsen et al., 2020; Rhein & Schmid, 2020). Regulators can act to leverage this influence by raising consumer awareness and knowledge around composite packaging to drive market actors to meet consumer demands.

Provided that the earlier proposed system interventions are in place, and there is a robust end-of-life pathway for composite packaging via chemical recycling, a knowledge sharing institute can be set up to provide consumers clear instructions on the disposal of composite products. If an end-of-life pathway is realised through the DKR 420 waste fraction, then composite packaging should be clearly labelled for disposal with packaging waste in the yellow bins and prohibited from disposal with residual household packaging. In case the consumer can play a role in separating parts of the packaging for correct disposal, they must be educated on the importance of doing so.

At the same time, a lot can be done to educate consumers about the impact of their product choices and preferences for convenience. Knowledge on the different product options, packaging types, and habits around coffee consumption can be better communicated. Humbert et al. (2009) conduct an LCA study on the environmental burdens associated with different coffee consumption habits, namely spray dried soluble coffee compared against espresso capsules and drip filter coffee. They find the spray dried option to be superior to either other consumption methods. The communication of such work to consumers is important, as Boz et al. (2020) clearly highlight that consumers display inadequate information on product and packaging sustainability when compared with measured quantitative sustainability. However, such an intervention can also face pushback from brand owners who have vested interests in their market product offerings. The proposed intervention is summarised in Table 17.

Table 17: System intervention 4.

Increase consumer awareness on proper packaging disposal and packaging sustainability	
Barriers addressed	• Consumers demand convenience and single serve portioned coffee • Consumer behaviour around correct packaging disposal limits design considerations by brand owners • Consumers lack a proper understanding of the waste hierarchies
Potential feasibility	• Research shows consumers are aware of negative environmental impacts of packaging, and of their power to influence brand owners through their purchasing decisions (Rhein & Schmid, 2020)
Intended effect	• Changing consumer behaviour has the potential to influence brand owners to make more environmentally impactful decisions
Potential setbacks	• Educating consumers on packaging sustainability first requires having a clear understanding of their current knowledge levels and how their decisions truly impact market actors • Brands may have vested interests against increasing consumer awareness • It can be hard to quantify the outcome of increased consumer awareness

Chapter 9 – Reflection and Conclusion

9.1. Research contribution

This work set out to study the potential of innovations in chemical recycling and advanced sorting, and how they could help solve the CE challenge of composite packaging such as the coffee capsules. Initially, this was to be a quantitative analysis, looking into the feedstock material requirements of chemical recycling, its quantitative environmental impacts and analysing how the existing collection and sorting system could supply that feedstock, at what additional system costs. However, the increasing lack of any quantitative empirical data on such technologies lead to a change in research objectives. This work is now rooted in a system stakeholder perspective of these innovations, and how they can contribute to a more circular economy for composite packaging waste.

Chapter 4 offers a qualitative exploration of different types of chemical recycling emerging in the EU. It provides an overview of the current possibilities for recycling composite packaging as researched through scientific literature and interviews with industry stakeholders developing these technologies commercially. It offers a reference point on the necessary considerations for stakeholders when choosing a suitable recycling technology for difficult packaging formats. The chapter focuses on selective dissolution for the separation of coffee capsule waste, due to it's potential for recovering packaging materials of the coffee capsules in a tighter recycling loop, with a higher material efficiency as compared with thermal depolymerisation.

Chapter 5 provides stakeholders with an understanding of how composite packaging behaves in the current collection and sorting infrastructure. The mapping of the capsule's pathway through a modern sorting plant (Figure 10) allows researchers an overview of the sorting steps involved, which is a necessary starting reference when considering product design for recycling.

Chapter 6 provides a flow diagram for a potential new sorting protocol for composite packaging, developed in partnership with stakeholders and validated with scientific literature. This serves as a reference for system actors to understand how a feedstock for chemical recycling through solvent dissolution could be acquired, and what sorting technologies would need to be implemented and assessed on the industrial scale. This was especially important considering no publications were found that present such a protocol in line with emerging chemical recycling.

