Closing the Loops of Fast-Moving Consumer Goods

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A Doctoral Thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Design Engineering

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Declaration of Originality

This thesis contains my own original work. Some parts of the thesis have previously been published in journals and at conferences and are reused within the respective copyright agreements.

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Abstract

The Fast-Moving Consumer Goods (FMCGs) sector aspires to transition to a Circular Economy (CE) but there is a lack of knowledge and support methods. This research has investigated how material resources flow in FMCG systems and developed new design support for the sector. Initially, the research focused on the moment when resources become obsolete which can disrupt flows. Consumers were found to have critical roles to ensure resource revalorisation and the findings of this study can inform the design of future revalorisation services. Further, it explored Product-Service Systems (PSSs) and studied the elements that could help overcome obsolescence and enable closed loops resource flows. A framework presents these elements, mapped against requirements for PSSs that close loops. Subsequently, the research focused on investigating the resource flow-system, which encompasses all the system elements in place to produce a resource flow. A new modelling method is proposed that describes the movements and transformations of resources and helps configure FMCG sector-specific system elements. The model can be used to explain how FMCG systems work. Finally, a tool called the Flow Mapper is presented, which embeds the modelling method as well as the process to apply it and analyse the model. The tool enables industrial users to develop a holistic view and an in-depth understanding of the resource flow-system informing the development of future systems solutions.

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1. Introduction

This chapter outlines the rationale for the research and introduces the research objectives. Further, the philosophical stance, industrial collaboration, research methodology and research structure are explained.

1.1. The challenge of transforming a linear journey

Humankind has left marks on planet earth since the earliest existence of our species. Some of the most ancient marks demonstrate that humans were able to manipulate materials. One example is the discovery of spears and other tools stemming from the Stone Age. Over time, humans have developed more advanced skills to manipulate what nature has provided and make materials work in our favour. As materials gradually became a central part of our life, so did the process of discarding materials as waste. Historically, awareness for waste grew when humans settled in cities (e.g., in Roman times) in which waste accumulated and was considered a problem as it could spread diseases (Barles, 2015). Waste from cities was mostly organic, which was of interest to agriculture and industry outside cities and encouraged successful waste management (Barles, 2015). However, centralisation and movement of people also created a need for the ability to store and transport food products (Berger, 2003). To address these new needs, packaging solutions were invented (Risch, 2009), which became increasingly more advanced throughout history. For example, discoveries of ceramic vessels used to ship and store food and beverages in Greek and Roman times, have advanced aesthetics and shapes that optimised the preservation and marketing functions of this packaging (Twede, 2002). Closer to date, significant development of packaging technology followed the advancements of material extraction and manufacturing in the industrial revolution and wartime (Ashby and Johnson, 2002).

Novel manipulations of materials, such as plastics, became (sometimes by accident) popular for packaging (Risch, 2009). Plastics struggled to gain acceptance from consumers at first due to their unusual experiential characteristics that seemed to make the material experience unappealing to consumers (Karana, 2009). Nevertheless, the material became an increasingly popular choice for packaging manufacturers because of its technical properties, e.g., lightweight, cheap, easy to manipulate and favourable preservation qualities (Risch, 2009). Eventually, plastics also became a preferred material for consumers, not in the least for their features that manifest disposability of the product (Lucas, 2002). This fostered the 'take-make-dispose' pattern that is characteristic of the linear economy (e.g., Boulding, 1966; EMF, 2014). Today, of the 311 million tonnes of plastic produced globally (2014), 26% is used for packaging (EMF, 2016). As it is the Fast-Moving Consumer Goods (FMCGs) sector that produces these goods, it is at the very centre of the linear economy.

Bright sides and dark sides of FMCGs

It is easy to take today's packaging and disposable goods for granted, but these seemingly mundane goods, and perhaps their mundanity itself, are the result of years of innovation (Berger, 2003). Packaging has allowed us to preserve, store and transport food, to extend the shelf lives of perishable foods and to reduce food losses due to spoilage (Risch, 2009). There even is evidence for the benefits of the frequently challenged case of the cucumber shrink wrap packaging (Dhall *et al.*, 2012). Packaging and other types of FMCGs, such as disposable products like toothbrushes, razors or nappies, have made safe and hygienic consumption increasingly convenient (Lucas, 2002; Risch, 2009). Some of the world's largest multinational FMCG manufacturers estimate that billions of people use at least one of their products daily, i.e., 2.5 billion (Unilever, 2019) and 5 billion (Procter & Gamble, 2019). It seems evident that the take-make-dispose pattern has been crucial to the commercial success of the FMCG sector.

If roughly half of the global population already touches at least one FMCG every day, one can only imagine the size of the volume that the entire FMCG sector puts through. Ancient waste management systems, such as the one in the Roman Empire, emerged partly due to a commercial interest in waste resources that were predominantly organic (Barles, 2015) but there appears to be much less interest in the fragmented and increasingly complex mix of materials coming out of households today (Hawkins, 2012). It is often cheaper and easier to discard these resources in landfill than to recover them (Zink and Geyer, 2018). Unfortunately, a significant number of FMCGs are not captured at all by waste management systems. Indeed, 32% of plastic packaging used globally is expected to leak into nature (EMF, 2016). Sadly, this means that humankind is leaving marks on the planet that are far more damaging than those from ancient times. With a rate far exceeding archaeological findings, there are worrisome discoveries of plastics affecting ecosystems and wildlife (Jambeck *et al.*, 2015).

Sustainability and a linear economy

Their reappearance in nature seems to increasingly make plastics a public scapegoat for environmental issues (Fearnley-Whittingstall and Rani, 2019; Stein, 2002). Indeed, plastics can be linked to unsustainable production and consumption. In fact, this research was initiated due to an interest in 'sustainable materials'. However, perhaps too much of the blame for environmental problems is placed on plastics. Plastics are typically long lasting, and therefore, their contribution is visible (Stein, 2002). More likely, however, is that the problems associated with plastics only explain a symptom of the root problems caused by linear FMCGs. The root of the problem relates to human demand on the planet, which is exceeding nature's ability to replenish resources and absorb waste (Weetman, 2016). There is a general concern for the severity of consumer behaviour in relation to waste generation (Cooper, 2005; Papanek, 1985; Taylor, 2017), but the FMCG sector's contribution to the depletion of resources and the accumulation of waste is significant. It relates both to processes to extract, convert and recover FMCGs that consume finite resources and produce greenhouse gas (GHG) emissions (EMF, 2019a) as well as to the continuous and structural disposal of packaging and products that is linked to today's 'waste crisis' (Hawkins, 2012). Concerns around the negative impacts on the environment caused by a linear economy have been a topic of discussion since the 1960s (Bhamra and Lofthouse, 2007; Braungart and McDonough, 2008; Cooper, 2005; Packard, 1960; Papanek, 1985). Initially, the discussion focused on a need for more sustainable production and consumption. The term sustainability became popular and was famously defined by the UN as 'seeking to meet the needs and aspirations of the present without compromising the ability to meet those of the future' (Brundtland, 1987). More recent interpretations can be found in the Sustainable Development Goals (SDGs), which suggest (Declaration point 9.) a 'world in which consumption and production patterns and use of all-natural resources – from air to land from rivers, lakes and aquifers to oceans and seas – are sustainable', implying that sustainability is about preservation and a balanced use of resources.

Sustainability, however, is not a straightforward objective. In design practice, sustainability is considered more a direction or strategy than the ultimate goal (Bhamra and Lofthouse, 2007; Lewis *et al.*, 2010), and it does not have a single specific target to strive for (Ceschin and Gaziulusoy, 2016). This is because sustainability does not provide an absolute result. For example, plastics can provide environmental benefits through weight reductions that, compared to heavier materials, reduce the GHG emissions and consumption of resources to fuel their transport (Stein, 2002). However, the same plastics may be lost as waste, and thus, the energy invested in it will be lost. As a result, achieving sustainable solutions often seems to be a compromise (Nyberg and Wright, 2013). Similarly, compromise is observed in suggestions to substitute plastics with materials that are biodegradable but may never end up in the anaerobic digestion facilities that can recover them (Corbin and Garmulewicz, 2018) and in striving to make FMCGs recyclable (EMF, 2017a; Procter & Gamble, 2018; WRAP, 2019a), which still requires significant energy inputs (Allwood, 2014). These strategies, therefore, can be perceived as 'less bad', rather than doing 'more good' (McDonough and Braungart, 1998). Perhaps, they even provide an argument to keep the profitable linear model alive.

Systems thinking for a circular economy

To achieve truly sustainable outcomes for sectors as high-paced as the FMCG sector, more rigorous changes to production and consumption systems are needed. The importance of a holistic approach was stressed in the sustainability definition (Brundtland, 1987), but researchers and industrial stakeholders appear to have predominantly focused only on specific aspects of the complex problem (Murray *et al.*, 2017). Looking at its parts only, however, limits our understanding of the system that creates the problems (Meadows, 2008). If the system produces an unsustainable outcome, it is the system as a whole that should be investigated, rather than only changing isolated elements (Ceschin and Gaziulusoy, 2016; Dewberry and Monteiro de Barros, 2009). Systems thinking is at the heart of the principles of the Circular Economy (CE). The concept of a CE suggests that an environmentally and economically prosperous future can be achieved through the efficient use of material resources (EMF, 2015; Stahel, 1997). The concept is inspired by ecosystems in nature (Benyus, 1998) and industry (Graedel and Allenby, 1995), in which flows of resources exist that continuously allow waste to become food for the next cycle (McDonough and Braungart, 1998).

It is suggested that the FMCG sector could transition to a CE to tackle its contribution to environmental impacts (e.g., Charnley *et al.*, 2015; EMF, 2013, 2016, 2017a; Kuzmina, *et al.*, 2019; McKinsey Global Institue, 2011). To enable this transition, thus, implies to use systems thinking to identify solutions (e.g., Bakker *et al.*, 2014; Blomsma, 2018; EMF, 2015) and to propose solutions that entail entire systems rather than single system elements (Ceschin and Gaziulusoy, 2016; Charnley *et al.*, 2011). Using these principles, the FMCG sector could aim to move away from linear flows caused by the take-make-dispose pattern and instead aim to flow materials and products in closed loops to preserve the material value and reduce environmental pressures.

The Ellen MacArthur Foundation (EMF) has investigated the sector's value potential (e.g., EMF, 2013, 2016, 2017a), and the support from governments for a CE is increasingly evident in emerging policy and legislation (European Commission, 2015a, 2018a; UNEP, 2014; United Nations, 2016). Further, the FMCG sector is publicly aspiring to transition to a CE, with targets to reduce the amount of material used in each product, increase the uptake of recycled materials and recyclable products, and improve collection points, and even reusable packaging (e.g., Nestlé, 2019; Procter & Gamble, 2018; Unilever, 2019). Nevertheless, beyond this promising vision, the evidence for sectorial change in the real world remains scarce. Solutions that do emerge in the sector do not appear to be systemic changes to the production and consumption system, and as a result, their impacts remain superficial and local. Perhaps this is because a new economic model, such as the CE, significantly changes the relationships between resources and economic value (Raworth, 2017). Additionally, its complexity and systemic nature allow the problem to be considered as wicked, and traditional design processes are not apt to solve such problems (Rittel and Webber, 1973). Observing emerging solutions leads to suggest that systems thinking is insufficiently used to understand and address problems caused by the production and consumption of FMCGs. This is plausible as traditional organisations often do not have adequate methods and strategies to address problems of such complexity (Pourdehnad *et al.*, 2011). It appears there is a lack of knowledge on systems thinking and associated methods that can enable the FMCG sector and industry in realising their aspirations to transition to a Circular Economy. As a result, closed loop FMCGs remain a vision rather than a reality.

1.2. Research aims and objectives

The overall aim of this research is to develop knowledge and methods for design research that support the FMCG sector in its transition to a CE. To achieve this, the aim is to develop knowledge on the relation between resource flows and FMCG systems and to translate this knowledge into practical and applicable methods for industrial users in the FMCG sector. The following research questions and objectives were formulated to structure this research:

Why does the FMCG sector lack circularity?

Waste generated by discarded FMCGs continues to be a global environmental concern. Different product categories are entering the domain of 'fast'. Consequently, the characteristics that make FMCGs perform so well in the linear economy could relate to the products or the way in which they are produced. The FMCG sector has public CE aspirations and is implementing sustainability efforts. However, environmental problems persist. ***Objective A*** *is to understand why the FMCG sector lacks circularity* (Chapter 2).

How is design used to deliver systemic solutions that close the loops of resources?

The CE has emerged as a promising concept that merges environmental and economic strategies for a sustainable future. It is suggested that design can be a catalyst for the FMCG sector's transition to a CE (Moreno *et al.*, 2016). There are several suggestions for design and the CE in the literature that seem to overlap with the use of life cycles thinking in design (Bhamra and Lofthouse, 2007). However, the CE implies enabling physically functioning journeys for resources, which may require a different consideration in design. ***Objective B*** *is to understand implications of using the design of systems to close loops* (Chapter 3).

What is the role of consumers in revalorisation services that close the loop of FMCGs?

Large FMCG manufacturers typically emphasise the responsibilities of consumers in recycling and reuse. FMCGs are physical products that consumers use, therefore, consumers indeed always have a role in ensuring the physical flow of resources. Revalorisation services are services that aim to extend the lifetime of resources (Mont, 2002), in the FMCG sector they can be used to close the loops of materials or components of FMCGs. When FMCGs become obsolete, a response is needed from the consumers who were using them (Burns, 2010). This response is required for conventional recycling as well as component or product reuse. The implications for consumers of this role appears to be poorly considered and this likely limits the understanding of poor consumer engagement in revalorisation services. ***Objective C*** *is to understand and define the role of consumers in closing loops* (Chapter 4).

How can Product-Service Systems contribute to closing loops?

Beyond the consumer, the business models behind revalorisation services are likely to influence whether resources will flow or not. Product-Service Systems (PSSs) are advocated as a business model for a CE as they can lead to sustainable production and consumption models. Such business models are often used to implement life-extension strategies with the aim to slow resource loops or close resource loops (Tukker, 2004). However, it is also suggested that PSSs' ability to close resource loops is implied rather than proven with evidence. Despite life extension in PSSs, resource obsolesce is inevitable and could have a structural role in closed-loop PSSs. ***Objective D*** is *to explore the potential of PSSs to enable closed-loop resource flows* (Chapter 5).

How do FMCG systems produce closed-loop resource flows?

Systemic solutions beyond the business model alone are suggested to enable a transition to the CE, but it is not always clear what systems are and how they ensure that loops are closed. Instead, investigating and comparing closed-loop FMCGs through systems thinking principles could provide deeper understanding of resource flows and new insights on the workings of the systems that disrupt or enable flow. Nevertheless, methods are abstract which limits their use for developing consistent and comparable models. A more consistent modelling method would allow development of new knowledge on the interrelated elements in closed-loop FMCGs and identify significant differences between systems and their behaviour in analysis. ***Objective E*** *is to develop a method to explain how systems produce closed-loop resource flows* (Chapter 6).

How can systems thinking support the FMCG sector in designing systems that produce closed-loop resource flows?

Systems thinking requires a holistic understanding of the system. Methods that consider the flow of resources often set high-level system boundaries based on geographics or review only narrow sections of the flow based on behaviour or business models. This limits their ability to enable users to develop a holistic view because enabling system elements may exist in relation to the entire closed-loop resource flow. There seems to be a gap of support to consider the entire resource flow and system in the design process. This limits the ability to design and implement FMCG systems for the CE. There is a need to develop and evaluate practical support for industry. ***Objective F*** *is to develop a tool that provides both a holistic and in-depth understanding of systems and supports the FMCG industry in designing closed-loop systems* (Chapter 7).

1.3. Research methodology

Several schools of thought have influenced and inspired the methodology of this research. This section outlines the most dominant influences and presents the overall structure of the methodology.

1.3.1. Wicked problems and systems thinking

The challenge of transitioning the FMCG sector to a CE can be interpreted as a wicked problem (Camillus, 2008; Rittel and Webber, 1973) because the problem to be solved has innumerable causes, can be framed in different ways and there is no such thing as a right answer, rather solutions are good or bad. Wicked problems can relate to both design and science problems (Farrell and Hooker, 2013), and systems engineering can be used to demonstrate them (Rittel and Webber, 1973). Systems thinking is a way to look at systems by seeing things as a whole with interrelated parts (Senge, 2006), allowing explanation of the operations and behaviour of a system rather than of its single parts (Richmond, 1993). The school of thought gained popularity in the 1920s when limitations were experienced in the then dominant approach of reductionism that focuses on detailing the understanding of single elements (Flood, 2010). This limited what can be learned about one such element (Gallagher and Appenzeller, 1999), for example, the existence of an organism cannot be understood solely in terms of behaviour of some fundamental parts (Flood, 2010). Rather, the contribution of surrounding elements as well as the system itself are vital to understanding of (Gedell *et al.*, 2011).

Systems thinking is at the heart of the principles for a CE, and it also underpins the methodology of this research. A key benefit of systems thinking is that it helps understand how things interrelate and bridge the gap between the nature of our problems and our ability to understand them (Richmond, 1993). Further, systems thinking is used to integrate and combine multiple domains, capturing the complex nature of problems across multiple domains (Dwyer, 2015; Miser and Quade, 1985). Systems thinking is also a suitable approach to take a holistic perspective, understanding the scope of problems and solutions (De Haan and De Heer, 2017; Rittel and Webber, 1973) and to review problems and solutions in relation to time, identifying the real impacts of systemic changes (Kasser and Mackley, 2008; Stahel, 2010; Sterman, 2002). Interpreting the challenges of the transition of the FMCG sector to a CE as a wicked problem positions both the current problematic situation and the final solution as a system (Buede, 2009). This positioning guided the work to focus on the overall objective of the system to produce closed-loop resource flows but focus on subsystems related to specific sections of the flow, i.e., the role of the consumer and the potential of PSSs. This allows to identify key elements of the system and develop understanding of their relation to the overall behaviour of the system of interest (Meadows, 2008).

1.3.2. Philosophical perspective

A research paradigm entails the principles that represent the researcher's worldview (Guba & Lincoln, 1994) and, with that, influencing what and how the research is approached and understanding is obtained on the research topic (Blessing and Chakrabarti, 2009). The paradigm adopted for this work considers both the ontological stance and the epistemological stance. The ontological stance involves understanding the form and nature of reality and what is there that can be known about it (Guba & Lincoln, 1994); and the epistemological stance involves understanding the relationship between the knower or would-be knower and what can be known (Guba & Lincoln, 1994). This work aims to develop understanding of a socio-technical system and its influence on physical resource flows. The flow of resources is, in this case, considered reality, i.e., it is a tangible and measurable outcome. However, whether and if resources flow, is subject to the operations of the sociotechnical system, which includes interrelated elements that are less certain and measurable (e.g., motivations, incentives). What there is to know about this reality, thus, depends on the knowledge that can be obtained about the operations behind the reality. The research adopts the critical realism paradigm, which holds that there is a real material world but that our knowledge of it is often socially conditioned and subject to challenge and reinterpretation (Della Porta & Keating, 2008). In critical realism, reality is stratified into three levels i.e., *empirical* (realm of events as we experience them) which is always based on human interpretation; *actual* (events that are true occurrences) which are often different from what is observed at the empirical level; and the *real* (causal structures). The primary goal of critical realism is to explain social events through reference to these causal mechanisms (Fletcher, 2017). This research focuses on identifying and understanding the mechanisms that drive the phenomenon of flowing resources, i.e. the elements and their interrelations that form the mechanisms. Although a resource flow can be considered the actual level, why resources do (not) flow depends on the causal structures, i.e., the real level. Investigating the empirical level and a search for causation, then, helps to explain social events and make recommendations to address social problems (Fletcher, 2017). Evidence of one or multiple realities can be obtained through qualitative studies of social phenomena (Creswell, 2007).

1.3.3. Qualitative research methods

Rather than locating a single root cause, a wicked problem is seen as a whole, and several solutions are needed that either lead to better or worse outcomes. This thesis uses design research methodology to investigate FMCG systems in two complimentary ways: first, investigating the moments in the resource flow that have a high risk for disruption, for example, the moment resources become obsolete seems inevitable, yet it is rarely planned-for (Burns, 2010); and second, investigating the structures of systems that produce the entire closed-loop resource flow. This differs from investigating specific system elements in isolation, e.g., recycling behaviour (Steg and Vlek, 2008). Rather, recycling behaviour can be considered an element of a larger sociotechnical system (Hughes, 1987). Qualitative research is a suitable approach to investigate phenomena in social systems and develop theory about them in a real-world context (Creswell, 2007; Morgan and Smircich, 1980). Further, qualitative data collection is considered a suitable method to obtain insights on complex problems (De Haan and De Heer, 2017). This thesis uses various qualitative research methods to systematically and qualitatively investigate the behaviour of systems, their interrelated elements and the system as whole. Further, this work focuses on theories on the influence of design on the behaviour of systems used to consume FMCGs, it can be considered design research which is why it adopts Design Research Methodology (Blessing and Chakrabarti, 2009).

Qualitative research allows researchers to discover or develop theory based on the experience of both collecting the data as well as analysing them (Baker *et al.*, 1992; Blessing and Chakrabarti, 2009; Creswell, 2007). The qualitative research process starts as soon as the first data are collected (Creswell, 2007) because the process of collection and analysis are conducted simultaneously (Baker *et al.*, 1992). The research process is iterative, and the theory emerges from the narrative to describe the entire process (Bansal and Corley, 2012). Further, this work follows a pragmatism paradigm, in line with post-positivism, in which the most important aspect is addressing the research problem. A focus on the practical implications of the research emphasises the importance to use methods for data collection and analysis that best address the research problem (Creswell, 2007). These beliefs grant freedom in choosing appropriate methods (Baker *et al.*, 1992; O'Reilly *et al.*, 2015; Robson, 2011) but stress the importance of clearly communicating the entire journey of the research (Bansal and Corley, 2012) and maintaining rigour in methods for data collection and analysis (Creswell, 2007).

1.3.4. Industry collaboration

The research was funded through an EPSRC industrial case with P&G which allowed university–industry collaboration. Collaboration can take many forms and exist on many levels (Katz and Martin, 1997). Therefore, it is worth clarifying the nature of this collaboration and how it contributed to the overall research methodology. P&G and Imperial College London have a long-standing strategic partnership. However, the collaboration on design and the CE started with this research. The motivation for the project was P&G's need for knowledge to support their ambition to design novel sustainable products (Procter & Gamble, 2015, 2018). The collaboration was initiated by the Reading Innovation Centre. P&G and other multinationals in the FMCG sector are actively seeking opportunities and strategies to change towards more sustainable practice, which encouraged a two-way collaboration (Sjöö and Hellström, 2019; Smets *et al.*, 2012; Vick and Robertson, 2018) and using the opportunity to learn first-hand from topical challenges in this transition. The collaboration allowed us to lead and conduct the research independently and autonomously while having a direct link to the audience that we intended to impact. In addition, we were free to interact with other players in the sector. The EPSRC industrial case programme advocates engagement between the PhD candidate and the industrial partner. To ensure mutual engagement, we created and leveraged opportunities to work in proximity with individuals in the company (Katz and Martin, 1997), i.e., through regular face-to-face meetings with the sponsor, secondments in the UK and the USA, and both extended (e.g., to conduct interviews and engage in projects and events) and short visits (e.g., to deliver seminars) to P&G offices worldwide. This strengthened the relationship and granted access to and involvement in several activities (Gertner *et al.*, 2011), ranging from knowledge-transfer seminars, exhibitions, co-authorship on internal publications, design sprints, training and formal and informal consultancy work. P&G supported our successful application for the EPSRC Impact Accelerator Account (Imperial College London - Early Stage), which funds impact-relevant activities that capitalise knowledge to deliver benefits of PhD research to end users across industry. This allowed us to recruit a research assistant who supported the design of the early versions of the tool for Objective F (Chapter 7). The close and interactive relation with P&G allowed us to build trust and expand our relationships within R&D and establish new connections with other relevant departments, e.g., materials, industrial design, marketing, manufacturing and procurement, thus using network participation as an enabler for the research collaboration (Sjöö and Hellström, 2019). P&G has embraced and encouraged our strategy to develop research findings that are relevant for the FMCG sector rather than only for P&G or its specific business units.

The industrial collaboration was used strategically to influence the focus of the research and the choice of research methods. First, to understand the skills and needs of individuals in the company we engaged in company activities using principles of ethnographic research (Creswell, 2007; Robson, 2011; Yin, 2018). This strategy ensured a natural influence from the industrial partner on the research directions (Zalewska-Kurek and Harms, 2020) and helped to deepen the understanding of topical industrial needs, the needs from relevant decision-makers across disciplinary boundaries, as well as roles of different actors in the system (Miser and Quade, 1985). Second, to quickly disseminate, test and expose findings, we leveraged a university–industry collaboration. This supported research innovation and allowed to bridge the gap between academic research and industrial application (Tseng *et al.*, 2020). Maintaining a close relationship with the partner accelerated the impact of the research (Shi *et al.*, 2020); encouraged the translation of theoretical results into tangible outcomes based on feedback and through Participatory Action Research (Creswell, 2007). For example, early research results were tested in workshops, which considerably helped to present the findings in a meaningful way. Further, the collaboration created opportunities to grow in new research directions (Sjöö and Hellström, 2019; Vick and Robertson, 2018). It also improved resonation with the audience, e.g., alignment on language or the form of outcomes (Gertner *et al.*, 2011), by adjusting the research focus and refining the presentation of outcomes during the research. In conclusion, the industry collaboration contributed to a deeper and more detailed understanding of the multi-actor network that contributes to the wickedness of the CE problem in FMCGs waste.

1.3.5. Research structure

The overall structure of this research follows Design Research Methodology (DRM), which was developed to support choosing a research type (Blessing and Chakrabarti, 2009). The research aligns with three of the DRM stages. The diagram in Figure 1.1 is used to depict this structure as well as the contributing industrial interactions and the pragmatic approach of qualitative research.