Chapters 7 and 8 focus on the entire system, involving all stakeholders along the coffee capsules' life cycle. They provide an overview on the system flows of materials, money and influence, and highlight the interconnection between them. This allows a clear picture of the innovation system and confirm that barriers to circularity are not always technical at the product or technology level, but often involve implicit interactions amongst various stakeholders at different levels.

Throughout the research, most of the data was gathered through rich interviews with stakeholders across the value chain. Its presentation here also offers valuable insights to stakeholders of each other's perceptions. It is often easier to access this information via research findings than through direct communication with one another. The findings may also help point researchers towards new stakeholders previously unconsidered.

9.2. Limitations

This work is certainly not without limitations. The first and main limitation here is the credibility of the research findings. Due to resource and time constraints, the sample size consisted of only 21 interviews, and some stakeholder groups such as the petrochemical industries, EU and German regulators could not be interviewed directly.

The next limitation is on the quality of the data collection and research methodology. Most semi-structured interviews had already taken place prior to the methodology being formally chosen for chapters 7 and 8. These interviews formed much of the content and structure of chapters 4, 5 and 6 as well. Ideally, the interviews should have been guided by a research methodology already in place from the start. The content of the interviews already covered much of the analysis done in chapters 4, 5 and 6, and the topics are summarised in Appendix A. Due to this, it was difficult to recall and extract information from interviews conducted prior to methodology selection. That left much of the analysis subject to my own interpretation, which is a threat to the research credibility. The barriers and interventions identified and presented here are subject to researcher bias, as well as bias from the interviewees, who may have chosen to highlight some factors over others due to issues of trust or hesitancy. Any further research into the system barriers should also separate the identified barriers by the different system levels, micro, macro and meso, and use a guiding framework to identify their interconnectedness. It is still a question which barriers are leading and cause a chain reaction by triggering other system barriers. This will be important research to tackle root causes and develop interventions that are highly impactful.

After proposing the interventions, further rounds of interviews could have been conducted to confirm and verify the findings and their impact. As mentioned under Research Methodology, Halbe and Pahl-Wostl (2019) propose a framework for designing system transitions. They invite interview participants to construct structured causal loop diagrams (CLDs), which press participants to find root causes and identify feedback loops. Through this, case-specific problems and solutions are developed based on local knowledge. Therefore, any follow up research should ground the stakeholder research with a solid methodology and gather thorough details on the roles of the stakeholders in the system, as well as select methods to reduce interview bias, collect credible data, and confirm the impact of proposed interventions.

A final limitation is on the transferability of this research. The work starts with a case study on coffee capsules to identify common material combinations in a composite packaging format. The remainder of the work tries to generalise the findings for most non-ferrous composite packaging, looking at the sorting and recycling of composite waste at scale in a DKR-420 bale. The work already highlights the large difference between the end-of-life of composite packaging compared with mono-plastic packaging. The barriers and interventions for circularity here are limited to the context of such composite waste, and any future researchers should be cautioned when trying to adapt the findings onto other types of packaging.

9.3. Future work

As this research was constrained for time, I propose a few considerations for future work. First, I would suggest expanding the pool of stakeholders interviewed, and engaging them in dialogue beyond semi-structured interviews, perhaps through participatory roundtable workshops. Gasde et al. (2020) present a methodology called Integrated Innovation and Sustainability Analysis, which aims for early involvement of stakeholders along with a sustainability assessment of the proposed innovation that results in feedback loops for technology development. Their methodology has been demonstrated in two collaborative R&D projects funded by the German Federal Ministry of Education and Research. I would also suggest that any further research into the potential of chemical recycling and advanced sorting that identifies barriers to a circular economy distinguishes them into different system levels, micro, meso and macro, and then analyses the interactions between the levels. A more comprehensive multi-level stakeholder analysis guided by firm methodology will also result in more robust proposed interventions.