Part I entails the research clarification stage, which involves review-based studies to develop a comprehensive understanding of the research problem (Blessing and Chakrabarti, 2009). This stage involved two review-based studies conducted mostly in parallel. The aim was, firstly, to apply a critical lens to the FMCG sector and its current approaches to address environmental issues to understand the existing situation through an industrial review (Objective A). Secondly, it aimed to build a theoretical knowledge foundation on design and the CE, establishing a preliminary set of success criteria and the desired outcome through a literature review (Objective B). Invaluable insights were also obtained through the two secondments in which the researcher was part of the every-day life in R&D offices as well as the extended visit in which the researcher was exposed to innovation in the company. These interactions allowed short, informal ethnographic studies that provided insights into industrial needs (Creswell, 2007; Robson, 2011; Yin, 2018). Part I of the research allowed us to define ‘establishing closed-loop resource flows’ as the main research problem. This follows the challenge of the sector to successfully establish such flows in practice, both for flowing reusable components or recyclable materials. Part I provided a focus for the next stage of research and

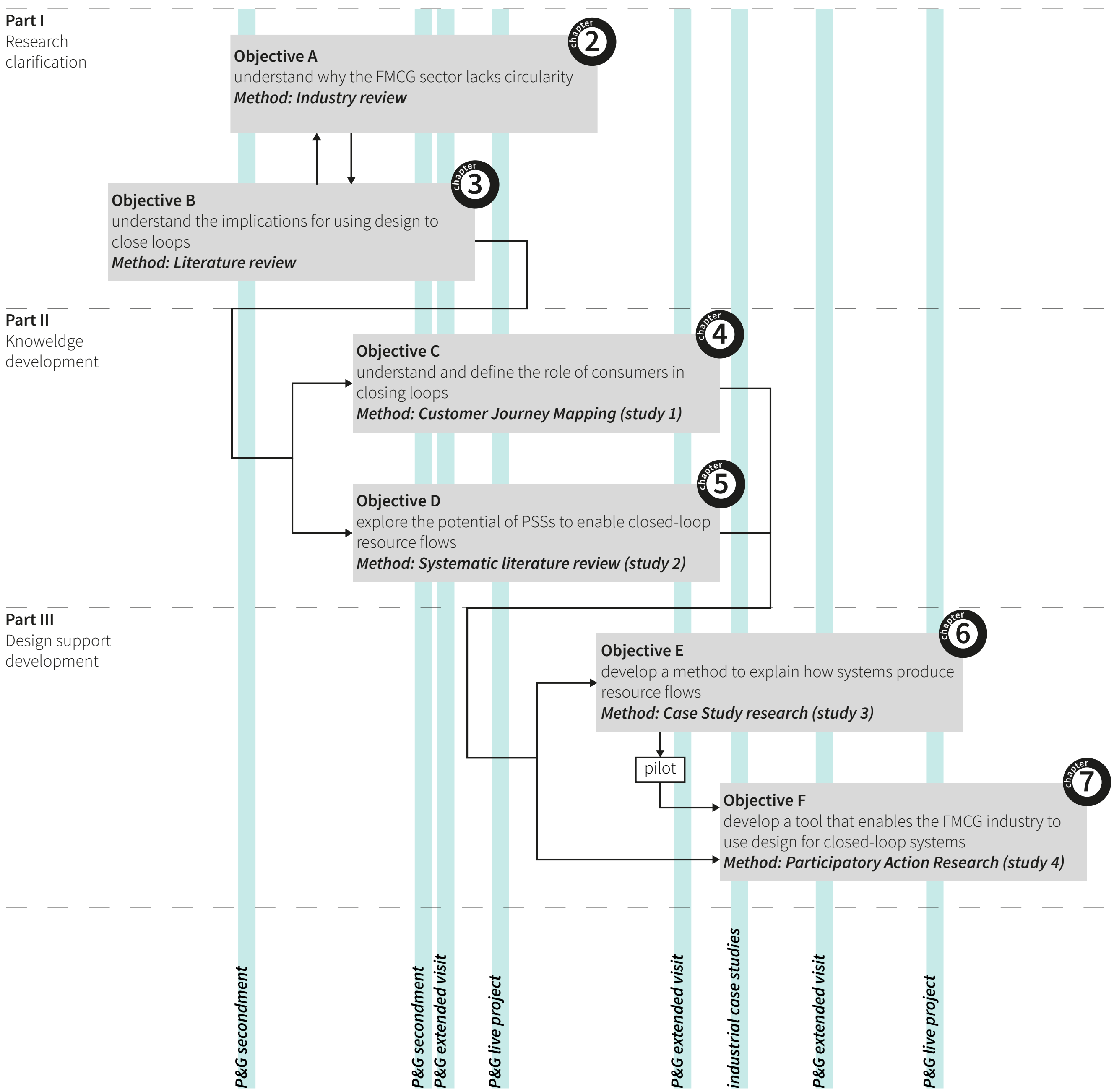


Figure 1.1 Diagram of the research structure.

defined the main phenomenon of interest, i.e., resource flows disrupted by obsolescence.

Part II entails the descriptive Study 1 stage, which focuses on knowledge development of the phenomenon of interest (Blessing and Chakrabarti, 2009), i.e., resource flows disrupted by obsolescence. Two studies were conducted in parallel. Particularly helpful at this stage was the engagement in a live project with P&G which provided feedback on preliminary findings of Study 1. This stage aims, firstly, to clarify factors that influence the disruption of resource flow by investigating the role of the consumer in revalorisation services for FMCGs through a structural comparison of customer journey maps in Study 1 (Objective C). Secondly, it aimed to further investigate factors that could be used to address the problem through a systematic literature review in Study 2 (Objective D). Part II provided a basis for the final stage, i.e., elements that could be part of the problem of flow disruptions, and thus could also lead to the solution.

Part III entails the prescriptive study stage, in which the focus shifted to developing support to improve design (Blessing and Chakrabarti, 2009). The insights obtained in Part II confirmed that the factors that influence flows are part of a larger system which requires better understanding to use it in design (Senge, 2006; Hughes, 1987). The work was heavily influenced by industrial interactions through the collection of empirical data from multiple companies in the FMCG sector. The studies were both theory-driven, i.e., developing methods based on System Dynamics and Function Structures, and empirically supported, i.e., components of the model are based on Case Study research in Study 3 (Objective E), and the tool development benefitted from empirical insights through Participatory Action Research in Study 4 (Objective F). A pilot for data collection in Study 3 was conducted, which served as the beginning of Study 3. However, the two studies were conducted mostly in parallel which allowed us to cross-contaminate insights on the modelling method.

1.4. Thesis overview

This thesis is structured in eight chapters, aligned with the overall structure of the research, as presented in Table 1.1. The overall aim of this research is to address the gap of knowledge and methods that can support the FMCG sector in their transition to a CE. The main contributions per chapter are presented in Table 1.1

Table 1.1 Overview of the thesis chapters and main contributions.

Part	Objective	Study	Chapter		Contributions
Part I			*1*	*Introduction*	
	A	Industry review	*2*	*Fast-Moving Consumer Goods, linear business as usual*	
	B	Literature review	*3*	*Unusual business: going circular*	• A resource life cycle diagram, visualising closed-loop resource flows in the CE.
Part II	C	Study 1	*4*	*Outlining the role of consumers in closing loops*	• Four archetypical roles of consumers and four dimensions that characterise them. • A conceptualisation of gateways as entry points for resources into revalorisation systems.
	D	Study 2	*5*	*Using Product-Service Systems as plans to produce closed-loop resource flows*	• A framework of twenty-one PSS elements mapped against four subfunctions that PSS should satisfy to close loops. • Circular Design Guidelines, which provide guidance on embedding PSS elements to close loops.
Part III	E	Study 3	*6*	*Explaining the systems that produce resource flows*	• A conceptualisation of the resource flow-systems as the system that encompasses interconnected system elements spanning across the sociotechnical system. • A function tree and functional model based on Flow Functions, providing means to describe the physical movements and transformations of resources as functions. • A library of System Elements that enable resource flows of FMCGs. • A method called Flow-Causality Diagram to model a resource flow-system.
	F	Study 4	*7*	*Developing a tool to support the design of products and systems for the Circular Economy*	• A State Model of key moments in the resource flow (operative, obsolete, recoverable, suppliable, market-ready and on market) that can be used to visualise the resource flow through Snapshots. • A tool called the Flow Mapper to enable industrial users to model a resource flow-system and analyse the model.
			8	*Summary, discussion and conclusions*	• The early principles of flow-centred design.

2. Fast-Moving Consumer Goods, Linear Business as Usual

This chapter investigates what characterises the FMCG industry and aims to understand why the sector lacks circularity despite increasing efforts by the sector to reduce environmental impacts. Based on a review of the literature and observations in the sector, it conceptualises key characteristics of the products we call FMCGs, and the FMCG sector. Finally, the chapter includes a review of the common approaches observed in the sector and the concerns these raise for a transition to the CE.

2.1. Food, beverages and so much more

FMCGs are products known to be consumed rapidly and regularly. The way these products are designed exemplifies the take-make-dispose pattern (EMF, 2015), characteristic for a linear economy. A linear economy is problematic as it is wasteful, i.e., products inevitably end up becoming waste; and depleting, i.e., materials and embedded resources are often sourced from finite resources. Other sectors such as fashion and electronics are also known to follow the linear pattern. Although few FMCGs are reused or recycled, the best-case scenario for many of these resources is to head for landfills or incinerators (Zink and Geyer, 2018). Even the few FMCGs that do make their way into recycling rarely remain in a closed-loop flow and are more likely to cascade into other applications than to become new packaging (Geyer *et al.,* 2017; Williams *et al.,* 2018). Traditionally, FMCGs are designed for a linear economy as they aim for disposability and repeat purchases. This can be traced back even to the 1900s when businesses started to make strategic decisions about the lifetime of products to guarantee replacement purchases of cheaper and less durable products (Andrews, 2015; Agrawal *et al.,* 2016). In contrast to a linear economy, the Circular Economy (CE) strives to use resources constantly and efficiently, aiming to establish flows in which resources are continuously restored and regenerated (EMF, 2015; Stahel 1997). Rather than flowing linearly into waste, circular flows entail reusable products or recyclable materials that flow continuously. A CE is often proposed to address unsustainable production and consumption systems in the FMCG sector. The largest multinational FMCG companies are publicly sharing targets in CSR reports adopting CE principles (Nestlé, 2019; Procter & Gamble, 2018; Unilever, 2019). Nevertheless, the increasing amount of waste, poor household recycling rates and lack of radically different alternatives to disposable products, all indicate this transition is either challenging or executed poorly.

This chapter reviews FMCGs and the FMCG sector, based on literature and observations from the (changing) industry. Its aim is to understand the general challenges and shortcomings of current strategies to transition to a CE, emerging in the sector. The term ‘FMCGs’ is commonly used to refer to the largest multinational companies that manufacture products in specific categories or to the products in those categories. Nevertheless, the sector includes other

Figure 2.1 Blog post related to the #NoStraw movement to exemplify new basic necessities.

large manufacturers as well as an increasing number of smaller businesses. The term also refers to the consumer products that these businesses offer the market. FMCGs are described as goods that are 'bought more often, have a lower unit cost and have a much shorter service life than durable goods' (Charnley *et al.,* 2015), or, more bluntly, as products that are cheap, accessible and short-lived (Park, 2015). FMCGs are sometimes known as 'Consumer Packaged Goods' and many of these products seem indeed to involve goods that are packaged for consumers. Descriptions of FMCGs often include several product categories. Common categories include food, beverages, personal care and household cleaning products (e.g., EMF 2013; Greenpeace 2018; Lueb 2014; Park 2015; Stewart and Niero 2018). But it is not uncommon to add other categories such as tobacco (Lueb, 2014), fashion or textiles (Charnley *et al.,* 2015; EMF, 2013; Park, 2015), cups, plates and cutlery (Haffmans *et al.,* 2018), take-away food and utensils (Schlosser, 2012), home-improvement goods (Mishra *et al.,* 2018), over-the-counter medicine and medical disposables (Haffmans *et al.,* 2018), and even gadgets, electronics or gifts (Charnley *et al.,* 2015). Some descriptions add 'packaging' as a separate category (Park, 2015; Stewart and Niero, 2018). Many of the products do come packaged, but for some the packaging itself seems to have a smaller role in the product offering, e.g., razors, toothbrushes or sponges. Interestingly, products in FMCG categories are not exclusively labelled as FMCGs. For example, a beverage such as water is considered an FMCG when is in a bottle, but not when drunk from the tap.

Figure 2.2 Gillette advertisement for female shaving.

Despite these descriptions of common characteristics of FMCGs and its several categories, it appears there is no consensus on what makes a product an FMCG. Based on the product categories, it can be argued that packaging, the contents of packaging, as well as a whole product, may all be considered FMCGs. In addition, FMCGs can be offered both to businesses as well as to consumers. To understand the sector's lack of circularity, this review aims to understand what FMCGs have in common and define the sector's key characteristics. The chapter ends with a review of the main strategies to transition to a CE observed in the industry and why they may be insufficient to change FMCG business as usual.

2.2. Characterising FMCGs as products

To characterise products that are considered FMCGs, one can look at the meaning of the words. The words fast-moving imply there might also be 'slow-moving consumer goods', however, FMCGs are not part of a taxonomy of slow- and fast- moving consumer goods. Although consumer goods with longer lifetimes are sometimes described as slower-moving (Bakker, Den Hollander, *et al.,* 2014; Bocken and Short, 2016) the term is not used in the same way as FMCGs. Neither can it be stated that goods are either fast-moving or slow-moving, as more and more types of consumer goods are becoming available as fast-moving variants, such as fashion and electronics. Therefore, rather than focusing only on definitions of FMCGs used in the literature, this review includes a focus on understanding and explaining common characteristics of the products. This allowed to conceptualise three key characteristics: steady needs, temporary satisfaction, and convenient offering.

2.2.1. Steady needs

As FMCGs are consumer products, a key thing to question is: what consumer needs do FMCGs satisfy? It appears that the most common FMCGs can satisfy various types of consumer needs. First, FMCGs include products that satisfy human's basic needs i.e., the physiological needs including food, hygiene and clothing. Second, many luxury goods have, over time, transformed into necessities (Maycroft, 2009), for example, nappies or straws. Simply their existence has made it a thoughtless habit for the average human to desire and routinely rely on them. Such a thoroughly unexceptional and mundane experience is easily taken for granted (Schlosser, 2012) and can, thus, shock consumers if it is taken away from them. For example, the anticipated ban for plastic straws sparked commotion over straws and concerns about 'life without straws', see Figure 2.1. Third, throughout history manufacturers have been able to influence social norms and behaviour, which resulted in newly established and steady consumer needs for specific products. For example, in 1915 The Gillette Safety Razor Company launched "The Great Underarm Campaign" and advertised the first razors for women, see Figure 2.2 which is thought to have played a significant role in normalising body hair removal by women (Basow, 1991).

What is similar in all three types of needs is that they are constant. Neither of the needs will expire nor are they likely to disappear without radical lifestyle changes by the consumer. The needs that FMCGs satisfy, thus, can considered to be steady. That said, key differences can be observed in the way that FMCGs satisfy steady needs. FMCGs can have different (perceived) value, yet satisfy the same stady need, see Figure 2.3. At the very minimum, FMCGs are staple items that exist as a commodity due to a homogenised value (Kopytoff, 1986). Commodities typically lack perceivable value and their purchases are driven by price or availability (McDonald *et al.,* 2001). To add value, companies differentiate their goods through branding, increased quality or other benefits such as hygiene or safety (McDonald *et al.,* 2001; Murphy

Figure 2.3 Examples of different values of the same type of FMCGs. From left to right: commodity deodorant (Boots), differentiated deodorant (Lush), premium deodorant (Axe), positional deodorant (Native i.e., customised scent and name on the packaging).

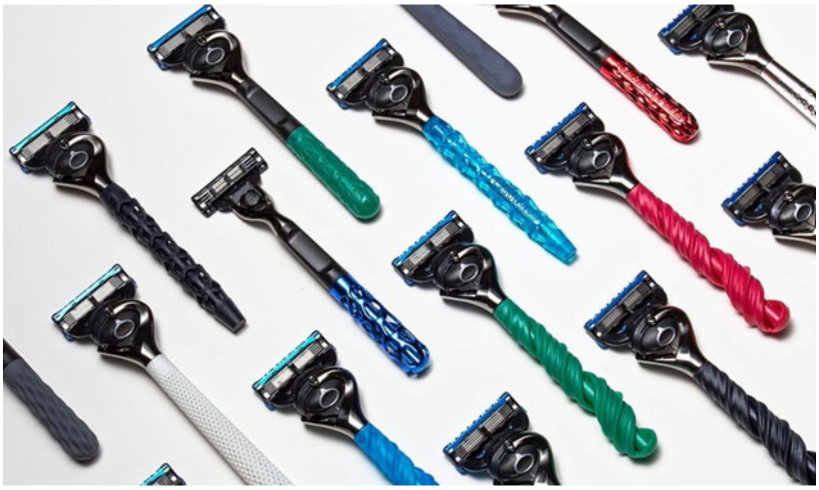


Figure 2.4 'Razor Maker' campaign by P&G (2019). Consumers can customise handles that are manufactured using additive manufacturing technologies.

and Enis, 1986). This strategy is especially useful to gain a competitive advantage in markets of low-differentiated goods (Magnier and Schoormans, 2017). Some differentiated goods can achieve a premium status i.e., conveying an impression of exclusiveness, excellence and luxury (Mugge *et al.,* 2014). The maximum value appears to come from premium brands that offer customised versions of their products, see Figure 2.4 and Figure 2.5. In this case, consumers may experience an exclusiveness over their product, suggesting that FMCGs can even become positional goods (Spangenberg, 2013).

2.2.2. Temporary satisfaction

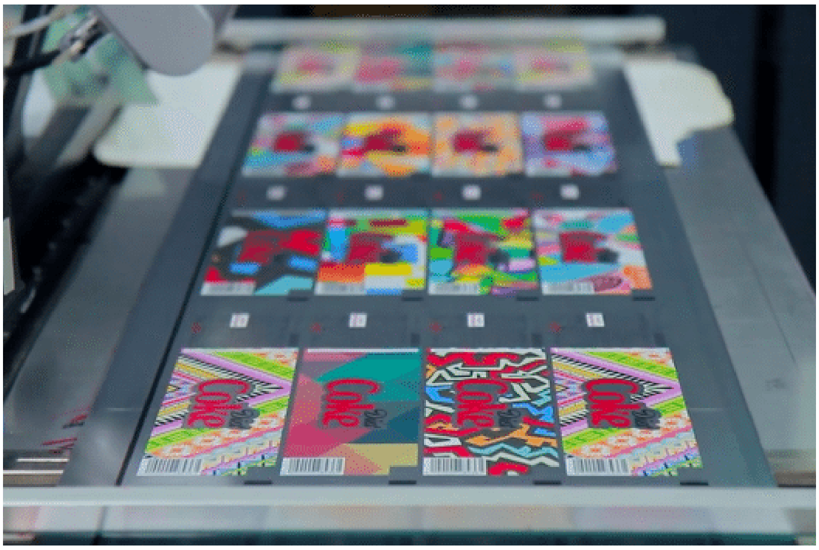


Figure 2.5 "Millions Of One Of a Kind Bottles" campaign by Coca Cola (2014). An algorithm to auto-generated millions of unique designs and aimed to make consumers feel extraordinary.

The FMCGs that consumer buy to satisfy their steady needs often have short lifespans, usually determined by the availability of a consumable component (De los Rios and Charnley, 2017). It is common to categorise consumer goods on durability, based on their estimated lifespan (Murakami *et al.,* 2010; OECD, 1993; United Nations, 2018a). However, all FMCGs are usually categorised as 'nondurable', i.e., products that are used up in less than a year. In reality, the lifespans of FMCGs are much shorter and varied depending on the product, e.g., minutes, hours, days or months. For example, many categories of FMCGs contain fresh produce that may expire which limits their shelf-life. Some products have a longer shelf-life, but the expiry process starts as soon the product is taken into use, e.g., after the packaging is opened or from the moment the product is used for the first time. The shortest lifespans are 'single use' i.e., intended to be only used once before they are thrown away (United Nations, 2018b). Whatever remains after the depletion of the consumable component, e.g., residues or packaging, is typically considered disposable (Kuzmina *et al.,* 2019). After disposal, consumer happily repurchases the product to obtain the same experience (Papanek, 1985). Therefore, due to their short lifespans, FMCGs deliver only a temporary satisfaction.

This triggers constant replacement purchases. The strategy was implemented as early as in the 1900s when some of the first FMCG businesses were founded. At that point in time, an international cartel agreed on a lifetime of 1500 hours for lightbulbs (Andrews, 2015) and DuPont designed stockings in a format prone to laddering (Agrawal *et al.,* 2016). Earlier designs of these products were longer-lasting but did not deliver continuous revenues. Which is why product use cycles were shortened through design, such as the use of inferior materials to impact durability and reliability of components (Maycroft, 2009). This practice is now described as ‘planned obsolescence’, a term with a negative connotation. Planned obsolescence, when used in business strategy, suggests that the goods that consumers constantly need, are designed to become obsolete rapidly (Andrews, 2015). Another form of planned obsolescence is when the resource itself remains intact, but due to ‘built-in obsolescence’ manufacturers anticipate that consumers will get tired of them (Papanek, 1985). This strategy is, for example, increasingly noticed in the fashion sector.

A temporary yet satisfying experience, guarantees a continuous consumer demand. This model encouraged the exploitation of the take-make-dispose pattern (EMF, 2015) that extended beyond perishable goods that have a naturally short lifespan. In the early 1900s, for example, an international cartel agreed on an industry standard of 1500 functional hours for lightbulbs (Andrews, 2015) and DuPont started using Nylon for stockings in a format prone to laddering (Agrawal *et al.,* 2016). These and other seemingly intentional strategies to produce products of inferior quality and reduced durability were soon adopted by several consumer goods sectors (Bhardwaj and Fairhurst, 2010; Thain and Bradley, 2014). Concerns were raised when it became apparent that the adoption of cheaper disposable goods by the public establishes a ‘throwaway society’ (Cooper, 2005), which amplifies the negative effects of a linear economy (Packard, 1960; Papanek, 1985).

2.2.3. Convenient offering

As they are part of our everyday life, FMCGs are typically extremely accessible to consumers making it relatively convenient to purchase them. In services, convenience is regarded as consumers’ perception of time and effort investment related to buying or using a service’ (Berry *et al.,* 2002, p. 4). Convenience is considered a strong force behind the success of many consumer goods (Bakker, Den Hollander, *et al.,* 2014). In marketing terms, a ‘convenience good’ is one on which consumers spend little effort to acquire, perceive a low risk in choosing them and deliver a prompt satisfaction (Copeland, 1923; Murphy and Enis, 1986). Convenience increases the value of the product offering. Water, for example, tastes always the same, but when bottled it is convenient and has economic potential (Butler and Tischler, 2015). FMCGs seem to strongly rely on offering convenience, firstly, by reducing the difficulty to consume and maintain products, e.g., food and drinks that are already prepared and portioned; and secondly, by providing reliability in the availability and value delivery of products, e.g., common brands can be found in any average supermarkets. Price usually goes up as effort decreases, i.e., consumers pay for convenience (Thain and Bradley, 2014; Womack and Jones, 2005). This statement contrasts notion commonly used in FMCG definitions i.e., that FMCGs are by definition inexpensive (e.g., Charnley *et al.,* 2015; Park, 2015). Not all consumers may be willing to pay for (more) convenience, (Lofthouse and Prendeville, 2018), but some might even be willing to pay more, such as for a reduced logistical burden through delivery and subscription services (Womack and Jones, 2005).

2.3. Characterising FMCGs as an industry

The FMCG sector refers to the economic activities that relate to the manufacturing of the products we call FMCGs. With around USD 12 trillion in annual sales, the FMCG industry is a dominant sector in the global economy (EMF, 2013). A total of 18 of the multinational FMCG manufacturers (OC&C Strategy Consultants, 2019) emerge in Fortune 500 (2019), see Figure 2.6. In addition to the multinationals, the sector includes manufacturers that operate on a national level, as well as an increasing number of emerging businesses that operate more regionally. Rather than investigating a single manufacturer or emerging businesses, the focus of this part of the review is understanding and explaining common characteristics of the sector. This allowed to conceptualise its key characteristics: volume-driven; materialistic throughput; and minimised responsibility.

2.3.1. Volume-driven

Satisfying steady consumer needs temporarily is a successful strategy to establish and foster a high demand. The FMCG sector is well-known for its mass volumes (EMF, 2013). The largest multinationals publicly take pride for daily reaching billions of people with their products (Procter & Gamble, 2018; Unilever, 2019). Such mass volumes are secured, firstly, because the products satisfy steady needs that are typically mundane and universal, therefore, allow businesses to identify markets globally. Secondly, by designing products that are as generic as possible but accepted by the largest possible market (Braungart and McDonough, 2008). Thirdly, centralising production because of globalisation has allowed to combine volumes for different markets and reduce costs (McDonald *et al.,* 2001; Stahel, 1994). Finally, lean manufacturing practices are increasingly adopted by the FMCG industry and allow to significantly optimise manufacturing processes to quickly adapt to consumer needs (Thevenot and Simpson, 2009) and inexpensively deliver large volumes (Ugarte *et al.,* 2016). Because they satisfy universal needs and can reach the global population, the rate at which FMCGs generate waste is correlated with the increase of population and income (McKinsey & Company, 2010).

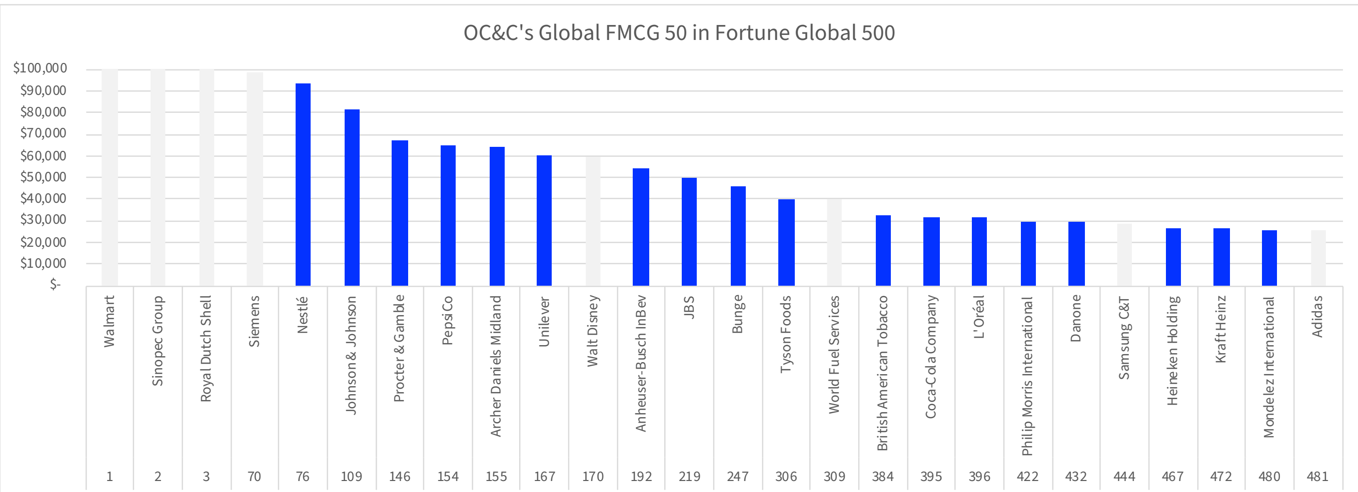


Figure 2.6 A total of 18 multinational FMCG manufacturers are part of Forbes Global 500.

2.3.2. Materialistic throughput

Figure 2.7 Citizens of Kamikatsu sort 45 different types of materials into 34 categories aiming to achieve a zero waste community. Kamikatsu is a remote Japanese mountain village with a population of roughly 1500, (image courtesy: nippon.com)

Although many consumer needs could be satisfied without the need of owning products, consumer goods are traditionally bought and owned by single consumers. This is also true for FMCGs, which are also disposed quickly after ownership since the satisfaction they give consumers is temporarily. New business models are emerging in the sector to reduce the waste created by FMCGs and manage the materialistic throughput by reusing products or components. Nevertheless, the majority of FMCGs still only follow a single-use linear approach and quickly become waste. On a global average, a person generates 0.74 kilogram of municipal solid waste per capita per day. On a national level this number ranges from 0.11 to 4.54 kilograms per capita per day, with the wealthiest nations being at the highest end of this range (World Bank Group, 2018). Estimates indicate that the FMCG sector is responsible for the vast majority (75%) of municipal solid waste (EMF, 2013). Roughly 40% (146 Mt in 2015) of global plastic production is used for the packaging sector (Geyer *et al*, 2017). In Europe, only a disappointingly 30% of all plastics are collected for recycling (European Commission, 2018b). Recycling rates for other common materials used for packaging are not as bad, but can certainly be improved. For example, the recovery of other packaging materials in the UK aluminium 52%; steel 77.3%; paper 79%, glass 67% (DEFRA, 2020).

The poor recovery rates of FMCGs can be linked to several waste management challenges. There are only very few examples of extremely successful recycling practices, such as in Figure 2.7. In most contexts, however, engagement in recycling by consumers is often poor (Steg and Vlek, 2008). As a result, collection rates are often low despite the existence and operational performance of the waste collection infrastructure (Jambeck *et al.,* 2015), especially in wealthier nations (Dahlén, 2008; World Bank Group, 2018). If the materials do get collected, the waste typically goes to a Material Recovery Facility (MRF). The technology in MRFs to identify and sort materials is constraint by measurable material properties and the physical geometry of products (Rahimi and García, 2017). The measured properties, however, can be erroneous if the volume or individual products contain contaminants. Initial sorting and cleaning of packaging, therefore, is required of consumers to ensure the recyclables will not be rejected by the technology (Ali and Courtenay, 2014). Materials can also be rejected if the design of a product does not allow correct identification, which can happen, for example, with sleeved packaging. The last step in waste management is the recovery of sorted waste materials into new suppliable material resources. Most materials commonly used for FMCGs can technically be recovered, but the processes are not without compromises and consequences. Paper, for example, degrades because the cellulose fibres shorten in each cycle (Ali and Courtenay, 2014); plastics' qualities deteriorate in each cycle (Rahimi and García, 2017); and glass cullet is contaminated by colour variations (Butler and Hooper, 2005). Metallic bonding is not affected by melting, which is why materials such as aluminium and steel can be recycled infinitely (Detzel and Mönckert, 2009), although the compromise here is the significant energy requirement (Allwood, 2012). On top of these challenges, the current material recovery practices for materials such as plastics are rarely cost-effective (Ali and Courtenay, 2014; Rahimi and García, 2017), which is why governments resort to exporting waste and alternative waste management practices (Geyer *et al*l, 2017; Zink and Geyer, 2018). Landfill and incineration remain one of the most mainstream practices for waste management today.

2.3.3. Minimal responsibility

Despite being obviously wasteful, the manufacturers of FMCGs appear to take minimal responsibility for these negative consequences. The largest multinational FMCG manufacturers all publish a Corporate Social Responsibility (CSR) report. CSR emerged as companies were urged by governments and consumers to claim responsibilities addressing societal difficulties (Pinkston and Carroll, 1996). It is important to note that CSR is not equal to Extended Producer Responsibility (EPR), which is a policy approach to allocate the responsibility for negative environmental impacts caused by manufacturers (Lewis and Gertsakis, 2009). Instead, CSR reports present the ambitions and targets of companies to deliver on environmental and social fronts, but the implementation and regulation of CSR rely primarily on the company's own resources (Sheehy, 2014). Therefore, some argue that CSR has a greater role in role in eliminating stakeholders' scepticism, than delivering against sustainable targets (Mahrinasari, 2019; Middlemiss, 2003).

By comparing CSR reports from the four of the largest multinationals, see Table 2.1, it becomes clear that the sector has an interest in the CE. This is evident by their shared targets that relate to the reduction of material use, uptake of recycled materials, as well as improving recyclability and collection of their products. It is worth noting that plastics are the only materials that are explicitly and elaborately mentioned in the reports. A broader review of CSR reporting in the consumer goods sector, showed that the systemic dimensions of circularity (e.g., consumer engagement, material quality or business models) are poorly represented (Stewart and Niero, 2018). Instead, targets in CSR reporting are often strategically set to anticipate emerging legislation (Koppius *et al.,* 2014). Environmental targets can lead to cost savings (Kraaijenhagen *et al.,* 2016), competitive advantages through differentiation (Lindgreen and Swaen, 2010), and build reputation to address pressure from the media (Pinkston and Carroll, 1996). CSR reporting, thus, is more likely used by FMCG multinationals as a strategic communication tool for brand equity (Mahrinasari, 2019; Middlemiss, 2003) or even as a camouflage to continue business as usual (Murray *et al.,* 2017). Instead, legislation is believed to be a more effective strategy to engage industry into the transition to a CE (Murray *et al.,* 2017; Yuan *et al.,* 2006). Although legislation for the industry is emerging (e.g., European Commission, 2018; United Nations, 2016), without enforcing legislation we continue to rely on the integrity of multinationals to act upon their own targets (Laufer, 2003).

2.4. Changing business as usual

Although 'satisfying steady needs, temporarily and conveniently' does not form an immediate environmental threat, the consequences can be disastrous when combined with an industry that is volume-driven, has a materialistic throughput and takes minimal responsibility. Apparent from their CSR reporting, the sector is well-aware of the concerns and consequences of their usual business. The pressure on FMCG manufactures to change is increasing due to

Table 2.1 Comparison of recent CSR reports and commitments by four leading FMCG companies.

		Company	**Commitment**		**Approach**
Materials	Reduce amount of material used	Pepsico	• Reduce 35% of virgin plastic use across our beverage portfolio	2025	• Increase use of recycled and alternative materials
		P&G	• Reduce our use of virgin petroleum plastic in packaging by 50%	2030	• Light weighting • Increase use of recycled and alternative materials • Reduce pack size (more concentrated forms)
		Unilever	• Reduce our virgin plastic packaging by 50% with one third coming from an absolute plastic reduction	2025	• Increase use of recycled and alternative materials • Reduce pack size (more concentrated forms) • Invest in and partner on reusable packaging and systems
	Increase the use of recycled material	Pepsico	• Increase recycled content in our plastics packaging to 25%	2025	• Partnerships • Improved recycling infrastructure
		Unilever	• Increase the recycled plastic material content in our packing to 25%	2025	
Intercepting materials	Improve recyclability of products	Nestlé	• Make 100% of our packaging recyclable or reusable	2025	• Design and materials selection
		Pepsico	• Design 100% of packaging to be recyclable, compostable or biodegradable	2025	
		P&G	• Achieve 100% recyclable or reusable packaging by 2030	2030	• Design and materials selection. • Advance technology for difficult to recycle items
		Unilever	• Design all our plastic packaging to be fully reusable, recyclable or compostable	2025	
	Improve the collection of products	Nestlé		2025	• Partner to establish or improve waste collection in areas with poor infrastructure • Encourage consumers in conventional recycling
		Pepsico	• Invest to increase recycling rates in key markets	2025	• Encourage consumers in conventional recycling • Partner to establish or improve waste collection in areas with poor infrastructure
		P&G	• Achieve 100% recyclable or reusable packaging	2030	• Partner to establish or improve waste collection in areas with poor infrastructure. • Reuse systems for difficult to recycle items.
		Unilever	• Help collect and process more plastic packaging than we sell	2025	• Increase use of recycled materials • Pay for collection of packaging • Partner to establish or improve waste collection in areas with poor infrastructure • Encourage consumers in conventional recycling
	Introduce reusable packaging	Nestlé	• Make 100% of our packaging recyclable or reusable	2025	• Invest in and partner on reusable packaging and systems
		P&G	• Achieve 100% recyclable or reusable packaging by 2030	2030	• Invest in and partner on reusable packaging and systems
		Unilever	• Design all our plastic packaging to be fully reusable, recyclable or compostable	2025	

legislation (United Nations, 2016). Further, what used to be distant environmental issues, are slowly becoming more direct threats to the linear business as usual. The CE is proposed to move away from this model, by using resources more efficiently such as in closed loops which could deliver both environmental as well as commercial benefits (EMF, 2015). Looking at CSR reporting and emerging businesses, it seems that the FMCG sector has an appetite for the CE. Observing the sector and reviewing the literature, it seems that changes led by industry to adopt a CE aim for a more sustainable practice. However, reviewing the common approaches suggested three main concerns which imply that that the changes businesses are making are not systemic and are unlikely to be sufficient for a transition to a CE.

2.4.1. A risky contingency plan

The FMCG sector is a dominant user of finite petrochemicals. Although the amount of crude oil used for plastics is relatively small today (Stein, 2002), it is predicted this demand will grow more rapidly than the demand for oil, in which case the demand for plastics will maintain the oil industry (EMF, 2016). In addition, to extract and manufacture plastics the sector consumes significant amounts of energy, which are predominantly also dependent on finite resources (Allwood, 2014; EMF, 2016). To make things worse, the sector mostly consumes virgin materials, which require significantly more energy to extract than recycled materials need to recover (Hopewell *et al.,* 2009).

A strong dependency on finite resources risks business contingency of the FMCG sector. First, the current strategy depletes the matter that is critical to the success of the practice. Maintaining business in this way will inevitably affect the future availability of the resources it requires succeeding. Second, the increasing scarcity of material resources makes the prices of these resources increasingly volatile (EMF, 2013; McKinsey Global Institue, 2011). Volatility of prices poses great uncertainty on the costs required to continue business.

2.4.1.1. Reducing volumes of finite resources

The most common approach by FMCG manufacturers to reduce the dependency on finite resource is to slim down the volumes. Firstly, by using less energy, which is typically reported in CSR reports in the form of (achieved) targets to cut the energy consumption in factories (Stewart and Niero, 2018). Second, by using fewer material resources. Material losses are reduced in production e.g., through lean manufacturing processes (Womack *et al*, 1992), as well as in product design by making products smaller, thinner and lighter by eliminating material (Boons and Howard-Grenville, 2009).

Reducing resources can reduce environmental impacts significantly (Allwood, 2014). Purchasing less materials, also has an immediate cost-benefit (Taylor, 2017), which may make it simply the lowest-hanging fruit for the sector. However, there are limitations to these approaches, because material weight reduction can conflict with other business objectives such as optimised production or reduced labour costs (Allwood, 2014). Further, although this approach is impactful, depending on fewer finite resources is not a long-term solution as this approach still requires a significant amount of material resources which will become waste (Braungart and McDonough, 2008; EMF, 2015; Moreno *et al.* 2016).

2.4.1.2. Shifting to more reliable resources

Manufacturers are increasingly exploring venues to substitute finite resources with alternatives, both for energy as well as for material resources (Muranko *et al.,* 2021; Park, 2015). Material substitution involves, in the first place, changing from plastics to other conventional materials in the sector. For example, the use of paper-based or metal materials. In the second place, manufacturers are exploring routes to change from petrochemical polymers to bio-derived alternatives. There is on-going research and development in the field of bio-based polymers (EMF, 2016; Lyons *et al.,* 2012; Rabnawaz *et al.,* 2017) but many of these technological advances are in infant stages and not commercially proven. In addition, there is uncertainty on the availability of renewable feedstock to substitute the petrochemical demand (EMF, 2016; Lambert and Wagner, 2017). Until these issues are solved or there is a serious legislative consequence or economic disadvantage to using crude oil plastics, industry will continue to source plastics from crude oil feedstocks (Allwood, 2014).

What is often overlooked with these approaches, however, is that they only solve part of the problem. None of the conventional materials are impact free, but unconventional materials can still have negative impacts which are just caused differently than those of conventional materials (Lewis *et al.,*2010). Introducing alternative materials in to embody conventional products also has implications for waste management. Bioplastics mixed with petrochemical plastics can contaminate conventional waste streams (Ali and Courtenay, 2014) and biodegradable materials do not typically biodegrade without anearobic digestion (Lambert and Wagner, 2017). On top of that, anaerobic digestion may not be best suited for biodegradable materials (Ali and Courtenay, 2014; Lambert and Wagner, 2017) and there is generally limited collection of compostable waste. Therefore, without systemic consideration of the introduction of new materials, material substitution mostly implies a substitution of the content of the linear flow, rather than an improvement to the flow itself.

2.4.2. Lost resources mean lost business

It is estimated that almost a third of the plastics used for packaging leak into the environment (EMF, 2016). The main causes are littering or leakage out of waste infrastructure due to lack of capacity or engagement (Jambeck *et al.,* 2015). Once out in nature, many plastics are taken by water streams (Geyer *et al.,* 2017) and they eventually accumulate in large quantities in the oceans (EMF, 2016). This is a severe environmental concern, because materials such as plastics can harm our ecosystems and wildlife, and, as recent studies show, even human health (Ragusa *et al.,* 2021).

Plastics are typically durable, which is why they remain visible in nature (Stein, 2002). This has caught the attention of consumers and has given plastic a poor reputation (Curtin, 2016; Fearnley-Whittingstall and Rani, 2019). This is reflected in the attitude of consumers who pressure manufacturers to invest in better waste management and alternative solutions, see Figure 2.8. On top of that, consumers today seem more willing to pay a premium for sustainability (Steg and Vlek, 2008). Emerging businesses in the sector are introducing reusable FMCGs (Muranko, *et al.,* 2021) which poses a risk for traditional manufacturers to lose customers looking for more sustainable solutions. Besides reputation, losing materials in waste suggests a significant loss of value. In the FMCG sector only 20% of the total material value (estimated at 3.2 trillion USD) is currently recovered (EMF, 2013). Further, the total natural capital cost of

Figure 2.8 An online activism group encouraged the public to ship empty crisp packaging back to manufacturers.

plastics in the consumer goods industry are estimated at USD 75 billion, of which USD 40 billion was related to plastic packaging (EMF, 2016; UNEP, 2014). Considering the volatility and scarcity of resources, it seems evident that such losses are simply unaffordable for the FMCG sector.

2.4.2.1. Building a sustainable image

In response to leakage of plastics, the FMCG sector has recently taken an interest in so-called 'ocean plastics', e.g., see Figure 2.9. Ocean plastics have become an appreciated material, to the extent that it is plausible to assume consumers are willing to pay more for plastics from the ocean than for recycled plastics in (Magnier *et al.,* 2019). The use of these materials by familiar brands plays is imperative to raising awareness for global waste issues. However, the use of 'sustainable materials' seems to have an equally vital role in brand reputation (Bahrudin, 2019). Indeed, it is fantastic that it is now technically feasible to clean up the ocean, but these operations are costly financially and environmentally (EMF, 2016). Materials such as ocean plastics are, thus, unlikely to be able to compete with conventional materials used by the sector and ocean plastics are most likely to remain exclusively for premium FMCGs.

Although the use of sustainable materials is important for awareness and to improve brand reputation, neither of these seem a structural solution to address linear flows of resources. A demand for ocean plastics can be used to fund clean-up operations, but it is undesired to establish a continuous demand for plastics extracted from the ocean. Sourcing ocean plastics, thus, appears a treatment of the linear economy's symptoms, rather than an approach to address the root causes of material losses. In fact, it could be perceived as a strategy to distract the attention from a company's contribution to negative impact (Laufer, 2003), also known as greenwashing.

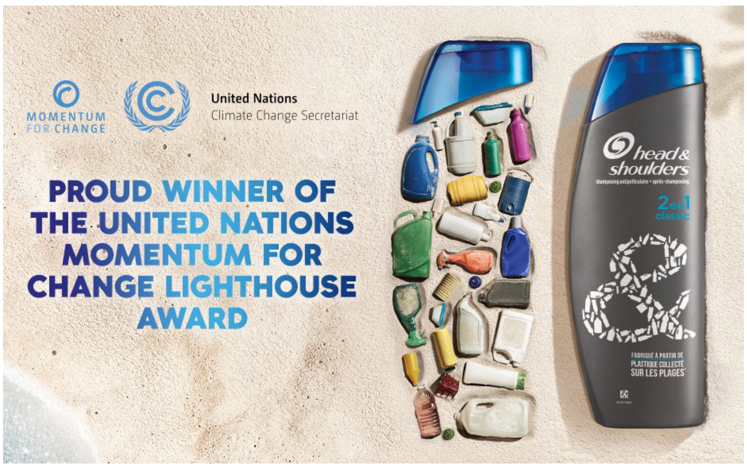


Figure 2.9 Ocean plastics embodying P&G's Head & Shoulders shampoo bottle.

2.4.2.2. Retaining resource value

The FMCG sector is proactively exploring routes to regain or retain control over their resources. On the one hand, a record number of custom recycling services are available today. Many these schemes are partnerships with Terracycle, a company aiming to eliminate waste through activities such as facilitating the recycling of hard-to-recycle waste (Terracycle, 2020). Smaller, independent companies have also emerged that see value in the collection and recovery of specific materials, for example, see Figure 2.10. Multinationals are also investing in citizen resource collection in countries where infrastructure is poor (Mr Green Africa, 2020), potentially getting closer to the untapped value of currently lost resources. On the other hand, the sector slowly sees an increase in the number of reusable FMCGs. In contrast to former suggestions that packaging could have a long life in cascaded applications (Shipton and Fisher, 2010), reuse of packaging for the same purpose seems a longer-term strategy to retain and, importantly, benefit from resource value (EMF, 2019c). Multinationals are following this trend and Terracycle's Loop appears to, again, have a crucial role in engaging the largest producers of FMCGs (Terracycle, 2020).

Figure 2.10 Example of Gumdrop's recycling of chewing gum.

These recycle and reuse schemes are rather exciting and perhaps the most systemic changes that can be observed in the sector. Not surprisingly, they also appear to be the most complex and the face several challenges. For example, Terracycle's materials are typically cascaded into urban furniture rather than used to substitute the demand for virgin material. This is alarming, because a recycling promise can cause a rebound effect and boost the consumption of FMCGs (Catlin and Wang, 2012). The effectiveness of promised recycling services, thus, is even more because it is likely to increase consumption volumes. Offering these services implies that the business is interested in recycling, which is concerning if poor engagement in recycling by consumers holds. Reuse systems are promising, although there the emerging businesses typically operate locally and there is little evidence for their success on scale. Consumer engagement, thus, appears also fundamental for the success of reuse services. For example, consumers do not want to feel locked-in to refill systems (Lofthouse *et al.,* 2009), perhaps this conflicts too much with FMCGs' characteristic of convenience. Thus, successfully retaining resource value in recycling or reuse, seems to require behaviour change of the masses.

2.4.3. Supply of recovered resources do not satisfy industry demand

Even though the recovery rates for some commonly used materials, such as aluminium, are promising (DEFRA, 2020), none of the materials conventionally used by the sector are used continuously in a closed-loop flow. This puts a strain on the environment because a shortage of recovered resources sustains a demand for virgin resources (Zink and Geyer, 2017). The lack of demand for recovered resources seems to have resulted in a lucrative business of exporting them to other countries. A total of 30% of plastics collected for recycling left the EU to be treated in third countries (European Commission, 2018b). Third countries apply different environmental values, typically with lower standards than the wealthier countries that are exporting the waste. This strategy was disrupted when China closed their borders to the import of recycled plastics in 2018, however, it seems to persist through illegal exports to countries incentivised by financial gains for accepting waste imports (Brooks *et al.,* 2018). Many of such countries have open waste sites, allowing the material to leak into nature and harm wildlife (Jambeck *et al.,* 2015) and thus further impacting the environment negatively.

Interest in recovered resources by the FMCG sector is slowly increasing, but their uptake remains low in comparison to virgin materials. There appears a vicious cycle where the supply of recovered resources may be available but does not meet the high standards of industry's demand for quantity and quality. As a result, the volume of plastics that makes it back into the sector is almost negligible (EMF, 2016). This is partly due to the volume that can be recovered, and only two types of polymers, PET and HDPE, are available in sufficient quantities (Rahimi and García, 2017). Quantities of other polymers are likely to remain insufficient if the demand for these materials is low, which in turn discourages investments in their recovery (Pringle *et al.,* 2016; Unilever, 2019). The lack of investments, then, affects quality because there is a lack of technology and capacity to recover resources to virgin like state (Rahimi and García, 2017). Further, recycled materials are often more expensive than virgin equivalents (Zink and Geyer, 2017). To address this, the FMCG sector makes efforts to improve both the quality and the quantity of recyclable resources.

2.4.3.1. Improving the quality of recovered resources

The FMCG sector can no longer ignore their direct influence on the poor quality of recycled resources, as many quality compromises find their roots in design. Manufacturers are addressing this, firstly, by redesigning products for recycling (WRAP, 2019a). FMCGs are traditionally designed to perform well in production, transport and use. For example, production is sped up using dual-injection moulding; transport is optimised by extending shelf-life using multi-layer materials; and user experience is boosted through contrasting materials. Although these deliver advanced product assembly, recycling requires clean and easily separable materials (Rousta and Dahlén, 2015). Several guidelines have recently emerged, urging and enabling manufacturers to improve the recyclability of their products (British Plastics Federation (BPF), 2018; RECOUP, 2019; WRAP, 2019a, 2019b). Secondly, manufacturers are investing in the sorting and recovery of resources. To overcome sorting limitations while retaining variety in materials and geometry, manufacturers are now exploring new technologies, such as invisible digital and chemical tags that can be read and used for sorting (EMF, 2019b). To achieve purity of materials and overcome degradation limitations of plastics, the sector also encourages the development of chemical recycling technology. Chemical recycling is a promising technology to recover plastics to a virgin like state and, once commercially successful, could decouple the prices of plastics from oil (Rahimi and García, 2017).

New strategies to product design and investments in advanced recycling technologies have emerged as solutions that appear to aim for minimal changes to the supply chain. The energy consumed and greenhouse gasses emitted by recycling should not be underestimated (Allwood, 2014). In fact, one of the reasons that chemical recycling is not implemented on industrial scale today is because it requires sizable energy inputs, which is costly (Rahimi and García, 2017). Instead, different types of technological developments might be more interesting. Technology to trace resources (EMF, 2019b), for example, is promising for a CE as it allows to generate data on the actual flows of resources. If this technology becomes feasible on the scale of municipal waste collection, it would also have potential to optimise the logistics of reuse models. Nevertheless, to scale this to a global scale and operate it within todays centralised supply chains poses a great logistical challenge.

2.4.3.2. Increasing the quantity of recovered resources

In certain markets it is or will be mandated to have a minimum recycled content of certain materials, e.g., by 2025 at least 25% of the PET in beverage bottles (European Union, 2019). Retailers can also push for recycled content, for example, the 'Green Dot' programme is widely adopted by German retailers and informs consumers of the recycled content and recyclability of those items (Fishbein, 1996). Only few multinationals, however, emphasise their intent to increase the percentage of recycled content in CSR reports, see Table 2.1. A plausible explanation is that recycled plastics can have a negative connotation for consumers (Baxter *et al.,* 2015). Several campaigns in the sector seem to focus on reviving the image of plastics and of recycled plastics, see Figure 2.12. Several targets in the CSR reports imply improvements to waste management infrastructure, see Table 2.1. The sector's confidence in recycling is also evident from partnerships, such as the Alliance to End Plastic Waste, which allies manufacturers with leading manufacturers of plastics and the oil industry (e.g., ExxonMobil, Dow, Henkel, Shell, Suez, Veolia) (Alliance to End Plastic Waste, 2019; Procter & Gamble, 2019).

Despite the increased investments in recycling, however, collection rates of recyclable materials have not seen much increase (DEFRA, 2020). The lack of consumer engagement, especially in wealthy and heavily consuming nations (World Bank Group, 2018), is concerning. There are several reasons why consumers may not engage in recycling (Steg and Vlek, 2008). One of the most mentioned is the lack of information for consumers (Welink, 2019). This problem exists, even though informing consumers on disposal and recycling through labels is often mandatory by law (European Union, 2019). Only few manufacturers take further initiative and use messaging to incentivise consumers to recycle, see Figure 2.13. Although recycling seems a solution that can be effective and is immediately available, seeing recycling as the best and a long-term solution will continue dependency on energy-resources, and sustains a demand for virgin resources (Allwood, 2014; Zink and Geyer, 2017).

Figure 2.11 Ribena provides instructions to remove the sleeving of this packaging.