Next, as the interventions in chapter 8 point out, research efforts are required in not just qualitatively assessing the innovation systems, but also in providing quantitative empirical data on these new technologies. As seen in chapter 7, the petrochemical industry is playing an influential role in the promotion of thermal depolymerisation for mono-plastic streams, despite any clear evidence that the technology has any environmental benefit. As for selective plastics dissolution, similarly no empirical data was found beyond the lab scale, for trials of collected consumer packaging. Information is still needed on the impacts of the used solvents and energy requirements for a process where large amounts of it are flashed for recovery. Research must be done to determine what are the optimum feedstocks for these technologies, their material efficiencies on an industrial scale, and whether they offer environmental impact benefits to warrant their promotion for improving material circularity.

Similarly future work should also assess the feasibility and impact of the proposed system interventions here. While I only suggest the potential interventions, it will require considerable joint research effort and collaboration to outline how to implement these interventions.

9.4. Conclusion

This work set out to answer "How can innovations such as chemical recycling and advanced sorting create a circular economy for composite packaging such as coffee capsules?". The concept of a circular economy for plastic packaging waste is widely discussed amongst private business as well as regulators. Technologies such as chemical recycling and advanced sorting have gained increasing attention in both spheres, and this work set out to analyse their potential implementation at the end of life of consumer packaging waste, and how they can contribute towards a circular economy for such products.

Information was gathered on these technologies through semi-structured interviews with commercial developers and reviews of scientific publications. Limited quantitative data was available on their environmental impacts and performance on the industrial scale with streams of post-consumer packaging waste. However, solvent dissolution was identified for its potential to recycle materials from composite packaging at a higher value close to their original form. Next, the current collection and sorting infrastructure was explored further to understand the infrastructure changes needed to implement solvent dissolution. A flow diagram of current state of the art sorting plants provides an understanding of how composite waste is currently sorted at its end of life. Two sorting technologies, NIR with equipped with deep learning and packaging markers are discussed for their potential to change how waste is currently sorted, and allow the isolation of clean and suitable feedstock for solvent dissolution. A sorting scheme incorporating these technologies is developed and presented for the recycling of composite packaging waste. Although the scheme provides a preliminary reference point for how such technologies can be implemented, further research and industrial experimentation is needed to determine the optimum arrangement and business case for different varieties of packaging waste and their combination with different forms of recycling.

The next section explores the overall system from a multi-level, multi-stakeholder perspective by mapping all the flows of materials, money and influence. The results reveal that technological barriers still exist in the form of underdeveloped technological capabilities. However, there is also a lack of demonstrated industrial data on the environmental impacts of these technologies, and low awareness of their importance in fulfilling the aim of a CE. There is also insufficient awareness amongst stakeholders for higher level circularity strategies. More research must be directed towards quantifiying how the proposed CE strategies actually achieve their intended aim for sustainable development. Apart from this, several other *softer* barriers are at play in the implementation of a CE. The barriers are seen to be interconnected, and while this work was constrained for timing, further work should place importance on understanding the interactions between the different barriers, to develop impactful system interventions. Overall, the transition to a circular economy for composite packaging is seen as a complex problem that will involve coordinated effort from all levels of stakeholders, and a significant amount of collaborative research.

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Appendix A – Stakeholder descriptions

Virgin aluminium producers

Supply virgin aluminium to packaging foil rollers to form aluminium packaging foils, laminates and metallization.

Material/packaging converters

Purchase materials and produce consumer packaging sold to brands and retailers. They may produce and market several types of packaging formats including rigids and foils, and provide brands and retailers consult on packaging and material selection.

Brand owners and retailers

Place and promote packaged products on the market. They have extended producer responsibilities to fulfill on all packaging placed on the market to support the costs of collection, sorting, and recycling.

End consumers

Private households, and with the expansion of the VerpackG, include out-of-home consumers producing similar packaging waste such as schools, offices, hospitals and commercial buildings.

Packaging waste collectors

Pick up and transport packaging waste to packaging sorting plants.

Packaging sorting plants

Sort and prepare incoming packaging waste for recycling, by producing material bales according to the DKR specified standard fractions which are sold on the recyclate market to different recyclers.