Figure 2.12 Ecover campaign promoting the recyclable content of plastics in their packaging.

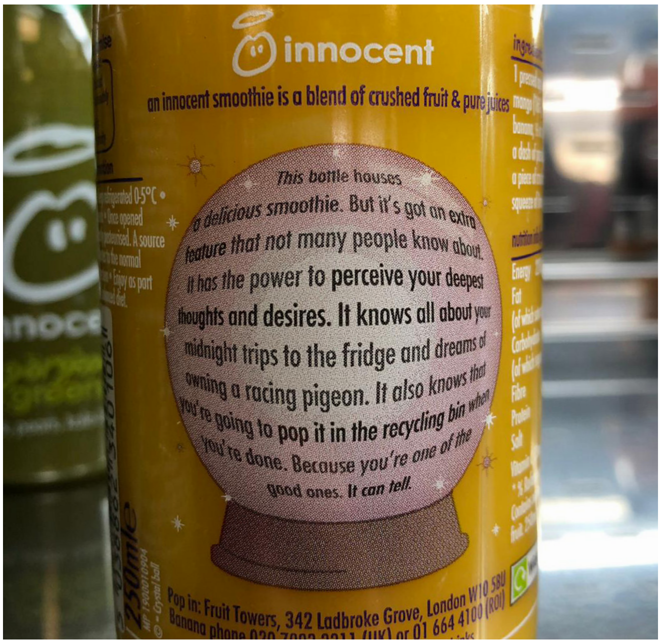


Figure 2.12 Ecover campaign promoting the recyclable content of plastics in their packaging.

2.5. Conclusions

FMCGs address consumers' steady needs by delivering temporary satisfaction through a convenient offering. This is concerning because the FMCG industry is volume-driven, has a materialistic throughput and takes minimal responsibility. The industry recognises its role in these problems and has shared public intentions to address the unsustainability of linear resource flows. However, the approaches mostly still imply linear flows, but with smaller volumes of resources or using different materials than plastics. More systemic suggestions, such as reuse and custom recycling schemes, are mentioned but there is little evidence for their successful uptake.

3. Unusual Business: Going Circular

This chapter presents a review of the literature on the CE, aimed at understanding implications for the design of systems that close resource loops. The review first presents the CE's core principles, main drivers and concerns, and continues to explore the role of design as a catalyst for a transition to a CE. The section concludes with three topics that appear to be overlooked in the literature and are addressed by this thesis.

3.1. The CE as a coalition of strategies

The term Circular Economy (CE) has become a buzzword in the last decade or so. But what is meant by a CE? There are many definitions of a CE (Henry *et al.,* 2021), and the concept has different meanings to various stakeholders (Kirchherr *et al.,* 2017). Despite its popularity, the adoption of the CE in practice appears to be slow. 'Design' may be a catalyst for improving the success and uptake of the CE (Ellen MacArthur Foundation, 2017a; Moreno *et al.,* 2016). This chapter reviews the CE and related design literature to understand how design can be used to close the loops of resource flows and support the transition to a CE. Despite the different definitions, all explanations of the CE appear to focus on its potential to benefit the environment in conjunction with the economy (Ghisellini *et al.,* 2016). These two strategies are reviewed separately to understand their different objectives.

3.1.1. The environmental strategy

The CE is proposed as a strategy to address environmental issues. The CE can be seen as an umbrella concept that groups a range of waste and resource management strategies (Blomsma and Brennan, 2017), resulting in a more efficient use of resources. The concept builds on three main principles: keeping products and materials in use, designing out waste and pollution and regenerating natural systems (EMF, 2019a). These principles can be translated into three goals that describe different ways of directing the flow of resources to deliver the environmental strategy.

Closing loops of resources

The first goal, and seemingly the most dominant in the theoretical concept, is to create circular or closed-loop flows of resources (Murray *et al.,* 2017). Although the CE addresses the need to balance all type of resources, circular flows in the literature often refer to tangible matter, such as products, construction or other artefacts, as well as the materials that embody them. Similar to the concept of reverse flows in closed-loop manufacturing, the intent is to have these resources flow back into economic systems (Prendeville *et al.,* 2014). The concept builds on previous theories and inspiration from nature that propose that 'waste equals food' (Braungart and McDonough, 2008), suggesting that any resource can and should become a nutrient for the next cycle. This perspective assumes that resources are, in fact, stocks and have a certain defined quantity that exists, moves and remains within the boundaries of a system (Meadows, 2008). In practice, this implies that the resources in a system can take different forms, such as products, components or materials (Blomsma and Tennant, 2020). Having them flow in a closed loop is feasible, either by retaining the entropy through the reuse and life extension of components and products or by transforming resources from one state to another through the recovery of materials, such as atom and molecule recycling (Blomsma and Tennant, 2020; Stahel, 2019).

The CE concept typically distinguishes two types of resources based on their origin and availability: biological and technical nutrients. Biological nutrients are plant-based materials, which are appealing for their potential suitability for faster-paced consumption due to their ability to be replenished quickly (Corbin and Garmulewicz, 2018; EMF, 2019a). Renewable resources may also be preferable when virgin-quality resources are required (EMF, 2019a), although even renewable resources require balanced and controlled management to avoid unhealthy concentrations (Reijnders, 2008). Technical nutrients are man-made materials, which have extraordinary technical properties essential for today's technology and everyday products (Bihouix, 2020; EMF, 2013). The processes to extract and convert these resources are often energy-intensive and expensive (Allwood, 2014). Transforming them back from product to material states can also compromise the (perceived) quality of resources (Baxter *et al.,* 2014; Zink and Geyer, 2017). Therefore, many urge preserving products made from technical nutrients to retain their embodied energy, rather than reducing products back to raw materials (Allwood and Cullen, 2011; EMF, 2019a).

Balancing resources

The second goal, and seemingly most popular in the manifestation of the CE in practice, is the prevention of losses and negative impacts for the use of resources (EMF, 2019a). A flow of material resources, whether circular or linear, usually requires other resources to enable it, such as energy. The CE suggests the need for an input-output balance of these resources (Murray *et al.,* 2017). This could be achieved, for example, by shifting to renewable energy (EMF, 2019a). Balancing resources also implies designing out any form of waste, including losses of energy (Braungart and McDonough, 2008) and time (Stahel, 2010). This stresses the importance of the pace of resource flows because products that can be used longer allow for the offset of high(er) energy investments and the replacement of the demand for new resources (Bocken *et al.,* 2016). A balance of resources also stresses the importance of the volume of resource flows, with the aim of achieving material efficiency by offering services with less material input (Allwood, 2014). To prevent such losses, the CE suggests keeping materials, components and products at their highest utility at all times (EMF, 2015).

Regenerate and restore resources

The third goal, and seemingly the most promising pledge of the CE, is the restoration and regeneration of the environment. Here, it seems that a CE cannot only prevent more damage but can also repair previous damage (Murray *et al.,* 2017). The idea is to move away from minimising negative impact and instead make things that support the ecosystem (McDonough and Braungart, 2013). For example, a mature CE could be intertwined with the linear economy, as it will upgrade and replace an obsolete resource stock with innovative materials (Stahel, 2019). The restorative (i.e., improving the environment) and regenerative (i.e., growing again) potential of the CE is promoted by leading bodies (EMF, 2015).

3.1.2. The economic strategy

On the other hand, the CE is also suggested as an economic model. The idea is that the efficient use of resources delivers economic benefits (Blomsma and Brennan, 2017; Yuan *et al.,* 2006). Some suggest that such resource efficiency would establish a harmony between the economy and the environment (Ghisellini *et al.,* 2016) or be compliant with the limits of environmental law (Murray *et al.,* 2017; Umeda *et al.,* 2000). Others suggest that the economic model can even resolve environmental problems (Yong, 2007). Two goals stand out for the economic strategy.

Decoupling economic growth

The first is to decouple economic growth from the extraction and production of material resources to manufacture goods (EMF, 2019a). 'Goods' are intended to make human lives easier and more pleasant (Norman, 1998). Today, these resources are a significant part of our economy, as their throughput is used to identify economic activity and rank economies (Boudling, 1970). Growth is traditionally expressed as the gross domestic product (GDP) (EMF, 2015; Raworth, 2017), the annual marketed value of all finished goods and services produced within a country. Increasing GPD implies increased production and consumption volumes of resources as a symptom of a healthy economy. GDP, however, does not consider resource throughput, or how and if resources flow back into environmental sinks as waste or a new resource (Jackson, 2009). Instead, the CE suggests decoupling economic growth from resource consumption (Ghisellini *et al.,* 2016) by maintaining resource stocks and encouraging technological change to reduce production and consumption (Boulding, 1966). Decoupling can be relative if the use of resources grows slower than the economy, or absolute if fewer resources are used overall (Jackson, 2009). It is believed that decoupling reduces the environmental pressure of economic growth (OECD, 2008) and it is assumed that this allows the economy to continue to grow without breaching ecological limits or running out of resources (Jackson, 2009).

Dematerialising value

The second goal is to dematerialise economic activity and ignite an absolute or relative reduction of either resource-per-unit of added value, or output (OECD, 2008). To achieve this, much attention has been given to the role of services in the CE. The CE draws upon the following theoretical concepts: the performance economy, which refers to maintaining and exploiting resources rather than selling them (Stahel, 2010; Stahel and Clift, 2016); the service economy, which includes replacing the manufacturing sector with a service sector (Stahel, 1994; Walker, 2008); and the sharing economy, which refers to renting or leasing products rather than owning them (Henry *et al.,* 2021; Mont *et al.,* 2020). These concepts share the notion that consumers can benefit from product performance without owning them (EMF, 2012; Tukker, 2004). Therefore, service-oriented consumption changes the object of consumption into an experience (Pine II and Gilmore, 2013) or even time spent in certain experiences (Tukker, 2004). In practice, this suggests offering the use or the results of products and services through Product-Service Systems (PSSs), which substitute one-off transactions for products (Bocken *et al.,* 2016; EMF, 2012; Manzini, 2009; Pine II and Gilmore, 2013; Tukker, 2004). Further, while products exist physically in time and space, services are processes that exist only in time (Morelli *et al.,* 2002). Therefore, growing a service economy could boost material intensity (Tasaki *et al.,* 2006) and substitute the demand for tangible resources with a need for 'renewable' human resources (Stahel, 2010; Stahel and Clift, 2016).

3.2. A new way forward, or no other way

Surely, (re)building a flourishing economy while overcoming environmental challenges sounds like a promising future. Indeed, many like to believe in this promise and are keen to adopt the strategies. However, the global population is predicted to increase further, and a greater part of the population will spend a greater disposable income on consumption (Weetman, 2016). In practice, the wealthier we are, the more we consume products and produce waste (World Bank Group, 2018). Thus, an acceleration and amplification of environmental impacts due to consumption increases, is a plausible scenario. Absolute decoupling might soon change from an aspiration to a dire necessity (Jackson, 2009). Not surprisingly, therefore, there are several concerns about the feasibility and sufficiency of a CE.

3.2.1. Circular economy believers

The interest in a CE arises from two main stakeholders: governments and industry. They have in common that their financial well-being is heavily and predominantly dependent on the use of resources. Their motivations to adopt a CE, however, are driven by different factors.

Governments: a persistent dream for economic growth

Traditionally, governments are driven by economic growth. Nations in which oil, gas and mineral sectors play a dominant role are called resource-driven (Dobbs *et al.,* 2013). A long-term resource-driven strategy can lead to national environmental issues that limit the ability to grow an economy further (Yong, 2007). China, for example, is an early CE adopter motivated by economic growth and driven by the following concerns. First, the emissions and pollution caused by manufacturing impact social stability (Yong, 2007). Second, the scarcity of resources required for manufacturing (Allwood and Cullen, 2015). China wanted to be independent from the international market for resources (Yong, 2007) and adopted a CE to use resources longer to reduce the need for new resources (Murray *et al.,* 2017). Third, waste is a costly problem, particularly if expensive processes only recover a fraction of the materials (Govindan and Hasanagic, 2018; Wilson *et al.,* 2017; Zink and Geyer, 2018).

In addition to social-environmental drivers, evidence for its success is a significant incentive to adopt a CE is. Success stories from Germany and Japan, which adopted CE principles earlier, may have convinced China to adopt its principles (Murray *et al.,* 2017; Yong, 2007). Some governments adopting CE principles actively advocate for its potential to create jobs (European Commission, 2014), indicating their confidence in its new economic potential. Global adoption of the CE could address economic inequality between countries (Weetman, 2016) but requires significant collaboration to improve knowledge-sharing and resource management (Geng *et al.,* 2019).

Industries: an insatiable hunger for opportunities

As the review in Chapter 2 implied, industry's primary need seems to be to sustain business as usual. As the environment is changing and governments are responding to this change, industry has little choice but to follow this lead. Industry's most obvious driver, thus, is legislative change. In fact, it is suggested that one of the reasons for the successful uptake of the CE, in comparison to other schools of sustainable thought, is that it largely emerged from legislation rather than academic research (Murray *et al.,* 2017). The second driver is confidence in new business-model opportunities. Although theorisation and application of circular business can be traced to the 1970s (EMF, 2012; Stahel, 2013), the CE has never been more popular than today. The slow uptake in Europe might be explained by the fact that many such alternative business models failed (Murray *et al.,* 2017). The publications by the EMF perform a critical role by showing examples of business in the CE (e.g., EMF, 2012, 2013, 2016), and companies may become proactive after seeing competitive advantages (Timmermans and Witjes, 2016). To overcome challenges of trailing potentially prospective business models (Murray *et al.,* 2017; Rahimifard and Sheldrick, 2015), China focused on smaller geographical scopes, such as provinces, cities and industrial parks, to push a network of businesses to adopt new business models (Yong, 2007; Yuan *et al.,* 2006). The third driver includes the indirect consequences of climate change, which are jeopardising business as usual. These consequences are not just a result of a government's legislative responses but also result from higher and more volatile resource prices (EMF, 2012, 2013, 2017a; McKinsey Global Institue, 2011). Eventually, industry will have no choice but to secure access to resources to future-proof their business (Weetman, 2016).

3.2.2. Critique and limitations

There are many promising and assuring reports on the CE and its potential to deliver a more sustainable future. However, the evidence of the success of a CE is scarce, both for governments (Ogunmakinde, 2019; Yong, 2007; Yuan *et al.,* 2006) and industry (Bocken *et al.,* 2017; Ghisellini *et al.,* 2016; Kuzmina *et al.,* 2019). Despite its popularity, there seems to be a justified debate around the ability of a CE to solve both environmental and economic problems.

Is the CE really environmentally sustainable?

The inefficient use of material resources is a great cause of unsustainable consumption; however, a focus solely or predominantly on the circular use of resources could overlook other causes. There are concerns that a CE justifies the consumption of resources. It is true that circularity may reduce the need for new materials by circulating materials longer (Prendeville *et al.,* 2014). However, unless global demand for resources stabilises, there will be a rate at which new materials must be added to closed-loop systems to increase their capacity to satisfy global demand (Allwood, 2014). The justification of consumption is also alarming in relation to possible rebound effects observed in circular practice, such as when improvements in efficiency increase consumption (Geng *et al.,* 2019; Ghisellini *et al.,* 2016; Sorrell *et al.,* 2020). There is a further concern that resources in closed loops cannot flow infinitely. Rather, the circulation of resources through recycling delays a resource's end-of-life (EOL) but does not prevent its final disposal (Zink and Geyer, 2018). On top of this, there seems little evidence of the restorative and regenerative abilities of the CE (Prendeville *et al.,* 2014), shedding doubt on whether circulation truly creates new nutrients. Because of this, some scholars emphasise that a CE insufficiently reduces the amount of resources used in the economy (Allwood, 2014; Zink and Geyer, 2018). Instead, economic models in which the boundaries are more respected, such as an organic economy (Wrigley, 2015) or a doughnut economy (Raworth, 2017), represent a better understanding of the environmental limits.

Another concern is that the processes that circulate resources require energy resource inputs. Due to its dominant focus on closed loops, a CE positions resource efficiency over and above environmental impact (Prendeville *et al.,* 2014). This approach can backfire, however, if long-lasting products that do not easily break down consume more energy than newer, more efficient products (Murray *et al.,* 2017). Manufacturing and recovering resources can also require significant energy inputs (Allwood, 2014). To facilitate this, the CE envisions a future with plenty of renewable energy (EMF, 2015; Webster, 2013). However, critics point out that this future state is not ready, and manufacturing of technology to produce renewable energy also requires material and energy resources (Allwood, 2014; Bihouix, 2020; Morlet *et al.,* 2016). Therefore, for the short- and medium-term, a CE could even accelerate environmental impacts (Allwood, 2014).

Finally, the CE seems to consistently neglect the social dimensions of sustainability (Homrich *et al.,* 2018; Kirchherr *et al.,* 2017; Murray *et al.,* 2017; Schenkel *et al.,* 2015). Despite ambiguity around the meaning of sustainability, it is widely recognised that the term refers to both social and environmental health (United Nations, 2016). Neglecting social factors may limit the ability of governments and industry to use the CE to perform well on social dimensions (Homrich *et al.,* 2018; Moreau *et al.,* 2017).

Is the CE really economically prosperous?

To date, GDP continues to be the dominant tool to measure economic health globally (Raworth, 2017). This is concerning, as it continues to incentivise the linear production and consumption of resources while systematically overlooking the capabilities of the economy to manage these material throughputs (Jackson, 2009). Provisional indicators for resource productivity have been proposed to measure progress towards a CE by the ratio of GDP to domestic material consumption (Euro/tonne), but these focus only on domestic resource movements and exclude imports and exports across borders (European Commission, 2011; Wiedman *et al.,* 2015). There also is a lack of data that assesses the efficiency of resources such as the percentage of post-consumer goods stocked by consumers, which limits the understanding of reuse and recycling potential (Singh and Ordoñez, 2016). It remains debatable, however, if a metric for resource efficiency will be appropriate for economic health. The efficient use of resources can make things 'less bad' (McDonough and Braungart, 2013), but there is little evidence that economic growth based on material use increases human wellbeing beyond a certain point (Allwood, 2014; Jackson, 2009). Resource efficiency might also be compromised if there is a growing demand for resources. Meanwhile, efficient use of resources does not make them less finite; it just delays their inevitable disposal (EMF, 2015).

There are also several concerns about implementation practicalities that cause CE business to seem less appealing. For example, pre-made commitments to future development or businesses may have made long-term capex investments in manufacturing equipment (Prendeville *et al.,* 2014). Just as in the natural ecosystem (Benyus,1988), governments and businesses require holistic interactions rather than isolated changes (Murray *et al.,* 2017). This stresses the importance of an engaged community of customers and consumers to the success of businesses and governments (Geng *et al.,* 2019; Kuzmina *et al.,* 2019). Adopting a CE requires investments in infrastructure and in business models, which require cross-sector collaboration (Prendeville *et al.,* 2014). Making these changes can be discouraged when the demand for recycled materials and reused products does not naturally emerge, as is implied by the CE (Hopewell *et al.,* 2009; Prendeville *et al.,* 2014; Zink and Geyer, 2017). On top of that, the CE promises the creation of new jobs (EMF 2015; Stahel and Clift, 2016), but local economies will likely experience short- to medium-term hits during transition phases (Allwood, 2014). Although evidence of success is an effective means of encouragement, case studies and commercial estimates remain on a high-level (e.g., EMF 2013, 2016), while the evidence and explanations for real-world success seem scarce (Murray *et al.,* 2017).

3.3. Catalysing the transition to the Circular Economy through design

Adopting a CE requires a complete reform of production and consumption systems. In addition to technology and infrastructure, these systems involve human activity (Yuan *et al.,* 2006) and business dynamics (Sterman, 2002), setting a severely complex and multifaceted task. It is evident from the CE literature that design could and should have a role in performing this task (EMF, 2013; Moreno *et al.,* 2016; Pigosso and McAloone, 2017). Design is known to be effective in exploiting commercial potential through designing luxury products for mass consumption (Maycroft, 2009), which supports the idea that it can contribute on the economic front. This is also not the first time that design is expected to support an environmental strategy. Design and the environment have been strongly linked since the 1960s (Packard, 1960; Papanek, 1985), as it was suggested that up to 80% of a product's environmental impacts are locked-in during design decisions (Graedel and Allenby, 1995). Designers, however, may have limited skills, influence and information to make different decisions (Sherwin and Evans, 1998). Instead, design briefs often follow strategic decisions (Bakker *et al.,* 2010; Bhamra and Lofthouse, 2007). For example, 'planned obsolescence' is considered a strategic decision for a short product lifetime to accelerate consumption (Cooper, 2010; Packard, 1960), and designers may not be in the position to decide differently (Agrawal *et al.,* 2016; Andrews, 2015). To use design as a catalyst for the transition to the CE, it must be able to satisfy both economically and environmentally. Assigning the complex task of reforming the systems that shape our economy to designers, therefore, requires reconsidering design objectives and expected deliverables.

3.3.1. Changes in design objectives

Design became increasingly involved with the environmental impacts associated with the production and consumption of resources through the consideration of product life cycles. The flow of resources is sometimes compared to these life cycles and appears to have adopted similar design objectives for the CE. However, it is not clear whether these adoptions provide sufficient understanding to consider resource flows in design.

3.3.1.1. Product Life cycles

Design involves decisions such as selecting materials and deciding on manufacturing processes, which can have a significant (indirect) environmental impact (Bhamra and Lofthouse, 2007; Lewis and Gertsakis, 2009). 'Life cycle design' involves designing products considering their whole life cycle, starting with the exploitation and processing of raw materials, to the EOL of products and materials (Alting and Legarth, 1995; Stark, 2011). Initially, life cycles were used to only identify supply chain optimisation opportunities (Filimonau, 2016; Hunt and Franklin, 1996; Thain and Bradley, 2014), but they received further attention when waste issues became more pressing (Alting and Legarth, 1995; Bakker *et al.,* 2010; Braungart and McDonough, 2008; Filimonau, 2016). The life cycle can be used to identify and quantify parameters that imply environmental impacts of the product in its life cycle (Alting and Legarth, 1995). An example is quantifying a product's embodied energy based on the energy invested in extracting the materials and manufacturing the product (Moraga *et al.,* 2019; Vogtländer, 2010). Concerns for products in use by consumers emerged as one of the most impactful phases in the life cycle (Allwood, 2012; Taylor, 2017).

Product life cycles are at the basis of sustainability and sustainable design, but a life cycle can have different meanings (Stark, 2011) depending on the timespan (Murakami *et al.,* 2010). A life cycle can, for example, refer to the journey of products conquering a market over time (Roozenburg and Eekels, 1998; Stark, 2011). Defining a life cycle depends on what one considers the start and end points. Although some argue that the product's life cycle starts at the design phase (Stark, 2011), it usually refers to the duration of the period in which goods are possessed (Murakami *et al.,* 2010). Life cycles are typically sectioned into phases. Phases are sometimes informally defined according to key stakeholders (e.g., supplier, manufacturer, customer, recycler) or as processing steps linked to the supply chain (e.g., raw material, manufacturing, use, recycling). However, more commonly, the phases indicate a break-down of origin (material processing), production (manufacturing and distribution), use (consumption) and EOL (disposal or recovery) (Vogtländer, 2010). Life cycle phases provide designers with an effective means of allocating environmental impacts using life cycle assessment (LCA) methods. For example, high embodied energy can be off-set through life-extension in the use phase. There are, however, recognised limitations to using LCAs to understand environmental impacts, including the insufficiency of their scope around carbon footprints (Guinée *et al.,* 2011) and a lack of transparency on specific causes of environmental impacts (Finnveden, 2000).

Over the years, design philosophies emerged that adopted life cycle thinking. Ecodesign, for example, aims to consider the environmental impact of a product in early decision-making (Bhamra and Lofthouse, 2007; Dewberry and Monteiro de Barros, 2009; Lofthouse, 2006; Prendeville *et al.,* 2014; Sherwin and Evans, 1998). Another example is design for sustainability (DfS), which emerged as a direction that involves the 'radical redesign of products and services striving towards a sustainable future' (Moreno *et al.,* 2016, p. 5). In contrast to other philosophies such as Design for Environment (Eastman, 2012; Lewis and Gertsakis, 2009), DfS considers both environmental and social impacts of a product (Bhamra and Lofthouse, 2007). Nevertheless, it is suggested that these directions still follow a linear process, as they focus predominantly on impact reduction but overlook the efficacy of resource flows (Moreno *et al.,* 2016). Another common philosophy that seems to provide a more holistic approach is design for X (DfX), which recognises that design may affect any phase of the product life cycle (Holt and Barnes, 2010). DfX uses engineering techniques to focus on a few vital aspects, such as costs and disassembly, which could be used to embed preventive approaches and design for a closed loop (Moreno *et al.,* 2016). Taxonomies and organisations have been proposed to map DfX approaches to circular strategies (Moreno *et al.,* 2016) and life cycle phases (Franconi *et al.,* 2019). Nevertheless, there are doubts as to whether DfX techniques are sufficiently integrated for holistic product development (Eastman, 2012; Holt and Barnes, 2010).

3.3.1.2. Circular flows of resources

Several strategies exist to use resources more efficiently. The strategies for the CE are often associated with the 3Rs of reduce, reuse and recycle (Yuan *et al.,* 2006), which are part of a waste management hierarchy introduced Europe in 1975 (Ceschin and Gaziulusoy, 2020). This hierarchy was later expanded to address criticism for not including preventative strategies and not distinguishing between disposal and recovery (Ceschin and Gaziulusoy, 2020). The current hierarchy involves prevention, reuse, recycling, recovery (waste to energy) and disposal (European Union, 2008). These strategies are embedded in the concept of a CE (Bakker *et al.,* 2014; Blomsma *et al.,* 2019), although the EMF further refined them to better align with circular business activities: maintain/prolong, reuse/redistribute, refurbish/remanufacture and recycle (see Figure 3.1). Similar to the waste management hierarchy, the circular strategies indicate an order of preference for action, such as the inner loop in the butterfly diagram, which is suggested to have the lowest environmental impact (EMF, 2012) and commonly aligns with the aim to extend product lifetime or longevity strategies (Blomsma *et al.,* 2018). Extended lifetimes are also described as slower resource loops (Bocken *et al.,* 2016). Other characterisations of resource flows are narrow loops and closed loops. Narrow loops aim to use fewer resources (Bocken *et al.,* 2016) and can be achieved through preventative strategies, such as efficiency and light-weighting and resource intensification strategies, such as product cascading and sharing (Blomsma *et al.,* 2018). Closed loops aim to close the post-use and production loop (Bocken *et al.,* 2016) and can be achieved with loop-closing methods, such as recycling and composting, and loop-extending methods, such as material cascading and waste-to-energy (Blomsma *et al.,* 2018).

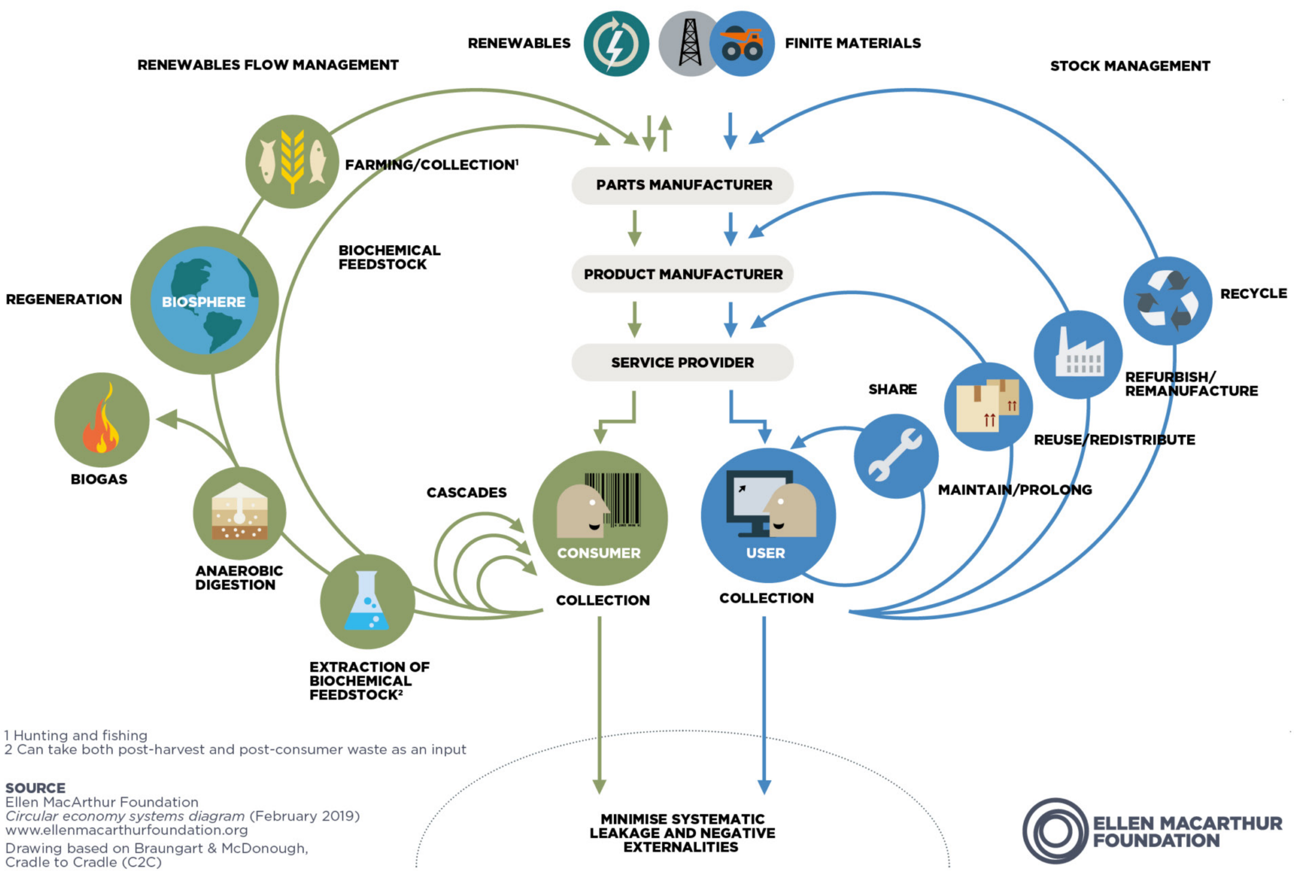


Figure 3.1 Butterfly diagram (EMF, 2012).

Circular strategies allow for translation into design objectives (Bocken *et al.,* 2016; Ceschin and Gaziulusoy, 2020). Common design objectives suggest product durability and service integration for a slow loop or material reduction for a narrow loop (e.g., Van Weelden *et al.,* 2016; Mestre and Cooper, 2017; Moreno *et al.,* 2016). Determining which strategy to use, however, is one of the biggest challenges for design research (Bakker *et al.,* 2014). Adhering to the hierarchy, much of the research on design for the CE has focused on product life extension through reparability, refurbishment or remanufacturing (Bakker *et al.,* 2014). This focus benefits from life cycle thinking, and often the resource flow is interpreted as a product life cycle (Franconi *et al.,* 2019; Mestre and Cooper, 2017). Where needed, modifications of the life cycle can be proposed to address discrepancies that complicate this interpretation. Product lifetimes could, for example, be counted only from when a product is released after manufacturing (Den Hollander *et al.,* 2017).

Despite such tactics to investigate flowing resources at more specific times, the common break-down of the life cycle in four phases does not provide a granular understanding of resource flows. Therefore, disruptions in resource flows can easily be missed. Disruptions could occur in the production phase, the use phase or the EOL phase. In the production phase, disruptions could result in production waste (EMF, 2015b). In the use phase, disruptions can result in leakage into nature (Jambeck *et al.,* 2015), hibernating obsolete resources in consumers' drawers (Wilson *et al.,* 2017) or the lack of interest in sharing models due to contaminated interaction (Baxter *et al.,* 2017). Disruptions in the EOL phase include the loss of materials that are too small to be sorted in a Material Recovery Facility (MRF) (WRAP, 2019a). Such disruptions seem to be linked to certain moments in the life cycle. One of these moments is obsolescence, which implies the end of the use phase, the point at which a user no longer considers a product useful or significant (Bakker *et al.,* 2019). Obsolescence has been studied in-depth, particularly in relation to slow loops, and includes studies of design that resists or postpones obsolescence (Den Hollander, 2018) or to avoid the event altogether (Chapman, 2009). Several resource flow disruptions in the use phase can be linked to obsolescence, such as the disposal of durable goods that we no longer want (Bakker *et al.,* 2014; Cooper, 2010; Packard, 1960) or the hibernation of durable products that we no longer use (Wilson *et al.,* 2017). Consumers typically desire a separation from products in the obsolete state. This part of the product experience is often overlooked in design (Macleod, 2017). It is conceivable that the physical state of the product has a direct role in how consumers treat it (Hawkins, 2012), but it is likely that complex user-interactions also play a role (Baxter, 2017; Cooper.,2005). Despite fe suggestions to reverse obsolescence (Den Hollander, 2018) and plan for it (Burns, 2010), there seems little knowledge of the relation between obsolescence and closed loops, including how to use design to influence the destiny of obsolete resources.

A lack of granularity on resource flow, thus, can overlook obsolescence and possibly other significant moments in the resource flow. Rather, a circular strategy gives a high-level description of a resource flow, while the life cycle interpretation provides an overly simplified break-down. They both give insights on the pace and volume of resource flows, but less information on the implications for their actual physical journeys. Flow is commonly understood as the volume of matter existing per unit of time within the boundaries of a system (Brunner and Rechberger, 2004). The notion that resource flow entails physical matter emerges mostly from the suggestion that flows in the bio- and tech-spheres should be pure (Braungart and McDonough, 2008; EMF, 2012). The suggestion to not mix biological and technological nutrients can be traced to their different processing requirements, such as anaerobic digestion versus recycling. The EMF clearly separates the two flows in the butterfly diagram (see Figure 3.1). There is only one loop for the biological nutrients but several loops for technical nutrients following different circular strategies. All of them appear to imply an end-to-end journey of resources. This implies that closed-loop resource flows not only entail recycling and composting materials (Blomsma *et al.,* 2018; Bocken *et al.,* 2016) but could also entail consecutive cycles of components through refurbishment or several use-cycles of products through sharing (EMF, 2012). Resources may transform into different entropies, such as products, components or materials, depending on the circular strategy (Blomsma and Tennant, 2020). The circular strategies imply that the value of the resources can be retained either in a single entropy or through changing entropies (Nußholz, 2017). Therefore, in a CE, the three entropies become a single loop of resources (Stahel, 2019). Similar to the biological and technological nutrients, the resource flows would require specific processes to become established.

3.3.2. New design deliverables

The attention to product life cycles in design objectives has had implications for what is considered the deliverable of design. A need for more environmentally friendly deliverables has led to new ways to design products as well as new types of deliverables altogether. Several of these deliverables appear to be adopted for a CE.

3.3.2.1. Changes in product design

Products are the primary deliverable of design for the linear economy. Initially, manufacturers responded to environmental concerns by designing 'environmentally friendly' products (Bhamra and Lofthouse, 2007) rendering them less environmentally harmful (Manzini, 1994; Peters, 2014). Nevertheless, more constrictive suggestions for product design also emerged from life cycle thinking, which appears to have been adopted for circular product design and support circular resource flows. For slow loops, products should be designed to be durable (e.g., Bakker, Wang, *et al.,* 2014). Longevity can be achieved by designing products that are not just technically durable (Allwood *et al.,* 2011) but that last emotionally by stimulating user attachment and using gracefully-ageing materials (Chapman, 2009; Mugge, 2017). Longevity can also be achieved by making products easy to disassemble, allowing their upgrade and repair (e.g., Pialot *et al.,* 2017) and avoiding replacement due to technical obsolescence (Bakker *et al.,* 2014). Further, emphasis is put on the opportunity to slow and narrow flows by sharing products between users. This implies considering the traces that can be left on products by users (Baxter *et al.,* 2014; Pedgley *et al.,* 2018).

There are also suggestions for products to ensure closed loops. Typically, these relate to choosing materials that are either biological or technical and allowing for disassembly and material identification (e.g., EMF, 2015; Mestre and Cooper, 2017; WRAP, 2019). There are conventional product design outcomes that appear to have considered resources in an obsolete state, such as faded razor-lubricant strips, worn-out toothbrush bristles (Maycroft, 2009) and laddered stockings (Andrews, 2015). Further, certain attributes of packaging were found to influence disposal behaviour, (Baxter *et al.,* 2016) and an emotional bond with products could encourage detachment (Choi *et al.,* 2018). Although there seems to be a notion for the conditions of materials and their ability to flow in a closed loop in the literature (Zink and Geyer, 2017), there does not seem to be support to explore and consider these relations in design.

3.3.2.2. Behaviour, services and systems design

As the environmental impacts of products and product design became more evident, it also became apparent that designing products in isolation is insufficient to disrupt the take-make-dispose pattern. Product design for sustainability has already shifted towards deliverables that include changes in consumer behaviour (Daae and Boks, 2015; Lilley, 2009; Mugge, 2017), as well as the services through which products are offered (Mont and Tukker, 2006; Tukker, 2004). Behaviours and services were consequently assigned more central roles in the design process; in user-centred design, the user takes centre stage (Wever *et al.,* 2008). In particular, PSSs have been praised for their ability to make the consumption of products more sustainable (Tukker, 2004). The notion that product design and business models should be integrated is widely encouraged and believed to lead to more sustainable and circular ways to deliver value (Bocken *et al.,* 2016; Ceschin and Gaziulusoy, 2016; Tukker, 2004). Through this thinking, business models are increasingly seen as design deliverables (Bocken *et al.,* 2013). Services that are result- or performance-oriented could even offer a completely dematerialised offer (Pigosso *et al.,* 2015). In this case, the product is simply an element of the overall solution and the value proposition shifts from a single transaction to multiple dematerialised transactions through circular business models (Kuzmina *et al.,* 2019). Business models are evidently an integral topic in the CE, and design science appears to focus on establishing relations between business models and design for the CE (Bocken *et al.,* 2016; Pigosso and McAloone, 2017). Specifically, a circular business model embeds a circular strategy in the offer, which should consequently change how resources flow (Nußholz, 2017).

To be profitable and stimulate consumers to participate, a PSSs must have an efficient take-back system (Mont, 2002). A take-back system requires manufacturers to collect and recycle their products or pay others to do so on their behalf (Toffel *et al.,* 2008). It is typically urged by governments or part of Extended Producer Responsibility policy (Quariguasi Frota Neto & Van Wassenhove, 2013). The specific objective of introducing take-back systems is to reduce the volume and toxicity of waste and ensuring the 'polluters' bear the full environmental and social costs of their activities by mitigating environmental and public health risks, promoting cost efficiency and protecting health and safety (Toffel *et al.,* 2008). The literature on take-back appears to focus predominantly on the infrastructure to operate take-back systems, such as Closed-Loop Supply Chains or Reverse Logistics (Agrawal *et al.,* 2015). Nevertheless, it is acknowledged that the successful operation of take-back systems also depends on participation of consumers (Mashhadi *et al.,* 2016) as well as collaboration and an effective business model (e.g., Breen, 2006). Recently, support grew for the idea that even larger systems need to be considered in designing for a CE. Some systems emphasise the opportunities in the industrial supply chain, such as closed-loop or circular supply chains. These opportunities go beyond only generating economic value by creating benefits for multiple actors and society over time (Schenkel *et al.,* 2015) and relating these benefits to remanufacturing, reusing and recycling in the product life cycle (Dora *et al.,* 2016). However, zooming out further is the idea that design can deliver whole systems (Charnley *et al.,* 2011; Moreno *et al.,* 2016). This notion aligns more with the concept of industrial ecology, which interprets industrial systems as natural ecosystems in which resources remain part of the wider systems (Graedel and Allenby, 1995). This can be seen as the macro level of the CE, which puts emphasis on both production and consumption (Yuan *et al.,* 2006). Circular strategies imply that value can be generated if resources flow (EMF, 2012). It is suggested that it is the behaviour of the whole system that creates the problem (Dewberry and Monteiro de Barros, 2009). Thus, tinkering with only the parts of the system, such as services, business models, behaviours and supply chains, may not be sufficiently and radically innovative (Dewberry and Monteiro de Barros, 2009).

3.4. Discussion

Based on this review a notion for a new type of life cycle emerges, see Figure 3.2 to visualise a generic closed-loop resource flow in the CE. In contrast to a product life cycle, the resource life cycle entails a journey over time in which resources can either transform between product, component and material states; or take shortcuts to continue to flow at a consistent utility. A closed-loop resource flow, here, is a type of circular resource flow in which post-consumer resources are retained or brought back into the economic cycle (Bocken *et al.,* 2016; Konietzko *et al.,* 2020b). Therefore, the journey of resources entails transformations of the resource, from material to component, component to product, and even product to material (Blomsma and Tennant, 2020), as well as movements of the resource, from a user to a recycling bin or from a material supplier to a product manufacturer. The diagram includes the four life cycle phases for reference, but the actual journey of the resource is more granular. The obsolete state has been included to differentiate it from the operative resource state, which indicates the resource in-use. The moment when the resource becomes obsolete, as well as other moments discussed in this chapter, risk disrupting this journey.

This literature review allowed to refine focus for the research. As indicated in Figure 3.2, the chapters of this thesis can be structured around the diagram. First, Chapter 4 and Chapter 5 focus on obsolescence to address a main a disruptor of flow by investigating consumers and PSSs; and second, Chapter 6 and 7 focus on the system that procures the entire resource flow. From this synthesis emerged three theoretical implications of the CE theory that appear to be overlooked as topics in the literature.

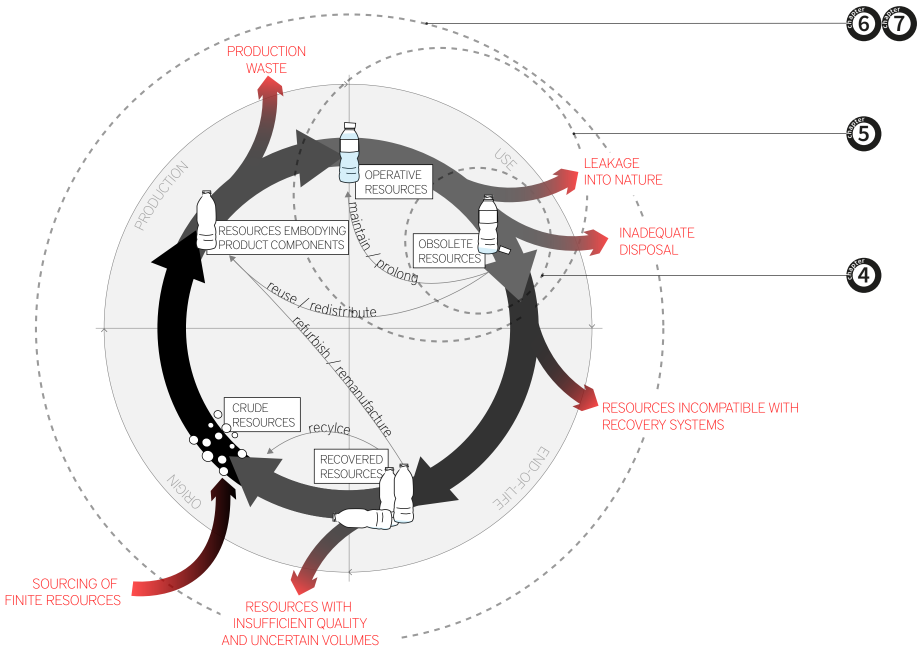


Figure 3.2 Resource life cycle diagram.

I) Resources are products, components and materials.

In a CE, products and materials are integrated into a single loop (Stahel, 2019). This implies that resources transform into different states (Blomsma and Tennant, 2020; Webster, 2013). In practice, this notion is challenging, because resource transformations, such as reducing the quality of materials, are not always technically feasible (Zink and Geyer, 2017) or are unlikely to occur due to disruptions, including a lack of engagement in recycling (Steg and Vlek, 2008). Design focuses on novel product to address these challenges, but there is no knowledge to support the design of resources at different moments in the flow.

II) Flow involves movement and transformation of resources.

Resource flows are sometimes interpreted as product life cycles. However, the theory of life cycles was developed to calculate and assess the environmental impacts associated with different phases of a product's journey. Instead, flows in the CE appear to be concerned with the journey's efficacy around its feasibility, volume and pace. This gap limits the potential to use design to address flow efficacy. Instead, there seems an opportunity to investigate resource flows more carefully by investigating critical moments in resource flows, such as when resources become obsolete (Burns, 2010; Den Hollander, 2018). A better understanding of this moment may allow us to exploit it in favour of circular rather than linear flow efficacy. A detailed investigation of the movements and transformations of the physical flow of resources could bridge the gap in design practice.

III) Systems produce resource flows.

Much of the theoretical concept of the CE has focused on the notion that economic benefits can be obtained from circularly flowing resources by using systems thinking. New design deliverables, however, suggests behaviours, services and business models, appear that relate only to certain sections of the resource flow. Rather, there is little consideration of the notion that it is a system as a whole that creates the undesired resource flows (Meadows, 2008) and that this overall behaviour is what the CE intends to change (Dewberry and Monteiro de Barros, 2009). There seems a lack of support to define such systems and use design to improve them. This limits what design can achieve for the CE.

3.5. Conclusions

This literature review investigated the environmental and economic opportunities and concerns for the adoption of a CE. Design is proposed as a catalyst for the transition to a CE. The aim of this review was to understand the implications of using the design of systems to close the loops of resources. Both the environmental and the economic benefits of a CE rely on the efficient use of resources. The CE concept specifically advocates flowing resources, such as products, components and materials, in closed loop flows to optimise their yield in economic systems through business models that dematerialise consumption. There are concerns that a CE justifies the consumption of resources and insufficiently addresses environmental impacts that result from closing loops. Further, there are concerns about the lack of evidence of economic success and whether this will sufficiently convince business to adopt CE principles. Design is challenged with the complex task of reforming the consumption and production systems that shape the economy, which has implications for design objectives and deliverables. Objectives are typically derived from circular strategies and, because the focus is mostly on slow loops through life extension, they are often interpreted as life cycles. This view, however, provides insufficient granularity of key moments in the resource flow, such as obsolescence, and does not appear to consider flow as a physical thing. Product deliverables have changed to align with circular strategies but extend not far beyond the design of a brand-new product rather than its past or future conditions. The CE suggests a broader design deliverable including services, behaviours and systems. A synthesis of the review leads to three theoretical implications that point to overlooked topics in design and CE literature: resources are products, components and materials; flow entails movement and transformation; systems produce flows. Following the resource flow diagram, the research will initially focus on obsolescence, which emerged as one of the most significant disruptive movements of the flow; and subsequently on the system as a whole that produces a circular resource flow.

4. Outlining the Role of Consumers in Closing Loops

This chapter presents a characterisation of the role of consumers in closing loops and presents gateways as entry points for resources in revalorisation. This work has previously been published in the Journal of Cleaner Production (Zeeuw van der Laan and Aurisicchio, 2019a) and to the Sustainable Innovation Conference (Zeeuw van der Laan and Aurisicchio, 2019b).

4.1. Responsibilities of revalorisation

Today's consumption of Fast-Moving Consumer Goods (FMCGs) threatens the environment as it contributes to global waste issues and to the depletion of resources leading to future shortages (EMF, 2017a). Despite the existence of recycling programmes, recovery rates of FMCG resources appear to be poor (De Wit *et al.* 2018) and only 2% of plastics globally used in packaging are estimated to exist in closed-loop recycling (EMF, 2016). Collection rates of obsolete resources are one of the main determinants of flow continuity (Breen, 2006; Corvellec and Stål, 2017; Gelbmann and Hammerl, 2015; Peeters *et al.,* 2017; Williams, 2007), and consumers have a key role in enable effective collection. This is because materials, components and products can only be taken through multiple lifecycles if they are collected effectively (Den Hollander *et al.,* 2017). Consumers are assigned an active role in the collection of resources in closed-loop systems, both in recycling and in reuse (Charnley *et al.,* 2015; Steg and Vlek, 2008; Wastling *et al.,* 2018). The collection implies activities that consumers are required to carry out, such as sorting, storing and separating. In addition to if consumers carry out the activities, how they are carried out impacts the quality of the revalorised resources (Nassour *et al.,* 2017; Rousta and Dahlén, 2015). Thus, it appears that to successfully establish a closed-loop flow of resources, these activities and their implications for consumers must be considered carefully to ensure their fulfilment.

To improve the fulfilment of the role of consumers of FMCGs, tactics and factors influencing recycling behaviour have been studied. For example, previous behavioural studies have investigated: the reasons for poor recycling behaviour (Guagnano *et al.,* 1995); how to increase the number of recyclers (Domina and Koch, 2002; Tonglet *et al.,* 2004); how to improve recycling practices (Dahlén and Lagerkvist, 2010; Derksen and Gartrell, 1993; Magnier and Schoormans, 2015); and how to encourage the uptake of reusable facilitating components over single-use ones (Lofthouse *et al.,* 2009; Poortinga and Whitaker, 2018; Ritch *et al.,* 2009). Examples of influencing factors are: infrastructure and technical facilities, which have shown to be supportive of the fulfilment of these roles (Poortinga and Whitaker, 2018; Steg and Vlek, 2008) and can increase the levels of recycling (Derksen and Gartrell, 1993); and product features such as geometry, which were found to impact disposal behaviour (Baxter *et al.,* 2016). Despite these efforts to understand how the role of consumers impacts resource flows and why the role is not fulfilled, it remains unclear what exactly the role implies for consumers; and which tactics can be used most effectively to increase fulfilment. In fact, activities that constitute the role of consumers are often overlooked in the design processes of circular packaging (De Koeijer *et al.,* 2017).

Which activities are required of consumers depends on the services available to revalorise the products, components or materials, i.e., giving new value to resources. It is suggested that services are to be designed in conjunction with products to deliver a Product-Service Systems (PSSs). PSSs are advocated for the transition to a circular economy (CE) (EMF, 2015) as they can dematerialise consumption, intensify resource use, and recover resources (Bakker, Den Hollander, *et al.,* 2014; Bakker, Wang, *et al.,* 2014; Mont, 2002; Stahel, 2013; Tukker, 2004), while at the same time considering the impact of changes on interrelated business models (Bocken *et al.,* 2016). PSSs can constitute a 'revalorisation service', which '*includes offers that aim at closing the product material cycle by taking products back, reusing usable parts in new products and recycling materials if reuse is not feasible*' (Mont, 2002, p. 241). This implies that revalorisation services are services offered to consumers to recycle materials or reuse products. Such services exist for FMCGs, either provided for specific branded products, e.g., a scheme to refill detergent bottles; to specific product types, e.g., a deposit-return scheme for plastic bottles; or to specific materials, e.g., a kerbside collection programme to recyclable packaging materials.

The design of PSSs that constitute revalorisation services has implications for the role of consumers. Recent studies of PSSs have highlighted that circular design has implications for the roles and behaviours of consumers (Baxter *et al.,* 2017; Boks and Daae, 2017; McAloone and Pigosso, 2018; Mugge, 2017). There are many ways to dispose and reuse FMCGs, however, their poor uptake by consumers and their incorrect use imply that the implications of the roles assigned to consumers in revalorisation are poorly understood. This understanding is important as it has the potential to improve the integration of consumers in PSSs, for example, when aiming to improve collection rates in recycling programmes. In addition, novel PSSs consisting of revalorisation services for FMCGs are emerging and research on the role of the consumer and the fulfilment of this role is needed to help companies modify their business models and interactions with consumers (Charnley *et al.,* 2015). Thus, rather than focusing on encouraging the uptake generally, we must understood what discourages the uptake and allows for errors in this role. Therefore, this work aims to understand and define the role of consumers in the use of revalorisation services for FMCGs.

The remainder of this chapter is structured as follows. In Section 2, we define FMCGs and obsolescence, and how these relate to consumers and resource flows. Section 3 explains how we selected, dissected and systematically compared revalorisation services for FMCGs to develop understanding on the roles of consumers. In Section 4, we present four archetypical consumer roles that we modelled using dimensions that emerged from the analysis. In Section 5, we present five types of gateways, i.e., entry points to revalorisation, and aspects of gateways that have implications for the weight of the consumer roles. We present three key insights and discuss their implications for the design of closed-loop PSSs in Section 6. In Section 8 we conclude on the contributions of this research.