EPROs

Extended producer responsibility organisations that collect packaging licensing fees from brand owners and engage with sorting plants to ensure the collection, sorting and recycling of packaging waste, ensuring compliance with national packaging waste laws.

Sorting technology providers

Develop and sell existing and new sorting technologies such as eddy current separators, NIR scanning belts, robot sorters and others to sorting plants and EPROs to improve material sorting efficiencies.

Mechanical recyclers

Recycle streams of mono plastics into regranulate for use in food or non-food applications.

Downcyclers

Recycle plastic aluminium bales from sorting plants into low-value applications such as garden furniture, crates and plant pots.

Incinerators

Incinerate low value recyclate bales from sorting plants to produce energy and recover materials from bottom ash.

Chemical recyclers (solvent dissolution)

Use targeted solvents to separate clean polymers and aluminium from mixed packaging waste. Products are sold to material reprocessors to be recombined for subsequent use into food-grade packaging.

Petrochemical companies

Process mono and mixed plastic streams into hydrocarbon oils which are sold to petrochemical companies for refining into virgin plastic feedstock. Also produce virgin plastic feedstock from fossil fuel sources. Includes oil and gas processors and chemicals and polymers producers which are often vertically integrated under one company.

Aluminium remelters

Melt scrap aluminium recovered from recycling to form clean recycled aluminium ingots which are sold for further reprocessing in application-specific use such as foil rolling.

Aluminium foil rollers

Produce aluminium foils for use in packaging applications such as the coffee capsule lids.

Industry organisations

Groups of industry stakeholders that are focused on fostering collaboration for shared goals. Provide training to members, conduct joint research, publish resources for members, and represent industry interests amongst policymakers.

Certification bodies

Implement and uphold criteria for industry certifications, assess and monitor organisation performance, and issue certification that validate an organisation's operations.

Appendix B – Stakeholder interviews

Table 18: Summary of stakeholder interviews.

No.	Stakeholder	Role of Interviewee	Discussed topics
1	Brand owner A	Packaging Sustainability Manager	• Challenges in implementing sustainability • Product design requirements • Design for recyclability • Consumer influence and awareness
2	Chemical recycler A (solvent dissolution)	Business Development Manager	• Process description (inputs, outputs, operating parameters, planned capacities) • Sorting requirements for feedstock • Validation of proposed sorting scheme • Influence of aluminium industry • Development of sorting technologies • Need for industrial experimentation
3	Chemical recycler B (solvent dissolution)	Chief Executive Officer	• Process description (inputs, outputs, operating parameters, planned capacities) • Sorting requirements for feedstock • Development of sorting technologies • Cultural attitudes surrounding investment • Validation of proposed sorting scheme
4	Chemical recycler C (solvent delamination)	Chief Executive Officer	• Process description (inputs, outputs, operating parameters, planned capacities) • Sorting requirements for feedstock • Material recycling quotas • Development of sorting technologies • Influence of aluminium industry • Shift towards mono-materials • Need for industrial experimentation • Need for funding
5	Chemical recycler D (thermal depolymerisation)	Chief Executive Officer	• Process description (inputs, outputs, operating parameters, planned capacities) • Issues recycling plastic aluminium with traditional pyrolysis • Economics of composite packaging recycling • Influence of petrochemical industry • Further processing and open loop recycling of pyrolysis oils
6	Chemical recycler E (thermal depolymerisation)	Business Development Partner	• Process description (inputs, outputs, operating parameters, planned capacities) • LCA studies on pyrolysis • ISCC+ certification for circular oils • Need for industrial sorting trials

7	Chemical recycler F (thermal depolymerisation)	Commercial Contracts Manager	• Process description (inputs, outputs, operating parameters, planned capacities) • Feedstock contracts and capacities • ISCC+ certification for circular oils • Influence of petrochemical industry • Shifting regulation for chemical recycling (gas burnt as fuel) • LCA studies on pyrolysis
8	Mechanical recycler A	Technical Sales Representative	• Partnership with sorting plants and sorting technology providers • Development of new sorting technologies • Influence of petrochemical industry • Potential of chemical recycling • Demand for mono-plastics for mechanical recycling
9	Downcycler A	Technical Sales Representative	• Challenges in recycling composites • Open loop recycling
10	EPRO A	Sales Manager	• Role of EPROs in system • Contract arrangements between EPROs, sorting plants and recyclers • Implementation of new sorting technologies • Potential for chemical recycling • Consumer awareness
11	EPRO B	Performance Manager	• Role of EPROs in system • Contract arrangements between EPROs, sorting plants and recyclers • Validation of proposed sorting scheme • Challenge of recycling composites • Economics of recycling composites
12	EPRO C	Senior Consultant	• Role of EPROs in system • Contract arrangements between EPROs, sorting plants and recyclers • Implementation of new sorting technologies • Potential for chemical recycling • Consumer awareness • Design for recycling guideline
13	EPRO D	Head of Recycling and Recyclate Trading	• Recyclate quotas for sorting plants in Germany • Lack of high-value packaging waste • Role and influence of consumers • Challenge of recycling composite packaging • Trading contracts between sorting plants and recyclers • Role of regulators
14	Sorting plant A	Waste Management Engineer	• Validation of proposed sorting scheme • Contract arrangement with EPROs • Economics of sorting • Importance of design-for-recycling guidelines

15	Sorting plant B	Consulting Engineer	• Validation of proposed sorting scheme • Challenges of chemical recycling • Economics of sorting • Importance of design-for-recycling guidelines
16	Sorting equipment provider A	Area Sales Manager	• Sorting technologies for composite packaging • Validation of proposed sorting scheme • Need for industrial demonstration • Initiatives for industrial demonstration
17	Sorting equipment provider B	Plastics Application Manager	• Limitations of chemical recycling • New sorting technologies • Need for industrial demonstration • Validation of proposed sorting scheme • Initiatives for industrial demonstration • Collaborative research
18	Sorting equipment provider C	Chief Executive Officer	• Limitations of chemical recycling • Limitations of sorting technologies • Need for industrial demonstration • Validation of proposed sorting scheme
19	Material/packaging converter A	Rigid Packaging Application Manager	• Partnerships with sorting technology providers and mechanical recyclers • Shift to mono-materials • Design for recycling guidelines
20	Aluminium recycler A	Area Sales Manager	• Technical bottlenecks in chemical recycling • Cultural bottlenecks amongst consumers
21	Aluminium foil roller A	Executive Director	• Interests of aluminium packaging industry • Shift to mono-materials • Importance of design-for-recycling guidelines • Importance of collaborative research

DerGrünePunkt

Product Specifications

Number.	Name of Fraction:	Fraction-No.:	Date:
00	Plastic Films	310	04/2009
01	Plastic Films	310-1	03/2018
02	Mixed Plastic Bottles	320	03/2018
03	Polyolefin Plastic Bottles	321	03/2018
04	Plastic Hollow Bodies	322	03/2018
05	Mixed Polyolefin-Items (MPO)	323	03/2018
06	Flexible PO-Items	323-2	03/2018
07	Polypropylene plus	324-1	03/2018
08	PET Bottles, transparent	325	03/2018
09	Mixed-PET 90/10	328-1	05/2018
10	Mixed-PET 70/30	328-2	05/2018
10a	PET Trays	328-5	06/2018
11	Polyethylene (PE)	329	03/2018
12	Cups	330	03/2018
13	Polystyrene (PS)	331	03/2018
14	Expanded Polystyrene (EPS)	340	03/2018
15	Mixed Plastics	350	03/2018
16	Rigid Plastics Quality 1	351-1	03/2018
17	Rigid Plastics Quality 2	351-2	03/2018
18	MPO By Product (KEG)	361	03/2018
19	Tinplate	412	08/2014
20	Aluminium	420	05/2018
21	Liquid Packaging Board (LPG)	510	03/2018
22	Paper, Board, Cardboard from Lightweight Packaging	550	03/2018
23	LVP Sorting Residues Medium and Oversize Fraction	831	05/2012
24	Supplement		08/2014

DerGrünePunkt

Product Specification 04/2009
Fraction-No. 310

Sorting fraction: **P L A S T I C   F I L M S**

A Specification/Description

Used, residue-drained, system-compatible items made of plastic film, surface > DIN A4, e.g. bags, carrier bags and shrink-wrapping film, incl. secondary components such as labels etc.