4.2. Obsolescence and revalorisation of FMCGs

To revalorise resources, consumers must act when they no longer can or want to use a product. The time from the moment in which a good is released for use until the moment in which it becomes obsolete, is defined as the product use cycle (Den Hollander *et al.,* 2017). The ends of the (typically very short) use cycles of FMCGs are marked by the moment it becomes obsolete, i.e., the product is no longer used or needed. Although obsolescence can be overcome, allowing products to go through multiple successive product use cycles (Den Hollander, 2018), most FMCGs only perform in a single short product use cycle. Its duration is determined by the minutes, days or weeks it takes to deplete the consumable components. Whether obsolete resources become waste or continue to flow in a closed loop, thus, depends on what happens in the moment in which they become obsolete. Here we review the literature on obsolescence and revalorisation services.

4.2.1. Obsolescence as a moment in the resource flow

When resources become obsolete is typically a strategic business decision that is embedded in the design of products (Papanek, 1985). For most FMCGs, obsolescence is an inevitable and obvious event due to the depletion of a consumable component. For some products, however, manufacturers can anticipate that consumers can get tired of them (Papanek, 1985), in which case consumers also influence when something becomes obsolete. The literature describes numerous forms of obsolescence, see Table 4.1, and labels them as relative and absolute forms of obsolescence. Relative obsolescence occurs when consumers decide to stop using a product (Burns, 2010; Cooper, 2004), resulting in a resource that is no longer used or needed. In these cases, obsolescence is caused by changes to the product (e.g., aesthetic) or to the context of use (e.g., societal, economic, technological, ecological, psychological). These changes influence the perception of the product, prompting consumers consider to stop using a resource. Absolute obsolescence is often defined as the failure of a physical product after consumption, e.g., when a product technically breaks down (Cooper,

Table 4.1 Forms of obsolescence.

Obsolescence		References	Causes
Relative	*Aesthetic*	(Burns, 2010; Van Nes *et al.,* 1999; Wilson *et al.,* 2015) also: desirable (Packard, 1960)	• Changes in appearance of resources, e.g., fading, dirty, worn out, making the product less desirable. • Loss of cosmetic and decorative value. • When a product is found to be out of fashion.
	Societal	(Burns, 2010)	• Societal changes that impact needs. • Legislation that sparks behavioural changes.
	Economic	(Burns, 2010)	• When (up)keeping products becomes too costly (e.g., maintenance and repair costs).
	Technological	(Burns, 2010; Cooper, 2004) also: functional (Packard, 1960)	• When a newer version becomes available that performs the function better.
	Ecological	(Wilson *et al.,* 2017)	•A new product with a less harmful impact on the environment is available.
	Psychological	(Van Nes *et al.,* 1999)	• Emotional value to favour a product over another product e.g., gift.
Absolute	*Qualitative*	(Packard, 1960) also: absolute (Cooper, 2004)	• Break down or wear of products.
	Functional	(Bartels *et al.,* 2012; Feldman and Sandborn, 2007)	• The functions of components are no longer used.
	Technological	(Bartels *et al.,* 2012; Feldman and Sandborn, 2007)	• When an older version is no longer supported.
	Logistical	(Bartels *et al.,* 2012; Feldman and Sandborn, 2007)	• When products or components are no longer available to procure.

2004). This definition, however, captures only one absolute cause for obsolescence. Other forms of absolute obsolescence are when a product still operates as intended, but the functions of components are no longer used (Bartels *et al.,* 2012), e.g., when consumables are depleted and packaging is empty. Obsolescence can also result from the lack of availability of support (technological) or availability of components (logistical) (Feldman and Sandborn, 2007). As such, absolute obsolescence occurs when a resource can no longer be used by consumers.

The moment in which a resource becomes obsolete is key in the flow of resources. Flows and stocks of resources are to be considered in the design of systems (EMF, 2013). The value of the resources in a flow is kept at its highest level if the flows are pure and the resources uncontaminated (EMF, 2015; Stahel, 1994). The value is also influenced by flow continuity (Allwood, 2014; Breen, 2006; Zeeuw van der Laan and Aurisicchio, 2019c; Zink and Geyer, 2017), which is dependent on the quality of the recovered versus the original resources and whether there is a market for the recovered resources (Bocken *et al.,* 2016; Zink and Geyer, 2017). Further, the value of resources can be preserved if resources are timely and effectively managed and moved (Wilson *et al.,* 2017) to establish a continuous flow that satisfies resource demand and diverts from sourcing new resources. This conceives the idea that the value of resources is subject to timing and location and reinforces the importance of understanding the moment in which resources become obsolescence.

Understanding how and where resources become obsolete can be used to exert control over resource flows. Although planned obsolescence is a strategy criticised for disrupting and shortening resource flows (Burns, 2010; Packard, 1960), the specification of an appropriate lifetime is suggested to make consumption more sustainable and produce extended loops (Bakker, Wang, *et al.,* 2014; Burns, 2010; Den Hollander, 2018). An appropriate lifetime may aim at extending the life of resources by postponing obsolescence and can delay the turnover of resources to balance the environmental impact. Nevertheless, postponing obsolescence does not consider the fact that it must be considered where resources should go once they are obsolete (Papanek, 1985). Instead, the concept to plan-for obsolescence (Burns, 2010) suggests that the inevitable obsolescence of resources can be anticipated and facilitated. This idea captures the notion of making a positive impact, for example, by timely offering services that prevent leakage of resources (Breen, 2006; EMF, 2016; Sinha *et al.,* 2016). Planning-for obsolescence, thus, can be used to avoid the disruption of resource flows due to obsolescence (Choi *et al.,* 2018; Macleod, 2017; Oguchi *et al.,* 2010; Wilson *et al.,* 2017). Resisting, postponing and reversing obsolescence through recovery operations were found to preserve product integrity and extend resource lifetime (Den Hollander, 2018). Further understanding of the causes of obsolescence (Burns, 2010; Longmuss and Poppe, 2017) and a specified lifetime (Zeeuw van der Laan and Aurisicchio, 2017, 2019c) are thus likely to favour the closure of resource loops.

4.2.2. Consumers as key stakeholders

Consumers of FMCGs are key stakeholders in the flow of resources because they own the resources in the moment in which resources become obsolete. It is widely acknowledged that the role of these ‘resource owners’ is critical in influencing product-related impacts (e.g., Bocken *et al.,* 2016; Boks and Daae, 2017; Dewberry *et al.,* 2017. The activities required of consumers in revalorisation services are comparable to those in reverse logistics systems i.e., acquisition of obsolete goods; collection; inspection and sorting; and disposition (Agrawal *et al.,* 2015; Shih, 2001). In reverse logistic systems, obsolete resources move from business-to-business (B2B) (Agrawal *et al.,* 2015) in the opposite direction for the purpose of recapturing value or facilitating proper disposal (Breen, 2006; Östlin *et al.,* 2008; Souza, 2013). Responsible stakeholders typically sign a contract that outlines roles and responsibilities regarding the ownership and movement of resources. Although contracts are sometimes also used in business-to-consumer (B2C) consumption systems (e.g., leasing) to increase control over resources (Souza, 2013), contracts do not guarantee the return of obsoletes (Breen, 2006). Despite the fact that the roles of stakeholders in B2B and B2C imply similar activities, the dynamics between service providers and consumers in closed-loop FMCGs differ. Therefore, their specific and critical roles in closing loops requires further investigation (Charnley *et al.,* 2015; Den Hollander, 2018; McAloone and Pigosso, 2018; Zeeuw van der Laan and Aurisicchio, 2019c).

4.3. Methods

This work intends to understand and define the role of consumers in services offered to revalorise FMCGs. We aim to derive this role by studying the activities that consumers are instructed to carry out to use revalorisation services. Firstly, the study investigates these services to identify dimensions that characterise the role of the consumer in revalorisation. Secondly, the study investigates the implied weight of the role of consumers. This section presents the methods used to select, collect and analyse the data.

4.3.1. Data selection and collection

To study activities for consumers in revalorisation, data was collected on several revalorisation services. To ensure a complete picture of the role of consumer and avoid overlooking early activities that have implications for revalorisation at a later stage, the aim was to collect data on the entire consumption journey, i.e., from purchasing until disposing products. To do so, data was collected on revalorisation services part of PSSs. In addition, data was collected on household recycling services, which can be seen as the most common type of revalorisation service for FMCGs. This data focused only on the last steps of the consumption journey (e.g., disposing products) and allowed to deepen the understanding of the implications of the role of the consumer at this critical stage.

Revalorisation services: PSSs

A dataset of PSSs for FMCG was composed, constituting a revalorisation service to either reuse components or products, or to recycle materials; and offered in conjunction with specific product brands or product types. The PSSs involved a tangible FMCG that was purchased by a consumer and a revalorisation service offered directly to the consumer. The FMCGs are consumed rapidly, i.e., in minutes, days, weeks, and are prone to be re-purchased after consumption. Cases of PSSs were collected through searching the World Wide Web. First, the search focused on revalorisation services offered in common categories of FMCGs i.e., food and beverages, personal care, baby care, home care and office supplies. This involved searching for (variation of) the terms 'reuse' or 'recycling' in combination with a product type such as 'detergent'. Next, the search focused on revalorisation services without a specific product type, to find offers for short-used products in less common categories. These cases were compared to our definition of FMCGs in Chapter 2 to assess whether they could be considered an FMCG. A total of eighteen PSSs formed the final dataset.

The scope for data collection was narrowed by focusing on offers on the European market, representative of high-income markets. When identical PSSs were found for common schemes, only one was selected. For example, bottle deposit schemes are used in several European countries and their working mechanism was found to be the same. Grolsch' beer bottles scheme in The Netherlands was chosen to represent these schemes. PSSs were only selected if they were direct-to-consumer offers and were in operation at the time of the research (between April and May 2018) to allow collection of accurate information on the services. For example, Heineken's Forwardable Bottle is a promising concept, but at the time of the research was only available in bars and restaurants which manage the obsolete bottles. The revalorisation service in this PSS is directed to businesses rather than consumers and therefore it was not selected.

Only FMCGs that are part of PSSs were included. For example, FMCGs raising awareness of environmental issues such as Head&Shoulders' beach plastic bottle and Ecover's ocean plastic bottle do not include revalorisation services. Emerging reusable coffee cups and water bottles are rarely offered with services. The Keepcup, for example, can be used at any coffee company and it does not provide a specialised service. In contrast, Dopper's refillable water bottle is part of a PSSs in which an application provides a service to locate public water refill points. Revalorisation services offered for specific materials were also excluded. For example, take-back schemes of fashion brands are often operated by one of few third parties (Stål and Corvellec, 2018) and intend to collect any discarded piece of garment by placing drop-off points in stores of 'fast-fashion' brands. As such, this service is focused on specific materials and not specific branded products or product types.

The data collected involved information on PSSs available to consumers. All PSSs required consumers to carry out activities to make use of the services and the data described the instructions for consumers. All revalorisation services were offered either by the manufacturer or by a third-party partner. The websites of these companies included dedicated pages and FAQs to inform and instruct consumers on the activities required of them. The information included, for example, how to use the service; how many collected resources are worthy of rewards; or where to take resources. We collected this data at the time of research and used it to identify and define the activities that consumers must carry out to use the revalorisation service.

Revalorisation services: household recycling

A dataset of household recycling services was composed, constituting services offered in London's twelve inner Boroughs (i.e., Camden, Greenwich, Hackney, Hammersmith and Fulham, Islington, Kensington and Chelsea, Lambeth, Lewisham, Southwark, Tower Hamlets, Wandsworth and Westminster). All household recycling systems focused offered to collect specific materials rather than branded products or product types. The locations were chosen as they were local to the researchers and known to have differences in the services offered in the different Boroughs. This allowed to develop understanding on a variety of services offered to a large group of consumers with consistent demographics. As household recycling accept material types rather than branded products or product categories, different involvement may be required of consumers.

Similar to the approach to create the PSSs dataset, the collected data involved information provided to consumers. To ensure a complete representation of the different collection systems between and within the Boroughs we selected five active postcodes at random in each Borough. The instructions for household recycling in the United Kingdom can be found online through various government sources, which typically lead to Borough specific websites. Additional data was gathered through Recycle Now, which is an online website that provides information on the availability of recycling services per postcode and which items can be included in recycling. The information provided to consumers was copied from the different websites into an Excel spreadsheet to compose a complete view per borough. The information included, for example, how, when and how frequently recycling collection services are offered, such as collection times and days; where to obtain collect-and-return products, such as bin liners or reusable containers; instructions for specific items, such as to flatten your cardboard and plastic bottles.

4.3.2. Data analysis

This section presents the methods used to analyse the data. First, the cases in both datasets were compared and categorised based on components of the FMCGs and/or the revalorisation services. Second, the activities required of consumers were identified, compared and organised through customer journey mapping. This allowed to systematically dissect and compare the cases in each set as well as between sets. Finally, the locations used in revalorisation services emerged as significant to the implications of required activities and were analysed further.

4.3.2.1. Comparison of the revalorisation services

The eighteen PSSs were compared both on the product as well as the service, see Table 4.2. All products constituted consumable components, which determine the overall functional value of the products (De los Rios and Charnley, 2017). The FMCGs' consumable components are: used-up, such as the water in Dopper, or the detergents in Splosh; removed, such as the content in a Repack envelope; or worn-out such as the razor blades in Boldking or the coffee grounds in Nespresso capsules. After the depletion of the consumable components, the FMCGs become obsolete. Differently from the other cases, Kartent has only a consumable component and its residue is what becomes obsolete. All other FMCGs have a second type of component, which delivers or presents consumable components to users. Such facilitating components typically exist after consumption and may even remain intact when FMCGs have become obsolete. Except for Kartent, the revalorisation services aim to collect the facilitating components . Other type of components can be identified for some of the eighteen FMCGs. For example, BIC, Fuji, HP, Boldking and Preserve have packaging components, which are not categorised as facilitating components in Table 4.2, because the revalorisation service does not apply to these components. Components used for the consumption of FMCGs were also not considered, therefore excluding the Nespresso coffee machine used to consume the capsules; Boldking's razor handle used to assemble the cartridges; Drinkfinity bottle used to assemble pods; and the HP Printer used to print the ink from cartridges.

Many of the manufacturers of FMCGs manage their own revalorisation service, but some work with a third partner. TerraCycle emerged as a prominent third-party company providing

Table 4.2 PSSs of FMCGs (including facilitating (F) and consumable (C) components) with revalorisation services

	PSSs	FMCG		Revalorisation service		
		C components	**F components**	**Service**	**Collect-and-return**	**Close loops of**
Food and beverages	*Dopper*	Water	Reusable bottle	App locates water points		F components
	Drinkfinity	Concentrated flavourings	Pods	Take-back	TerraCycle post label	Materials
	Grolsch	Beer	Glass bottle and crown cap	Take-back	Grolsch crate	F components
	Jacob's	Biscuits	Wrapper	Take-back	TerraCycle post label	Materials
	Milk&More	Milk	Glass bottle and foil cap	Take-back		F components
	Nespresso	Coffee grounds	Single-use capsules	Take-back	Nespresso envelop or post label	Materials
Home care	*Ecover*	Detergent	Reusable bottle	Refill station		F components
	Splosh	Detergent	Reusable bottle	Refill delivery		F components
Office	*BIC (pen)*	Ink	Pen components	Take-back	TerraCycle post label	Materials
	Fuji (dispo camera)	Film	Camera components	Photo development		F components
	HP	Ink	Cartridge components	Take-back	HP envelope	Materials
	Repack	Various e-commerce	Reusable envelope	Take-back	Repack address label (part of envelope)	F components
Outdoor	*Kartent*	Cardboard tent		Collection		Materials
Personal care	*Boldking*	Metal blades	Cartridge components	Take-back	Boldking envelope	Materials
	Garnier	Cosmetic	Plastic bottles	Take-back	TerraCycle post label	Materials
	Lush	Cosmetic	Plastic pots	Take-back		Materials
	MAC	Cosmetic	Plastic pots	Take-back		Materials
	Preserve	Bristles	Handle	Take-back	Preserve post label	Materials

Table 4.3 Three types of revalorisation services for household recycling

Borough	Revalorisation service		
	Reusable containers	**Non-reusable bags**	**Communal containers**
Camden	Green recycling container	Recycling bags	
Greenwich	Blue-top bin	Clear sacks	Communal bins
Hackney		Green sacks	Communal bins
Hammersmith and Fulham		Smart Sacks	Reusable bag*
Islington	Green boxes	Clear bags	Communal bins
Kensington and Chelsea		Clear recycling bags	Mixed bank recycling
Lambeth	Green wheelie bin	Clear recycling sack service	Green communal bins
Lewisham	Green reusable recycling bins / recycling wheelie bins	Clear sacks	Communal recycling bins
Southwark	Blue wheelie or blue box	Clear non-reusable sack	Blue Communal Bin
Tower Hamlets	Purple wheelie bin	Clear non-reusable sack	
Wandsworth		Clear non-reusable sack	Orange lid communal bin*
Westminster	Black box	Clear non-reusable sack	Communal recycling bins*

** reusable bags are available to transport recyclables to communal containers* revalorisation services for multiple cases in the dataset. Most of the revalorisation services are take-back services. However, in some PSSs the offer of other types of service resulted in closed loops of components and materials. The services are presented in Table 4.2. We further characterised the revalorisation service based on the type of resource linked to revalorisation i.e., components or materials and the resources provided to collect and/or return obsolete FMCGs.

The twelve London Boroughs were compared only on the service, since they accept a wide range of products based on different material specifics. Despite the many differences in household recycling between Boroughs, the service offerings could be structured in three main types of revalorisation services, see Table 4.3. The three types are named after the collect-and-return products offered. The communal containers required consumers not to use any bin liners, but some of the Boroughs offered reusable bags for consumers to gather recyclables and enable the transport to their nearest communal container. Interestingly, all Boroughs offered multiple types of services, which appears to be linked to the fact that different property types have different requirements for collection. All services involved a form of mixed recycling, supposedly simplifying the tasks for consumers to sort, separate and store different resources based on material.

Customer journey mapping

A CJM is a visual representation of an individual's experience with products and services over time (Crosier and Handford, 2012; Shih, 2001; Stickdorn *et al.,* 2016). CJMs can be used to present all the steps that customers go through (Bellos and Ferguson, 2017) and have already been used to understand the role of stakeholders in circular business models (Antikainen and Paloheimo, 2017; Sinclair *et al.,* 2018; Stål and Corvellec, 2018). The main actor in our CJMs is the consumer . CJMs are often used to represent a first encounter with a product (Bettencourt and Ulwick, 2008; Crosier and Handford, 2012; Johnston and Kong, 2011; Shih *et al.,* 2006) but we used them to map the consumer's common and repeated journey. The journey included the FMCGs' complete use cycle split in three stages: purchase, use and disposal . This has allowed to observe whether early commitment was used to engage customers in revalorisation (Breen, 2006).

Customer journey mapping was used to dissect the revalorisation services and identify and compare the activities that consumers are required to carry out, and analyse the factors that have implications for carrying out the activities. The CJMs are research-based (Stickdorn *et al.,* 2016) as the steps are defined based on the data collected from service providers' websites. Each step in the CJM represents an activity that required of consumers. The activities are marked by touchpoints that indicate when consumers interact with products and services (Stickdorn *et al.,* 2016). The activities and touchpoints of each PSS were mapped in a CJM as presented in Figures 4.1 and 4.2. The full set of CJMs is included in Appendix A. This visual representation was performed systematically to allow for comparison of PSSs and identification of similarities and differences.

Some PSSs offer multiple routes to purchase or revalorise the FMCG, in which case only one route was mapped. For example, TerraCycle commonly offers both the delivery of items to one of their drop-off locations, or the assembly of a parcel and its shipping by post. If present, the post box option was mapped TerraCycle's take-back schemes, as their drop-off points

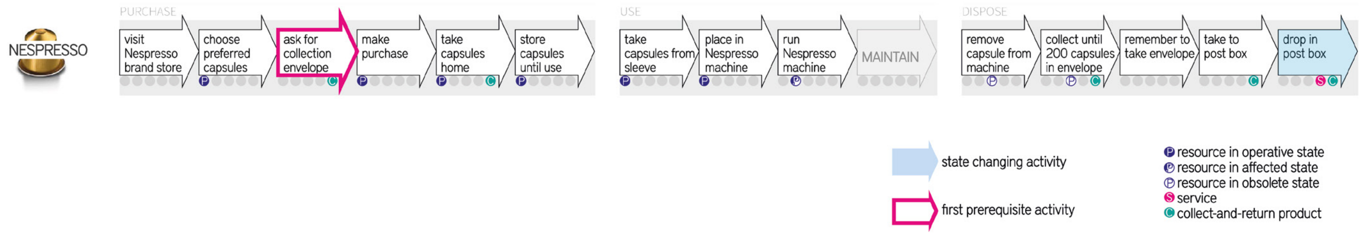


Figure 4.1 Example of a CJM constructed for PSSs (Nespresso)

seemed less widespread in Europe. For brand stores that offered post and in-store option, drop-off in brand stores was mapped. Further, the common journey of offline sales of FMCGs was mapped, except if the goods were only available through online channels (i.e., Boldking, Drinkfinity, Kartent, Milk&More, Repack, Splosh, Preserve).

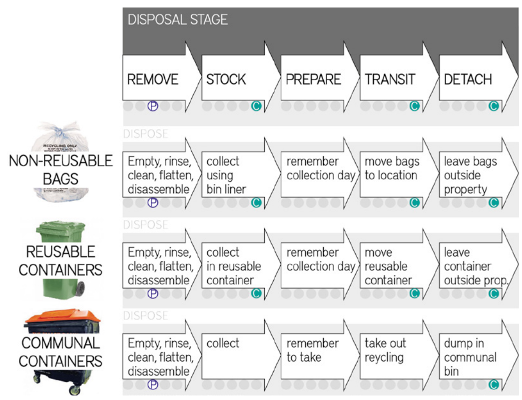


Figure 4.2 CJMs for the three type of household recycling services .

Activities

The activities were derived from the information gathered on the PSSs and household recycling services. The activities in the were coded and categorised to develop a set of activities that reoccurred in the PSSs, see Table 4.4. To ensure early activities that are required for revalorisation were captured, the entire consumption journey was captured and structured in three stages i.e., purchase, use and disposal. The activities always occurred in the sequence presented in Table 4.4. In all PSSs, consumers 'become owner' and 'consume' but the other activities did not always occur. Several activities, however, were commonly required. For example, despite variety in the service locations (e.g., post boxes, drop-off points) the activities required of consumers in the disposal stage of these PSSs always included 'stocking', 'preparing' and 'transiting'. Further, as can be seen in Table 4.4, some activities reoccurred in multiple stages of the journey. For example, numerous activities in all three stages could be categorised as 'preparing' activities and all PSSs included such activity at least once in the journey.

For the household recycling services only activities in the disposal stage were mapped, see Table 4.5. Although the activities could be aligned with those in the disposal stage of the PSSs, they used different touchpoints. Nevertheless, the instructions implied that there were activities required of consumers before the disposal stage, such as obtaining bins or collect-and-return products; as well as after the disposal stage, such as taking reusable containers or reusable bags back into one's property. There were differences in the required activities per Borough, for example, Kensington and Chelsea emphasised to remove lids and tops of packaging, while Lewisham noted that this is not necessary for bottles and jars. Most likely, the logic behind these nuances in instructions are the result of the capabilities of the Material Recovery Facility to which a Borough transports the collected resources. The activities were summarised and captured with the afore defined activity to 'remove'.

Touchpoints

Touchpoints are direct and indirect interactions of consumers with products and services during activities. Touchpoints were categorised in five categories presented in Table 4.6. Touchpoints could be identified for all activities but not all touchpoints were identified for each activity, see Table 4.4 and 4.5. The activities 'visiting (web)shops' and 'preparing' (in disposal stage) are the only two that occurred without any touchpoints in one or more

Table 4.4 Activities required in PSSs.

	Activity	Possible touchpoints	Description
Purchase stage	'visit (web)shop'	· · · S ·	Visit a retailer, brand-specific store or access a web-shop online.
	'choose product'	P · · S C	Select FMCG from the (online) offering.
	'prepare'	P · Ⓟ S C	Add a collection-and-return product or refill consumable.
	'purchase'	P · · S C	Make payment.
	'become owner'	P · · · C	Take home, receive or go to FMCG.
	'stock'	P · · · ·	Keep inventory of operative resources.
Use stage	'remove'	P · · · C	Unpack for consumption (removed parts are not revalorised).
	'prepare'	P · Ⓟ · ·	Assemble FMCG or refill consumable.
	'consume'	· P′ · S ·	Deplete consumable components.
	'maintain'	· P′ · · ·	Extend lifetime of affected resources.
Disposal stage	'remove'	· · Ⓟ · ·	Disassemble and remove residue consumables (removed parts are not revalorised).
	'stock'	· · Ⓟ · C	Keep inventory of obsolete resources.
	'prepare'	· · Ⓟ S C	Assemble parcels of obsolete resources and/or plan and remember to take them into transit.
	'transit'	· · Ⓟ · C	Move obsolete resources to designated locations.
	'detach'	· · Ⓟ S C	Deposit or abandon obsolete resource.

Table 4.5 Activities required in household recycling services.

	Activity	Possible touchpoints	Description
Disposal stage	'remove'	· · Ⓟ · ·	Empty, rinse, clean, wash and dry resources; squash, flatten or compress containers and large items; do or don't remove lids and labels.
	'stock'	· · · · C	Keep inventory of obsolete resources.
	'prepare'	· · · · ·	Plan and/or remember to take resources into transit.
	'transit'	· · · · C	Move obsolete resources to designated locations, sometimes at set times.
	'detach'	· · · · C	Deposit resources or leave outside property.

cases. Touchpoints may be sensitive to atmosphere and time (Stein and Ramaseshan, 2016). Accordingly, the conditions of the FMCGs in PSSs were found to change over time as a result of consumption. For example, FMCGs increasingly deteriorate in the course of their consumption until they become obsolete. In the literature it has been suggested that recovery operations can reverse obsolescence (Den Hollander, 2018). The conditions in which resources are considered obsolete are thus impermanent. In fact, obsolete resources were found to change into 'as new' resources through revalorisation services e.g., a refill service. The term state was used to categorise resources in three specific conditions. Resources in operative state are FMCGs equipped with both consumable and facilitating components with a value equal to a finished

Table 4.6 Categorised touchpoints and their descriptions.