The supplement is part of this specification!

B Purity

At least 92 % by mass in accordance with the specification/description.

C Impurities

Max. total amount of impurities	8 % by mass

Metallic and mineral impurities with a unit weight of > 100 g are not permitted!

Other metal items	< 0.5 % by mass
Other plastic items	< 4 % by mass
Other residues items	< 4 % by mass

Examples of impurities:

- Glass
- Paper, cardboard
- Composite paper/cardboard materials (e.g. beverage cartons)
- Aluminised plastics
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Delivery form

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 23 t
- Dry-stored
- Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction No. and production date

Product Specification 03/2018
Fraction-No. 329

Sorting fraction:	**P O L Y E T H Y L E N E**

A Specification/Description

Used, residue-drained, rigid, system-compatible items made of polyethylene, volume ≤ 5 litres, e.g. bottles and trays, incl. secondary components such as lids, labels etc.

The supplement is part of this specification!

B Purity

At least 94 % by mass according to specification/description.

C Impurities

Max. total amount of impurities	6 % by mass

Metallic or mineral impurities with a unit weight of > 100 g and cartridges for sealants are not permitted!

Other metal items	< 0.5 % by mass
Rigid PP items	< 3 % by mass
Foamed plastics incl. EPS items	< 0.5 % by mass
Plastic films	< 5 % by mass
Other residues	< 3 % by mass

Examples of impurities:

- Glass
- Paper, Board, Cardboard
- Composite paper/cardboard materials (e.g. liquid packaging boards)
- Aluminised plastics
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of Delivery

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 17 t
- Dry-stored
- Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction no. and production date

DerGrünePunkt

Product Specification 03/2018
Fraction-No. 324-1

Sorting fraction:	**P O L Y P R O P Y L E N E p l u s**

A Specification/Description

Used, rigid, system-compatible items made of polypropylene, volume ≤ 5 litres, e.g. bottles, cups and trays, incl. secondary components such as lids, labels etc. as well as completely emptied films such as bags.

The supplement is part of this specification!

B Purity

At least 96 % by mass according to specification/description – at least 90 % by mass rigid PP items

C Impurities

Max. total amount of impurities	4 % by mass

Metallic or mineral impurities with a unit weight of > 100 g and cartridges for sealants are not permitted!

Other metal items	< 0.5 % by mass
Rigid PE items	< 1 % by mass
Expanded plastics incl. EPS items	< 0.5 % by mass
Paper, cardboard, carton, Composite paper/cardboard materials (e.g. liquid packaging boards)	< 1 % by mass
Other residues	< 3 % by mass

Examples of impurities:
- Glass
- Aluminised plastics
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of Delivery

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 17 t
- Dry-stored
- Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction no. and production date

DerGrünePunkt

Product Specification 03/2018

Fraction-No. 331

Sorting fraction:	**P O L Y S T Y R E N E**

A Specification/Description

Used, residue-drained, rigid, system-compatible items made of polystyrene, volume ≤ 1 litre, e.g. cups and trays, incl. secondary components such as lids, labels etc.

The supplement is part of this specification!

B Purity

At least 94 % by mass according to specification/description.

C Impurities

Max. total amount of impurities	6 % by mass
Metallic or mineral impurities with a unit weight of > 100 g are not permitted!	
Other metal items	< 0.5 % by mass
Expanded plastics incl. EPS items	< 1 % by mass
Other plastic items	< 4 % by mass
Other residues	< 2 % by mass

Examples of impurities:

- Glass
- Paper, Board, Cardboard
- Composite paper/cardboard materials (e.g. liquid packaging boards)
- Aluminised plastics
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of Delivery

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 19 t
- Dry-stored
- Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction no. and production date

DerGrünePunkt

Product Specification 03/2018
Fraction-No. 350

Sorting fraction:	**M I X E D P L A S T I C S**

A Specification/Description

Used, residue-drained, system-compatible items made of plastics that are typical for packaging (PE, PP, PS, PET) incl. secondary components such as lids, labels etc.

The supplement is part of this specification!

B Purity

At least 90 % by mass according to specification/description.

C Impurities

Max. total amount of impurities	10 % by mass
Metallic or mineral impurities with a unit weight of > 100 g are not permitted!	
Paper, cardboard	< 5 % by mass
Other metal items	< 2 % by mass
PET bottles, transparent	< 4 % by mass
PVC items other than packaging	< 0.5 % by mass
Other residues	< 3 % by mass

Examples of impurities:
- Glass
- Composite paper/cardboard materials (e.g. liquid packaging boards)
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of Delivery

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 21 t
- Dry-stored
- Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction no. and production date

DerGrünePunkt

Product Specification 05/2018
Fraction-No. 328-1

Sorting fraction:	**Mixed PET 90 / 10**

A Specification/Description

Used, residue-drained rigid, system-compatible items made of polyethylene terephthalate (PET), volume ≤ 5 litres composed as follows:

1. Transparent bottles, e.g. detergent bottles, beverage bottles

2. Other rigid PET items, e.g. cups, bowls

Clear, coloured, opaque, incl. secondary components such as lids, labels, etc.

The supplement is part of this specification!

B Purity

At least 98 % by mass according to specification/description.

At least 90 % PET bottles, transparent

Maximum 10 % other rigid items made of PET

C Impurities

Maximum total content of impurities	2 % by mass
Metallic or mineral impurities with a unit weight of > 100 g are not permitted!	
Other metal items	< 0.5 % by mass
Other plastic items	< 2 % by mass
PVC items	< 0.1 % by mass
Other residues	< 2 % by mass

Examples of impurities:
- Glass
- Paper, Board, Cardboard
- Paper/board/cardboard composite materials (e.g. liquid packaging boards)
- Aluminised plastics
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of Delivery

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 17 t
- Dry-stored
- Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction no. and production date

DerGrünePunkt

Product Specification 08/2014
Fraction-No. 412

Sorting fraction:	**T I N P L A T E**

A Specification/Description

Used, residue-drained, system-compatible items made of tinplate such as beverage and food cans as well as buckets incl. secondary components such as labels etc.

B Purity / Metal Content

At least 67 % by mass (rejection boundary), deducted standard quality 82% by mass minimum

The supplement is part of this specification!

C Impurities

Max. total amount of impurities 33 % by mass non metals

The amount of impurities between 18.1 % by mass and 33 % by mass may/possible cause deduction on commission according to contract.

Closed hollow containers (e.g. fire extinguishers), explosive devices and electrical appliances, copper cables, batteries and radiation sources are not permitted!

Examples of impurities:

- Glass
- Liquid packaging boards
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of Delivery

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 23 t
- Loose fill with bulk weight on wagon and truck of 0.25 t/m³ minimum
- Labelling via delivery note provided with sender, recipient and denominations

Product Specification 05/2018
Fraction-No. 420

Sorting fraction:	**A L U M I N I U M**

A Specification/Description

Used, residue-drained, system-compatible items made of aluminium or containing aluminium foil, such as trays, wrapping foil, incl. secondary components such as lids, labels, etc.

The supplement is part of this specification!

B Purity

At least 65 % by mass (rejection boundary), deducted standard quality 90% by mass.