	Touchpoint	Description
P	Resource in operative state	FMCG as new.
P′	Resource in affected state	FMCG's state has changed due to consumption.
Ⓟ	Resource in obsolete state	FMCG can or is no longer used or is no longer needed.
S	Service	Any service offered during the use cycle.
C	Collect-and-return product	Items provided to consumers to make use of revalorisation services.

good. FMCGs can also be in a state in which consumables are visibly diminished or there are signs of wear, but they are not yet obsolete. This was named the affected state. The obsolete state was assigned to resources that can no longer be used or are no longer needed.

The service touchpoints include a variety of services. Mapping the entire use cycle ensured service touchpoints were included that were contextual to the revalorisation services such as online sales channels or subscription services. Post boxes and offline sales in retail or brand-specific stores were, therefore, not marked with a touchpoint. The mapped service touchpoints include interactions between consumers and companies through the web, mobile applications, software, refill stations and drop-off locations. The touchpoint named 'collect-and-return products' includes the resources that are provided to or acquired by consumers to make use of some of the take-back services. Common types in PSSs include containers, envelopes and post labels for a self-assembled parcel. For household recycling services the common types align with the types of revalorisation service i.e., non-reusable

Table 4.7 Information related to locations of the revalorisation services.

	Revalorisation service	Locations		
		Whereabouts	Time	How to use
Household recycling	*Non-reusable bags*	• On the pavement in close proximity of one's property	• Usually weekly at set times	• Position without causing obstruction • May be fined for leaving rubbish, using wrong hours, causing obstruction • Must be in the right reusable container or non-reusable bag
	Reusable containers			
	Communal containers	• Located at or near the property	• Use at specific hours to not disturb the neighbours	• Do not typically accept bin liners
PSSs	*BIC (TerraCycle)*	• Located at elementary schools	• Opening hours of venue	• Find and drop in TerraCycle box
	Boldking	• Post box		• Boldking envelope can contain 12 razors at once
	Dopper	• Water fountains in public locations e.g., parks • Water taps inside e.g., pubs	• Any time • Opening hours of venue	• Locate refill points through the app
	Drinkfinity (TerraCycle)	• Post box	• Any time	
	Ecover	• Selected retailers have refill stations	• Opening hours of venue	• Refill at the refill station
	Fuji disposable camera	• Specialised shop offering photo development service	• Opening hours of venue	• Leave camera
	Garnier (TerraCycle)	• Post box	• Any time	• Bundle and apply TerraCycle post label
	Grolsch (bottle deposit)	• Selected retailers accept it	Opening hours of venue	• Enter bottles or crates with bottles into the reverse vending machine
	HP cartridge	• Post box	• Any time	• HP envelope can contain up to 3 cartridges
	Jacob's (TerraCycle)	• Post box	• Any time	• Bundle and apply TerraCycle post label
	Kartent	• Campsite of the festival	• Set time at end of festival	• Have left the tent
	Lush	• All Lush brand stores	• Opening hours of venue	• Five pots needed for free product
	MAC	• All MAC brand stores	• Opening hours of venue	• Six items needed to receive reward
	Milk&More	• Doorstep of your property	• Delivery at agree and set times	• Place them outside the night before
	Nespresso	Post box	• Any time	• Preferred to fill the collection envelope i.e., 200 capsules
	Repack	• Post box	• Any time	
	Splosh	•Personal mailbox at home	Delivery is during office hours	• Fits through mailbox • Consumer does not have to be in
	Preserve	• Post box	• Any time	• Five items needed to receive discounts

bags, reusable containers and communal containers. Each type is indispensable to the use of the revalorisation service.

4.3.2.2. Analysis of locations used in revalorisation services

The activities indicated that obsolete resources must reach specific locations. These locations, therefore, emerged as significant to the implications of activities. Information in the collected data that was specific to the description of the location and the use of locations was gathered and organised, presented in Table 4.7. The data gave indications on the whereabouts of locations, e.g., on the pavement in close proximity to one's property (non-reusable bags and reusable containers), in elementary schools (BIC), in a select number of retailers (Ecover), regular post boxes (e.g., Boldking, Dopper); at what time (not) to use locations, e.g., opening hours of retailers or schools (Lush, MAC), weekly set times (non-reusable bags and reusable containers), hours that do not disturb neighbours (communal containers), after a new delivery is scheduled (Milk&More, Splosh); and how (not) to use locations, e.g., with or without bin liners (dependent on household recycling service) or other collect-and return products, with a specific amount of resources (e.g., Lush, MAC, Boldking).

The locations varied, although there were also similarities between them. For example, locations might be visited regularly such as public post boxes, drop-off boxes in schools or communal containers in residential areas. However, consumers may have to deposit obsolete resources or obtain consumable components in locations that are more exclusive such as a brand-specific store, or selected retailers. Some locations were nearer to the consumer, for example, by using the consumer's own doorstep at specific times. In some cases, the location coincides with where resources are consumed and become obsolete, such as a music festival site where obsolete components are left behind and a home where consumable components are delivered directly.

4.4. Characterisation of the roles of consumers

Four archetypical roles of consumers were modelled using the four dimensions that emerged from the analysis of the eighteen PSSs. The dimensions are: the form of obsolescence; the resource state change; the prerequisite activity; and the facilitators (i.e., efforts and investments) of activities. In the analysis, we aimed at identifying how resources in the PSSs flowed by investigating: why and how FMCGs change to the obsolete state; what activities consumers of PSSs must carry out to make resources lose the obsolete state; and what these activities entail.The archetypical roles and their variants are mapped against the dimensions in Table 4.8. The roles are named after the implied interaction between the consumer and the obsolete resource.

1) ***Keep obsolete resources***. The depletion of the consumable components makes the facilitating components functionally obsolete, although they remain intact. Consumers *keep* the obsolete resources and replenish them with new consumable components so that they become operative again. Two variants of this role emerged based on when the prerequisite revalorisation activities must be carried out, when effort is invested by consumers, and what incentives exist.

2) ***Bring obsolete resources***. Although a few facilitating components remain intact, they are mostly impacted or altered due to consumption or remain assembled to consumable

components once they become obsolete. Consumers *bring* obsolete resources to designated locations where they deposit them without further ado. Once deposited in the designated locations, resources can be intercepted by service providers and thus become recoverable. Four variants of this role emerged based on the different prerequisite activities for revalorisation, the investment of money or effort, and the existence or not of an explicit incentive.

3) ***Consign obsolete resources***. Both the facilitating components and the residue of the consumable become obsolete but remain inseparable. Consumers see value in the residue of the consumable and, therefore, *consign* the obsolete resources to service providers who can retrieve the value for them. In contrast to bring, consumers who consign make certain that the obsolete resource is received. Their invested effort moves the recoverable facilitating components to the service providers for interception.

4) ***Abandon obsolete resources***. With absence of facilitating components, it is the residue of the consumable that becomes obsolete at the end of an agreed use cycle. Consumers *abandon* obsolete resources in designated locations at set times as the place and time for use are predefined. Consumers are incentivised by the convenience to leave behind the resources.

In Figure 4.3 the four roles are marked on the lifecycle of resources composed of origin, production, use and end of life phases. In the use phase consumers are involved in the flow of resources. Once the resources have become obsolete consumers actively contribute to establishing the flow of resources in one of two ways. Consumers who *keep* obsolete resources establish a closed-loop flow by changing obsolete resources into operative resources, essentially reusing components. Consumers who *bring, consign and abandon* resources establish a closed-loop flow by changing obsolete resources into recoverable resources. These will either be components that are reused or materials that are recycled. As can be seen from Table 4.8 the most common role is *bring* (13) obsolete resources followed by *keep* (3) obsolete resources, and *consign* (1) and *abandon* (1) obsolete resources. In the remainder of this section, we elaborate on the dimensions and how they are used to model these archetypical roles.

Table 4.8 Four archetypical roles and the dimensions used to model them. The various stages of the customer journey are indicated with p: purchase stage; u: use stage; d: disposal stage.

Role of consumer	PSSs	Form of obsolescence	State change to	Prerequisite activity	Facilitators	
					Investments	Incentives
1) Keep obsolete resources	Splosh	Functional	Operative	'purchase' (p)	Efforts (u)	Implicit
	Dopper, Ecover	Functional	Operative	'prepare' (d)	Efforts (p)	Explicit
2) Bring obsolete resources	Boldking	Technological	Recoverable	'prepare' (p)	Money	None
	Grolsch, Milk&More, Repack	Qualitative [Grolsch, Milk&More] Functional [Repack]	Recoverable	'purchase' (p)	Money	Explicit
	HP, Nespresso	Programmed	Recoverable	'unpack' (u) [HP] 'prepare' (p) [Nespresso]	Effort (d)	None
	BIC, Preserve, Jacob's, Garnier, Lush, MAC, Drinkfinity	Technological [BIC, Preserve] Qualitative [Jacob's] Functional [Garnier, Lush, MAC] Programmed [Drinkfinity]	Recoverable	'stock' (d)	Effort (d)	Explicit
3) Consign obsolete resources	Fuji	Programmed	Recoverable	'prepare' (d)	Effort (d)	Implicit
4) Abandon obsolete resources	Kartent	Situational	Recoverable	'purchase' (p)	Effort (p)	Implicit

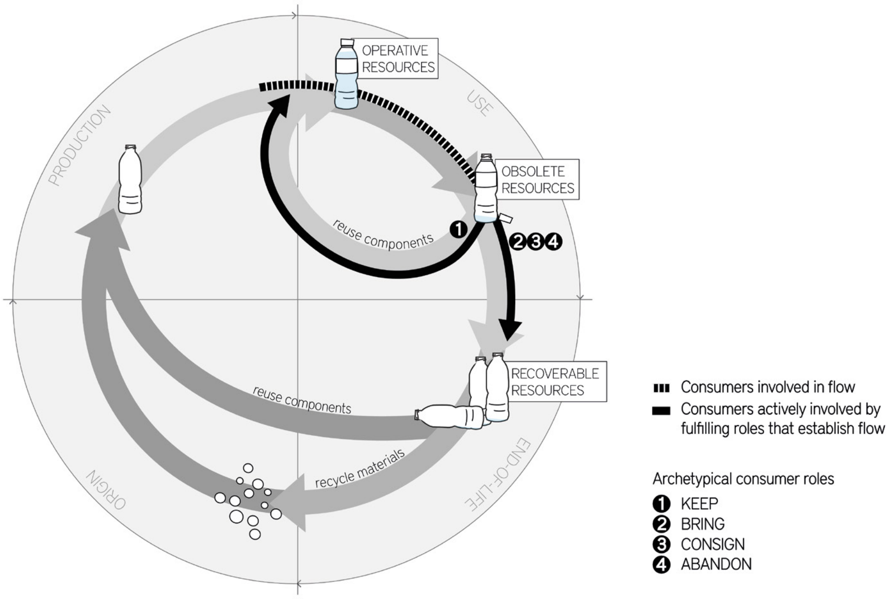


Figure 4.3 Representation of the resource lifecycle illustrating the involvement of consumers in the flow of resources and the influence of the four archetypical consumer roles.

4.4.1. Form of obsolescence

Resources in the obsolete state and the manifestation of this state were studied in-depth to diagnose the form of obsolescence in each PSS. We distinguished indicators of obsolescence and the condition of the resource in the obsolete state as presented in Table 4.9. Three forms of obsolescence were identified in line with those described in the literature: technological, qualitative and functional obsolescence. Two additional forms have been named programmed and situational obsolescence.

Some consumable components of FMCGs are sensitive to wear and tear such as Boldking's razor blades and Preserve's toothbrush bristles. The worn-out components cannot be easily disassembled from the unaffected facilitating components, which might explain why only the materials are revalorised. Consumers are likely to use affected resources until the experience becomes too unsatisfying compared to consuming the identical but new and better-performing resources in the operative state. Consumers' final decision to replace the resource is subject to the availability of the new resources. The value consumers can perceive

Table 4.9 Forms of obsolescence and their causes as identified in the PSSs.

Obsolescence	Cause	Indicators	PSSs	Resource in obsolete state	
Technological (relative)	A newer version is available that performs the function better.	Wear and tear	BIC, Boldking, Preserve	Facilitating components assembled	Residual consumable
Qualitative					
(absolute)	Break down or wear.	Clearly visible	Grolsch, Jacob's, Milk&More,	Facilitating components impacted	Consumable used-up
Functional (absolute)	The functions of components are no longer used.	Clearly visible	Dopper, Ecover, Garnier, Lush, Mac, Repack, Splosh	Facilitating components intact	Consumable used-up
Programmed					
(absolute)	There is a threshold to the number uses.	Clearly indicated	Drinkfinity, HP, Fuji, Nespresso	Facilitating components altered and assembled	Residual consumable
Situational (absolute)	The duration of the use cycle and the location of use are fixed.	Clearly indicated	Kartent		Residual consumable

of FMCGs is thus influenced both by the performance of the FMCG as well as by the presence of its replacement.

Qualitative obsolescence

Consumption can damage facilitating components causing them to break-down. Damage to components devalue them as it compromises the ability to reuse components such as for Jacob's wrappers, Grolsch' crown cap, and Milk&More's foil cap. Nevertheless, some of the facilitating components might remain undamaged and can become operative again albeit after expert processing and replacement of the damaged components such as for Grolsch' and Milk&More's bottles.

Functional obsolescence

With consumable components used-up, functions of facilitating components such as containing, preserving and transporting are no longer used making these components obsolete. All PSSs in which we identified functional obsolescence involved packaging and the facilitating components remained intact. This form of obsolescence is suitable for keep, as undamaged components demonstrate potential value to consumers, exemplified by the reusable bottles of Dopper, Ecover and Splosh. Functional obsolescence is also appropriate if providers intend to revalorise components rather than materials such as Repack for bring.

Programmed obsolescence

Although not grounded in the literature, the term programmed obsolescence has occasionally been used in the biology literature to describe the ageing of cells (Fragala, 2015; Orgel, 1973). Cells, such as those in the human body, are suggested to have an intrinsic biological or molecular clock that counts a predetermined and finite number of cell divisions, after which they become obsolete (Blythe and Macphee, 2013). The term is used here because a similar threshold was observed for the number of uses of FMCGs: Nespresso's capsules and Drinkfinity's pods can be used once; Fuji's cameras count-down 27 photos; and HP's software sets a predetermined threshold for the use of a cartridge. Once the threshold is reached, the FMCG is unable to deliver the initial value again. Further uses are prevented because consumable components are depleted, or consumption has altered the facilitating components. The alterations to facilitating components are not necessarily irreversible, but their recovery generally requires specialist disassembly from the residue of consumable components.

Situational obsolescence

If the use cycle of a resource is agreed on with the consumer, the resource can no longer be used by or deliver value to the consumer after the agreed use time or outside the agreed location. The resource thus becomes obsolete because the duration of the use cycle and location of use are fixed. This form of obsolescence was identified only for Kartent, who defined use time as the duration of the festival and the location of use as the festival site.

4.4.2. Resource state changes

A variety of offerings were identified as revalorisation services, including refill stations and take-back services. All services were found to close resource loops by permitting resources to lose the obsolete state. Obsolete resources changed either to the operative state, in which they instantly became 'as new', or to the recoverable state, in which they were recovered

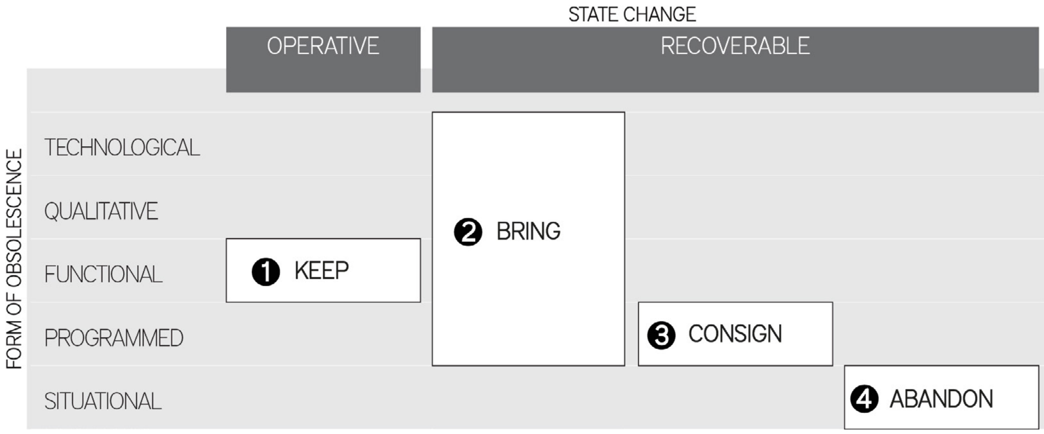


Figure 4.4 Archetypical roles mapped against state change and form of obsolescence.

through further processing steps. The two types of state changes are mapped against the forms of obsolescence in Figure 4.4.

A change to the operative state

Services that permit consumers to replenish obsolete facilitating components with new consumable components make obsolete resources operative. Resources can only become operative if consumers invest time to either to go to a refill station or request the delivery of consumables. The change from an obsolete state to an operative state is only modelled for keep. Resources become operative during 'preparatory' activities in which packaging is replenished with consumable components. Consumers 'prepare' either in the purchase or the use stage. Consequently, carrying out those activities closes the loop and extends the lifetime of facilitating components. It is worth noting that it is important for the facilitating components to remain intact to reverse from the obsolete to the operative state without the need for complex processing of resources.

A change to the recoverable state

Obsolete resources that await recovery have been defined as presources (Den Hollander, 2018). However, to permit their recovery, obsolete resources must be intercepted in volumes sufficient for economic resource recovery processes. Interception takes place in designated locations where service providers have systems in place for further processing. Resources are positioned in these locations if consumers carry out required activities. Once there, the resources become recoverable as soon as consumers 'detach' from them. In the simplest form this implies that consumers bring obsolete resources to designated locations. In the studied PSSs we identified designated locations as common as public post boxes and schools, as well as more exclusive locations such as brand-specific stores.

Resources can also be intercepted in locations where consumers consign obsolete resources to retrieve value, such as in photo developing shops. Due to programmed obsolescence, the residue of the consumable component and the facilitating component remain assembled. Only the photo developer can disassemble the obsolete resources and separate the valuable residue from the facilitating components. Hence, the activities carried out by consumers position all components in the designated location, permitting interception of the facilitating components. Service providers can also intercept obsolete resources in locations where consumers abandon them. Situational obsolescence can then be used to position obsolete resources in designated locations at set times.

4.4.3. Prerequisite activities

Resources were found to lose their obsolete state during one of two activities i.e., 'prepare' or 'detach'. Nevertheless, those activities could only be carried out if consumers had performed prior activities. One or multiple activities were found to be essential for revalorisation in each PSS. We defined the first indispensable activity for each PSSs as the prerequisite activity and used it to model the archetypical roles. Only the five activities highlighted in Figure 4.5 were found to be possible prerequisites.

'Prepare' (purchase stage)

Consumers may be required to 'prepare' for revalorisation as early as in the purchase stage. In several PSSs, consumers must obtain a collect-and-return product before making a purchase if their role is to bring obsolete resources. 'Prepare' is the first indispensable activity for two PSSs: Boldking's consumers must add a stamped envelope to their order of blades; and Nespresso's consumers must request the envelope.

'Purchase' (purchase stage)

The consumers of Grolsch, Milk&More and Repack's 'purchase' not only the FMCGs but also a surplus to use the revalorisation service. These three PSSs interestingly are the only variants of bring that aim to reuse the components rather than recycle the materials that embody them. 'Purchasing' can also be the prerequisite for keep if consumers must order consumable components that are indispensable to make obsolete resources operative, such as for Splosh. Finally, to permit to abandon obsolete resources, consumers must plan far ahead and 'purchase' a Kartent in advance of the event.

'Remove' (use stage)

For HP, consumers stumble on the collect-and-return product when removing the FMCG from its packaging. As the stamped collect-and-return envelope is indispensable, consumers must 'remove' it from the packaging but also retain it until the cartridge becomes obsolete and needs to be returned to HP.

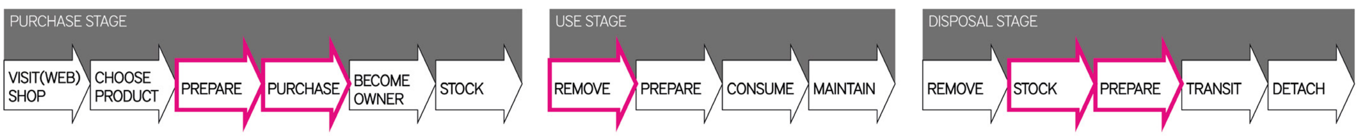
'Stock' (disposal stage)

It is not uncommon for service providers to only accept and sometimes reward a minimum amount of resources that are intercepted as a bundle. For example, Lush and MAC exchange five and six obsolete resources respectively for a free product. It appears that such 'stocking' is the first prerequisite activity for the majority of PSSs in which consumers bring obsolete resources to designated locations. Preserve and the four PSSs operated by TerraCycle use the public post box system to intercept resources. In those cases, the successive activity requires consumers to 'prepare' by retrieving accessible, free-of-charge and downloadable collect-and-return products to assemble and stamp the bundle. It must be noted that these PSSs also offer alternative journeys such as drop-off points which have not been mapped.

'Prepare' (disposal stage)

Physical movement of obsolete resources to designated locations is an indispensable

Figure 4.5 The activities that can be prerequisites for state changes.



activity in many PSSs. However, prior to 'transit' consumers must carry out 'preparatory' activities such as planning and remembering to move obsolete resources. This requires of consumers to invest time to organise and plan the movement of obsolete resources into 'transit'. The logistical management of resources were not supported by any service provider. 'Preparatory' activities can be the prerequisite for two roles. First, consumers who keep obsolete resources may be required to remember to take them to refill points. Second, consumers who consign will only retrieve the value they see in the residue of the consumable if they remember to take obsolete resources to the photo developing service provider.

4.4.4. Facilitators of activities

Carrying out prerequisite activities and other indispensable activities depends on the motivation of consumers. The CJMs were studied to understand what brings about such engagement. We defined the engagement-creating elements as facilitators and categorised them into investments if they were input made by consumers, and incentives if they were output of the system from which consumers benefitted. We found combinations of investments and incentives as presented in Figure 4.6 and used them to model variants of archetypical roles.

4.4.4.1. Investments

Investment of money

In some PSSs for bring consumers were required to pay-into revalorisation services when 'purchasing'. Money was either paid as a deposit or for the collect-and-return product. Such facilitators seem a way of creating an early commitment to the PSSs.

Investment of effort

If there was no monetary investment, we identified investment of effort in one single or multiple activities. Efforts include, for example, time required for planning and transportation; or space required to 'stock' products. Efforts were invested in activities during which the state changes, in the prerequisite or in the successive indispensable activities. If the key investment was effort, we distinguished whether the purchase, use or disposal stage required most effort.

An early investment of effort is made for abandon. Kartent's consumers are 'purchasing' the FMCG exceptionally far in advance to its consumption, which is an investment of effort as it requires planning. This is important for the PSS as it allows the provider to organise logistics for resources from the designated location. An early investment of effort is made for keep when 'preparing' in the purchase stage to replenish obsoletes with consumable components at designated locations such as at refill stations in retailers, e.g., Ecover. The same activity for this role can occur in the use stage, e.g., Splosh. However, the efforts to order Splosh' refills online at the consumer's convenience are probably less costly compared to time-intensive

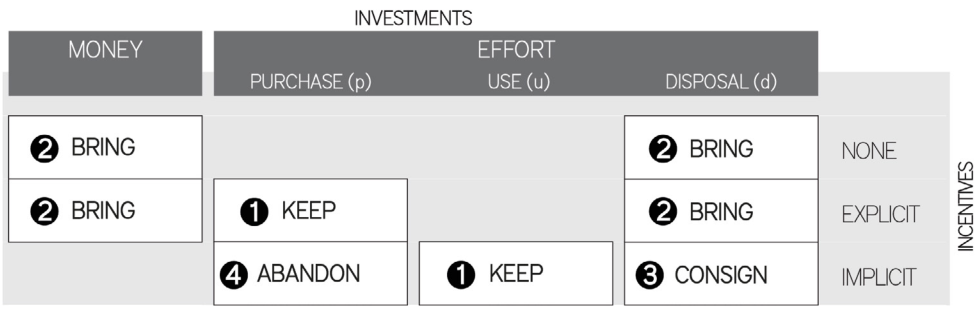


Figure 4.6 Archetypical roles mapped against investments and incentives.

'preparing' activities such as planning and remembering to take obsolete facilitating on a visit to a specific store.

Effort could also be invested in the disposal stage, as is common for bring, for example when 'stocking' is the first prerequisite activity. If the collect-and-return product required to use a revalorisation service is provided for free, this eliminates the need for early consumer investment. Instead, the efforts are all made in 'stocking', 'preparing' and 'transiting' obsolete resources. This is a similar effort to that invested in the disposal stage for consign, for which consumers are required to 'prepare' to organise 'transit' of the obsolete resource. The effort that consumers must invest in each of the activities for the different PSSs depends on factors such as travel distance to the location, how often they have to visit the location or how many resources they have to stock.

4.4.4.2. Incentives

None

Although two variants of bring required an investment of money or effort in the disposal stage, they had no identifiable incentive. We assume that the providers of these services depend on the intrinsic motivation of consumers (Steg and Vlek, 2008) for their engagement.