At least 90 % by mass according to specification/description

C Impurities

Maximum total content of impurities	10 % by mass
Solid impurities with a unit weight of > 100 g and closed hollow containers (e.g. fire-extinguishers) and explosives are not permitted!	
Items made of paper, board, cardboard and of plastic that do not contain any aluminium and/or any aluminium foil	< 3 % by mass
Liquid packaging boards	< 2 % by mass
Magnetic iron-metal items	< 3 % by mass
Other residues	< 5 % by mass

Examples of impurities:

- Glass
- Cartons for liquids
- Metallised material
- Tinplate cans
- Light fitting components (e.g. light bulbs, fluorescent tubes)
- Plastics
- Foreign materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of delivery

- Transportable bales
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 23 t
- No stretch wrappings
- Production via customary bale press
- Labelling via Identified with DSD bale label stating the sorting plant no., fraction no. and production date

DerGrünePunkt

Product Specification 03/2018
Fraction-No. 550

Sorting fraction:	**Paper, Board, Cardboard from Lightweight Packaging**

A Specification/Description

Used, residue-drained, system-compatible items made of paper, board or cardboard as well as composite paper/cardboard materials except liquid packaging boards, incl. secondary components such as labels etc.

The supplement is part of this specification!

B Purity

At least 90 % by mass according to specification/description.

C Impurities

Max. total amount of impurities	10 % by mass
Metallic or mineral impurities with a unit weight of > 100 g are not permitted!	
Liquid packaging boards	< 4 % by mass
Plastic items	< 3 % by mass
Metal items	< 0.5 % by mass
Other residues	< 3.5 % by mass

Examples of impurities:

- Glass
- Wax-, bitumen- and oilpaper
- Other materials (e.g. rubber, stones, wood, textiles, nappies)
- Compostable waste (e.g. food, garden waste)

D Form of Delivery

- Transportable bales
- No cross-wiring and dry-stored
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 22 t
- Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction no. and production date

Product Specification 08/2019
Fraction-No. 831

Sorting fraction: **L V P S O R T I N G R E S I D U E S**
M E D I U M A N D O V E R S I Z E F R A C T I O N

A Specification/Description

1. Material Properties

LVP input residues largely free of FE- and NF-metals, minerality oversize and fine grains as so called left-over LVP-residues after sorting according to contract.

2. Chemical and physical parameters

Lower heating value	kJ/kg OS	> 13,000
Item size		
Undersize fraction	items < 10 mm	< 5 % by mass
Oversize fraction	items > 300 mm	< 5 % by mass

B Purity

At least 90 % by mass according to specification/description.

C Form of Delivery

- Transportable bales
- No cross-wiring and dry-stored
- Dimension and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.60 m x 2.40 m; lateral loading height min. 2.60 m) can be loaded with a minimum loading of 23 t

  Produced with customary bale presses
- Identified with DSD bale label stating the sorting plant no., fraction no. and production date

DerGrünePunkt

Supplement (08/2014)

The supplement is part of the specification!

A Specification/description

The system compatibility of packaging in terms of its content is the requirement for licensing and will be checked by an expert respectively.

Basically, only unground products from the sorting process of light weight packaging of household collection systems that are operated by contracting parties of the Duales System Deutschland GmbH will be accepted.

B Purity

The purity of the sorting fraction will be determined by sampling according to LAGA PN 98 (status: December 2001) and subsequent analysis (e.g. manual sorting and weighing or chemical analysis).

The regulations apply to DSD quality testing scheme (annex 7).

C Impurities

Impurities are substances that technically complicate or impede the recycling of the sorting fraction, irrespectively of whether, in any particular case, complication or prevention occurs.

Impurities are all materials and items that are not described in Point A (specification/description).

These include for instance:

- Packaging made of other sorting fractions which do not comply with the specification.
- Non-system components which have been sorted incorrectly
- etc.

The fractions of individual impurities or groups of impurities are limited separately as far as this is technically necessary.

The maximum total impurity content is the proportion of all impurities in the fraction and must in any case be undercut.

D Form of Delivery

Terms of delivery for each specification are to be observed by the sorting plant's loading services.

Sorting plants with a total plant capacity of 35.000 t/a (or bigger) must enable free loading of sea containers as well as the necessary photographic documentation regarding collection of the fractions in question for the client or a third party contractor