Explicit incentives

Explicit rewards including money, vouchers, deposits, TerraCycle collection points and free or discounted products are categorised as explicit incentives. These are used both for keep and bring to motivate consumers. For bring, explicit incentives were either the pay-back of the monetary investment or a stand-alone reward possibly introduced to compensate for the invested efforts. For keep, explicit incentives included free consumables such as the water from public refill points or discounted consumables such as detergents from refill stations. As the explicit rewards have low monetary value, the materialistic value that consumers can attribute to them seems low and suggests that they are probably only complementary to consumers who may be also incentivised by external factors such as intrinsic motivation.

Implicit incentives

Other incentives were identified, although they were not as explicit. An implicit incentive is, for example, increased convenience experienced as a result of the use of the service. For example, to abandon a Kartent is more convenient than carrying a durable tent back and forth. For keep, receiving your refills at home is more convenient than going to a store to purchase them. Another type of implicit incentive was identified for consign as the value that consumers see in the obsolete resource is what motivates them to carry out the activities. In that case specifically, the incentive, to 'prepare' and 'transit' an obsolete camera to a photo developing service where the facilitating components are intercepted for reuse is simply to retrieve one's photos.

4.5. Gateways to revalorisation

The four archetypical consumer roles provide understanding of the role that consumers have in closing loops. Although the activities required of consumers in all PSSs are comparable, the four dimensions used to characterise the roles indicate that the weight of these roles is subject to various factors. The locations associated with revalorisation appeared to impact this weight in different ways. For example, to keep a Splosh bottle and receive refills via post at home, seems to be less of a burden than to keep an Ecover bottle and visiting a refill station. The first study has made it evident that the role of consumers involves managing and operating certain logistics that are essential to placing obsolete resources in specific locations. In this study, we define these locations as 'gateways' as they represent entry points for obsolete resources to revalorisation. Five types of gateways emerged from our second study, see Table 4.10.

1) ***Timebound assigned spots***. These locations are impermanent gateways through which specific resources can enter revalorisation only during specific timeslots. For example, consumers can place empty milk bottles on their doorstep prior to delivery of new milk by Milk&More. The timeslots may be harsh, as consumers in some Boroughs even risk to be fined if they place non-reusable bags for household recycling on the kerbside outside the timeslot. Reusable bins or non-reusable bags (i.e., bin liners) must be used by consumers to inform collectors on the type of resources offered. These collect-and-return products are typically freely available to consumers but may have to be collected or requested.

2) ***Open-access drop-off***. Some gateways are not exclusive to specific resources nor revalorisation services. Rather, they are a gateway to a generic infrastructure to transport resources. For example, consumers can place empty Repack envelops into royal mail post boxes. All the cases using post boxes involve royal mail, which allows entries at any time and are typically widely available in residential areas. The collect-and-return products such as envelopes and labels, are essential to bundle, protect and address resources. These collect-and-return products had to be obtained and sometimes paid for by consumers.

3) ***Regular venues***. Some gateways are located in regularly visited places such as in or near common retailers or schools. For example, TerraCycle places numerous drop-off points

Table 4.10 Types of gateways and examples from the studied FMCGs illustrating similar activities related to each of the gateways.

Household recycling					
	Non-reusable bags, reusable containers		Communal containers		
PSSs					
	Milk&More	Boldking, Drinkfinity (TC), Garnier (TC), HP cartridge, Jacob's (TC), Nespresso, Repack, Preserve	BIC (TC), Dopper, Grolsch	Ecover, Fuji, Lush, MAC	Kartent, Splosh
Gateway	*Timebound assigned spots*	*Open-access drop-off*	*Regular venues*	*Exclusive venues*	*Consumption scene*
	Pavement near property, doorstep	Post box, public water fountain	Residential areas, building storage, retailers, schools	Brand-specific or service-specific stores, selected retailers	At home, on site

in central places such as elementary schools to collect segregated resources. Although such locations are regularly visited, the access to the box is subject to opening hours of the venue. Similarly, gateways in the form of communal bins are situated in locations in residential areas regularly passed by consumers. Due to noise disturbance, most Boroughs suggest that communal bins should not be used at inconsiderate hours. Only few of the household recycling services using communal containers offer a reusable bag to help the consumer sort and transport the recyclables. Similarly, Grolsch' beers can be bought in a crate which can be returned together with the empty bottles.

4) ***Exclusive venues***. A number of gateways are located in brand-specific stores. These have in common with regular venues that they are subject to opening hours, however, it is probable that fewer venues exist. Although the exclusive venues may be regular for some consumers, the majority of visits to such venues are occasional or pre-planned.

5) ***Consumption scene***. Where resources are consumed can dictate the location of revalorisation. For example, Splosh delivers refills to consumers' homes which turns the consumption scene into the gateway as soon as these consumables arrive. Similarly, for Kartent, the consumption scene on festival sites is transformed into a gateway as it is the exact location where the obsolete tents are collected.

The five gateways are not exclusive to the archetypical roles of consumers or any of the dimensions. Instead, we identified two main aspects of gateways that impact the weight of consumer roles i.e., the accessibility of gateways and the entry criteria of gateways.

4.5.1. Accessibility of gateways

Resources must reach gateways to be successful in revalorisation. Consumers must therefore access gateways. Whether or not a gateway is easily accessible, thus, impacts the weight of consumer roles. Compare, for example, bringing Milk&More's bottles to one's doorstep, to keeping Ecover bottles and transiting them to selected retailers. Three factors emerged from our analysis of the locations which influence the accessibility of a gateway.

Occurrence density

The travel distance to gateways stands out as a direct cause for the accessibility of gateways. As this distance is relative to single consumer, we take a more systemic perspective by reviewing the density with which gateways occur. This does not only indicate how likely it is to have a gateway in close proximity, but it also indicates how many consumers are expected to share a single gateway.

Of the five gateways, the consumption scene appears to have the highest occurrence density as it has a 1:1 occurrence to consumer ratio. For example, the home is a gateway solely for one single consumer. The timebound-assigned spots also have a high occurrence density and are in very close proximity to consumers. Some, such as doorsteps, might even be privately owned. Regular venues and open-access drop-offs are typically available in very close proximity to consumers. High occurrence density cuts travel distance and thus is likely to improve accessibility. In contrast, exclusive venues, such as a Lush or MAC brand store, are less common and would thus have a low occurrence density. In this case, consumers would have to search for gateways, and it is likely they have to travel longer.

Visitation frequency

All five gateways are located in supposedly convenient places as they are in locations that consumers are already likely to visit. Nevertheless, how frequently the locations are visited needs to be taken into account as this could determine how likely it is that the gateways will (already) be accessed when the consumer needs to. The visitation frequency varied for the five gateways. For example, regular venues, such as schools and retailers, are visited frequently, while exclusive venues, such as a brand-specific store, are likely to be visited only for specific needs.

Timebound assigned spots and open-access drop-offs are indeed locations that consumers pass on a very regular basis which could make these locations more accessible. Nevertheless, it must not be overlooked that passing a gateway is not the same as visiting a gateway with the intent of using it and this will require consumers to 'prepare' (i.e., remember) for this disposal. From this perspective, some gateways even appear inconvenient and out of one's way. For example, a common gateway to bring obsolete resources is the place of purchase. Although this seems logic, combining a journey made to purchase FMCGs with the intent to dispose in this location does not happen without planning in advance.

Time constraint

The majority of the gateways can only be accessed at set times. A time constraint reduces the accessibility of gateways as it demands of consumers to accurately plan their activities within timeslots. In particular, a time constraint in combination with low occurrence density and visitation frequency, seems to make gateways increasingly inaccessible. Only the open-access drop-offs can be accessed at all times, removing the time constraint completely.

The time constraint has a different meaning for the consumption scene as the logistics managed by the consumer are less affected by these time constraints. This is because the gateway might be subject to a timeslot, but it doesn't require the consumer to be present at the same time. For example, Kartent collects its tents after consumers have abandoned them and Splosh fits in the mailbox and thus can deliver without the consumer's presence.

4.5.2. Entry criteria of gateways

Resources cannot just enter revalorisation at any gateway. Resource flows are most valuable if they are pure and uncontaminated (EMF 2015). Therefore, segregating resources for revalorisation is key to the success of these services. Gateways can contribute to the segregation if they apply entry criteria. Although our study did not include gathering data on the underlying reasons for the entry criteria, it is reasonable to assume that they are used to match the capabilities of recovery technologies to improve segregation e.g., removing lids for sorting limitations in Material Recovery Facilities or the ability to identify specific materials. To achieve valuable flows, the volumes manged must also be considered. It is plausible that companies can only afford fully segregated resource flows by intercepting centralised volumes of obsolete resources, as this may reduce the complexity and costs of collection and transportation e.g., shipping a reasonable volume of resources at once.

In what condition resources are expected to enter gateways, has implications for consumers. Compare, for example, the considerations for consumers of managing a single resource, such as a single Repack envelope, to managing the gathering of a certain amount of a specific resource, such as the twelve Boldking razors. Two factors related to the entry criteria of gateways emerged from our analysis that influence the role of the consumer.

Level of resource segregation

All revalorisation services indicate that resources need to be sorted and separated in specific ways. Even household recycling services that accepted a mix of resources, require consumers to 'remove' certain components and clean residue. For the revalorisation services reviewed in this work, we can differentiate between 'segregated flows' i.e., only a single type of resource is in the flow, such as Lush' black pots or Grolsch' beer bottles; and 'semi-segregated flows' i.e., multiple resources flow together, such as in the mixed household recycling services.

Consumers have to perform activities to sustain segregation and prevent contamination in resource flows, which influence the weight of their roles. A semi-segregated flow appears to mitigate the weight of roles as consumers can 'stock' obsolete resources in fewer separate spaces and they will 'prepare' and 'transit' fewer volumes of resources. Fully segregated flows, in contrast, would require consumers to 'stock', 'prepare' and 'transit' numerous volumes of various resources and thus imposing an increasingly complex logistical challenge. There is a risk that consumers are not prepared to take on this challenge for the various resources.

Some gateways are equipped to facilitate activities and ease the role of the consumer. For example, some collect-and-return products can help consumers to segregate and stock obsolete resources. Most gateways accept a single fully or semi-segregated resource as they flow resource-specific flows. The open-access drop-offs are an exception as these gateways are a generic and public infrastructure, and thus can accept many different resources and establishing different resource flows. The resources do have to be sorted and bundled according to entry criteria, but consumers may be eased by the fact that the transit can be the same for multiple resources.

Minimum flow quantity

In some cases, revalorisation services instruct consumers to return specific quantities. Saving up resources separately implies that consumers must allocate space inside their homes to store anticipated amounts of resources.

A minimum flow quantity as an entry criterion has implications for consumers. Some gateways can only be used if this specific quantity is available, for example if shipping labels are used for specific quantity for open-access drop-offs. It is not uncommon that only a minimum amount of resources that is intercepted as a bundle is rewarded, such as is common with PSSs using regular venues.

In contrast, gateways that do not set a minimum flow quantity give the consumer flexibility in when they can use the revalorisation and thus reducing the weight of their role. Household recycling services, for example, are available on a regular basis using timebound assigned spots. Consumers still have to 'stock' and 'transit' these resources until the day of collection, but they do not have to consider the amount of resources or having to 'prepare' this visit.

4.6. Discussion

This work outlined the role of consumers in the revalorisation of FMCGs and thus in closing FMCGs' resource loops. Firstly, we have modelled four archetypical roles using dimensions that emerged from the dissection and systematic comparative analysis of eighteen PSSs. The archetypical roles are keep, bring, consign, and abandon obsolete resources. Secondly, we have identified five types of gateways, i.e., designated locations in which serve as entry points to revalorisation. The gateways differ in terms of their accessibility and entry criteria, which influence the roles of the consumers. As opposed to research on business models (Bocken *et al.,* 2016; Tukker, 2004) and consumer behaviour (Maletz, 2017; Wastling *et al.,* 2018) in the circular economy, this work aimed first at identifying the flow of resources and then deriving the contributions that have to be made by consumers to establish those flows. This work confirms that consumers' roles are critical in closing resource loops (Breen, 2006; Charnley *et al.,* 2015) and provides new understanding of how such roles are integrated in PSSs. This work has implications for three aspects of PSSs that aim to produce closed-loop resource flows for FMCGs. We now highlight these implications and discuss them against the literature.

4.6.1. Revalorisation takes off in gateways

FMCGs are tangible resources. Revalorising FMCGs, thus, will always require to physically access these resources. In the studied PSSs, obsolete resources were positioned in gateways, i.e., entry points for revalorisation. Only from these locations resources can continue to flow (Zeeuw van der Laan and Aurisicchio, 2019b), for example, using infrastructure enabling the journey towards the reuse of components or recycling of materials (EMF, 2015). This implies that PSSs always require a stakeholder to position obsolete resources in gateways. Based on the results, we articulate two tactics that were used to achieve this:

- Consumers (1) move obsolete resources to gateways where providers of revalorisation services intercept or replenish the resources;
- Consumers do not move obsolete resources, but (2) resources become obsolete in gateways where revalorisation takes place.

As resources are to be accounted for at all times in the circular economy, it is worth understanding which stakeholders access them in the various types of PSSs (Manzini and Vezzoli, 2003; Mont, 2002; Tukker, 2004). Although in this work it was the consumer who fulfilled the role that positioned obsolete resources in locations designated for revalorisation, the tactics seem applicable to consumers in all types of PSSs. For example, consumers in 'use-oriented' PSSs are stakeholders who do not have permanent ownership of resources but, instead, they are charged for the time they use a resource (Tukker, 2004). The service provider and consumer agree on the duration of use and on the location that the resource must be returned to. Therefore, the role of the consumer involves moving obsolete resources to designated locations, a tactic used in many of the archetypical roles. In this case, however, the responsibilities are formally agreed, and this can be seen as an additional explicit incentive, reducing the risk of unfulfilled roles.

The tactics also appear applicable to other types of stakeholders in PSSs. For example, manufacturers of resources are expected to fulfil new roles as they are encouraged to become or partner with service providers. Consequently, manufacturers are incentivised to prolong the life of their resources, which slows and narrows the resource loops (Bartels *et al.,* 2012;

Bocken *et al.,* 2016; Stahel, 1994). However, to manage waste, they have to carefully consider material flows (Corvellec and Stål, 2017) and product lifetimes (Bakker *et al.,* 2014b). Similar to consumers, manufacturers will then face various forms of obsolescence and have to decide when they can no longer use their resources. To flow these obsolete resources in closed loops, they must also reach gateways. This implies that manufacturers who are service providers now must fulfil a role that positions obsolete resources in these locations.

4.6.2. The roles of consumers come at a cost

Whether it is an investment of money or effort, the archetypical roles have costly implications for consumers. However, understanding the exact cost of the roles of consumers is challenging as it is influenced by systemic elements, such as the accessibility of gateways and their entry criteria. These aspects influence the time that consumers need to invest in planning and carrying out activities, and the impracticalities that consumers face in managing resources in bulk. Therefore, quantifying the value of this cost is complex. Nevertheless, the accessibility and entry criteria of gateways give an indication of the implications for consumers and allows to imagine ways to mitigate these costs to improve recovery rates (Zeeuw van der Laan and Aurisicchio, 2019b). This work has developed understanding of the influences of systemic elements on the role of consumers, and implies that PSSs can be designed to reduce or cut the costs of consumers' roles. Based on the results, we articulate three tactics that were used to achieve this:

- Rather than picking-up consumable components, (1) the consumable components are moved towards the obsolete resources, such as when consumers keep them.
- Instead of in exclusive locations, such as a brand-specific store, (2) gateways can be located more conveniently, such as one's doorstep in bring.
- Instead of moving resources once they are obsolete, (3) resources become obsolete in gateways, such as when consumers simply abandon them.

Common tactics to increase the fulfilment of the roles do not typically address endured costs. For example, when consumers are required to keep obsolete components, tactics include banning single-use alternatives e.g., the ban of plastic bags (Ritch *et al.,* 2009); and punishing their use in comparison to reusables e.g., a penalty for using a disposable coffee cup (Poortinga and Whitaker, 2018). Other common tactics focus on the design of facilitating components, such as designing components that: are durable in performance and can recover from functional obsolescence in multiple product use cycles (Den Hollander, 2018; Lofthouse *et al.,* 2009); and are emotionally durable to resist relative forms of obsolescence (Chapman, 2009; Den Hollander, 2018). Regardless of these tactics, the costs to fulfil the role to keep remain equal or become, arguably, higher.

In practice, consumers who have to keep are required to carry out 'preparing' and 'transiting' prerequisite activities, similar to the activities carried out to bring obsolete resources. Carrying out such activities is subject to the availability of technical facilities and infrastructure (Steg and Vlek, 2008). This work showed that systemic elements as straightforward as locations differ significantly in PSSs and can have implications for the role of consumers. Little is known on which specific elements can influence consumers, and thus it is not unlikely that many more have weighty implications for consumers. In addition, insufficiently facilitated (prerequisite) activities could thus put their fulfilment of roles at risk. Without adopting tactics to eliminate or devalue costly activities, consumers may experience large costs for their role, such as the value that they may attribute to the inconvenience of recycling (Domina and Koch, 2002; Rousta *et al.,* 2015; Sidique *et al.,* 2010). Therefore, further understanding on impactful systemic elements could help to optimise revalorisation services and improve their uptake.

4.6.3. Obsolete resources can have a specific perceivable value

FMCGs are often altered as a consequence of consumption and undergo physical changes that can devalue the resources (Haffmans *et al.,* 2018; De los Rios and Charnley, 2017) and cause them to become obsolete (Bartels *et al.,* 2012; Burns, 2010; Cooper, 2004; Feldman and Sandborn, 2007; Van Nes *et al.,* 1999; Packard, 1960). In the studied PSSs, the conditions of some obsolete resources involved physical alterations. Resources, however, became obsolete for various reasons and they remained in various physical conditions, some of which seem easily reversible. It appears that the value that consumers perceive of obsolete resources in PSSs differs from the initial value perceived, but it does not necessarily drop. This implies that PSSs can induce a specific perceivable value of obsolete resources. Based on the results, we articulate five tactics that were used to achieve this:

- The perceivable value of obsolete resources is increased using (1) knowledge of the existence of a revalorisation service. In that case, functional obsolescence as in keep fosters the potential value of obsolete resources as facilitating components remain intact.
- The measurable value of obsolete resources is prompted using (2) explicit incentives, such as those identified in some variants of bring when consumers receive a discount on a next purchase as a reward.
- The (3) investments made by consumers prior to consumption, consisting of money or effort as seen in other variants of bring, promote a perceivable value that lasts even when the resources become obsolete. For example, when having paid for a collect-and-return product, as early as when purchasing the product
- The perceivable value of obsolete resources is influenced by the (4) physical change of the resource. Rather than decreasing the perceivable value, however, physical change can be used to increase it, as identified in consign. In this case, it is thought that the value that one can perceive of the obsolete resource increases to the extent that retrieving it can become an incentive.
- The perceivable value of obsolete resources is lowered by (5) intentionally expiring the product use cycle, such as when using either situational obsolescence in abandon, or technological obsolescence to make a resource obsolete by offering a replacement.

Dominant tactics to improve recycling behaviour include increasing awareness and knowledge of environmental issues related to consumption to build intrinsic personal values that incentivise consumers to fulfil their roles (Magnier and Schoormans, 2015; Singhirunnusorn *et al.,* 2012) or positioning this behaviour as normative (Babader *et al.,* 2016; Barr, 2007; Poortinga and Whitaker, 2018). Nevertheless, not everyone seems to be receptive to these incentives nor are they sufficient to always guarantee engagement (Steg and Vlek, 2008) and collection rates are shown to remain low (EMF, 2017a).

It might, instead, be more effective to use the value that consumers can perceive of obsolete resources, as this value can be used to elicit behaviour (Haffmans *et al.,* 2018; Scheepens *et al.,* 2016). For example, people were more likely to litter obsolete packaging if it had features that they associated with something as valueless as waste (Baxter *et al.,* 2016). As such, tactics that imply an association with a specific value could be used to elicit specific behaviour. Although money seems to imply a self-evident association with value, offers of monetary incentives are found to not always be successful in nudging environmental behaviour as those who do engage in programmes such as recycling are driven altruistically (Steg and Vlek, 2008). Rather, tactics can be used to induce perceptions of non-monetary value. For example, the uptake of recycling was found to be strongly influenced by whether consumers were aware of programmes (Jenkins *et al.,* 2003), suggesting a successful use of the tactic to generate awareness of revalorisation services.

In PSSs tactics could then be used to strategically exert control over the value that can be perceived of resources and timely elicit the required behaviour. For example, expiring the product use cycle can be used to instantly drop the perceivable value, such as by using a one-for-one take-back service in which consumers receive a new resource only when they have returned the obsolete one (Östlin *et al.,* 2008). Physical change of resources during consumption was used by Fuji to gradually increase the perceivable value of obsolete resources. The latter is a type of value-creation that can be related to the co-creation which develops psychological ownership over resources and leads to personal attachment (Baxter *et al.,* 2015). This could explain why the use of this tactic is successful in the fulfilment of the role of *consigning* obsolete resources. Which tactic is appropriate to use in a PSS and whether to induce a low or high perceivable value depends on the role that consumers are required to fulfil, and influences whether consumers will fulfil it.

4.7. Limitations and future work

The researchers note that a limited number of PSSs fit our scope at the time of the research. New PSSs are emerging, which could make cases of interest for future work. Household recycling schemes in other areas of the UK and outside the UK could be included to further compare the role of consumers and the influence of systemic elements on this role. We acknowledge that the archetypical roles are representative of a specific product category and services, as the research has focused on FMCGs. Additional roles could be identified by systematically studying other stakeholders such as manufacturers; PSSs that are use-oriented or result-oriented; and PSSs based on products in other categories.

This work presents a comprehensive understanding of the roles of consumers in the specific context of closed-loop FMCGs. Although two roles are based on one data point only, we believe that they are conceptually distinct from the other roles and expect that they provide the FMCG sector with opportunities to explore new value propositions to consumers and develop and implement circular business models. Further research on the roles of stakeholders in closing resource loops can strengthen the current archetypical roles and develop a comprehensive set that can be used to design PSSs with closed resource loops.

This study is based on information that is available to consumers who use revalorisation services provided by parties offering those services. Our interpretation of this secondary data thus represents how the activities are theoretically carried out. The dataset was suitable to systematically compare the activities amongst various PSSs and develop conceptual archetypical roles but does not give us insights in the agenda of companies that offer these services; how and whether consumers in the real-world carry out the activities as suggested; or how successful each archetypical role is. When collecting the data on the PSSs we have come across FAQ pages and blogs that have given us an opportunity to further understand the PSSs as well as how well consumers engage with the systems. Further consumer research is needed to understand the actual behaviour and measure the extent to which consumers fulfil the archetypical roles, and how each dimension influences this. This work discusses the presence of the cost of a role and the possibly perceivable value of obsolete resources in PSSs. To qualify and quantify the value that is attributed to these, perception studies in PSSs need to be undertaken.

4.8. Conclusions

Consumers have a critical role in the revalorisation of obsolete resources in the circular economy. Using customer journey mapping we have dissected PSSs that consist of FMCGs and revalorisation services. Four dimensions, emerged from the systematic comparative analysis of PSSs, were used to model consumers' archetypical roles in closing resource loops, namely: the form of obsolescence; the prerequisite activities; the type of state change; and the facilitators of the activities. Consumers were found to fulfil one of four archetypical roles to position resources in designated locations: *keep, bring, consign* or *abandon* obsolete resources. The role of consumer is influenced by various factors. Adding data on household recycling, we studied the locations involved in revalorisation and identified five type of 'gateways' i.e., entry points to revalorisation. Two aspects of gateways were identified to have implications for consumers: the accessibility of gateways, for which occurrence density, visitation frequency and time constraints are determining factors; and the entry criteria of gateways, for which the level of resource segregation and the minimum flow quantity are determining factors.

To our knowledge, this work is the first to characterise in detail the roles of consumers in closing FMCGs' resource loops. We have taken a novel approach by first identifying the flow of resources and then deriving the contributions that have to be made by consumers to establish the flows. This work presents novel understanding of the roles of consumers in closing loops as well as understanding of systemic elements that have implications for this role. The results provide designers of PSSs with dimensions to model these roles and offers them insights to model them to ensure their fulfilment. We have identified that obsolescence is a state of resources. The obsolete state can reverse to the operative state or change to a recoverable state. We have proposed forms of obsolescence with causes that had not yet been articulated in the literature.

The archetypical roles of consumers modelled in this research shed new light on circular behaviour and studies of PSSs, and how this behaviour can be influenced to control resource flows and close resource loops. First, revalorisation takes place in designated locations, i.e., gateways, and consumers are the key stakeholders that must position obsolete resources there. Second, fulfilling archetypical roles comes at a cost, but tactics can be used to design PSSs that cut or eliminate this cost. Third, obsolete resources in PSSs can have perceivable value, which can be induced by the design of the PSS and used to increase role fulfilment by eliciting specific behaviour.

Both the archetypical roles and the dimensions to model them as well as the factors related to gateways that influence these roles, are suggested to be used in the design of PSSs for the circular economy. This study has focused only on products in the FMCGs sector and the consumer as a stakeholder. Additional roles are likely to exist and might be modelled using the proposed dimensions. An evolved set of archetypal roles has the potential to be applicable to an even wider range of stakeholders in circular PSSs. The dataset was created from secondary data and thus to understand the success of each archetypical role and the influence of the dimensions, further research on consumers and PSSs is needed.

5. Using Product-Service Systems as Plans to Produce Closed-Loop Resource Flows

This chapter explores the potential of PSSs to enable closed-loop resource flows. It presents a framework of PSS elements that can enable closed-loop resource flows, as well as a set of guidelines on how to use the elements in design. This work has been published in the Journal of Cleaner Production (Zeeuw van der Laan and Aurisicchio, 2020) and at the 2019 CIRP Lifecycle Engineering Conference (Zeeuw van der Laan and Aurisicchio, 2019c).

5.1. The implied potential of product-service systems

Millions of products are produced, consumed and disposed of every day, leading to the depletion of resources and the abundance of waste (Stahel, 2013). A circular economy is suggested to disrupt this linear pattern (EMF, 2012; Stahel, 2013). In a circular economy, resources (i.e., products, components and materials) circulate through successive lifecycles. Today's lack of resource circulation is predominantly caused by gaps occurring within and at the end of product use, for example, when resources end up in landfills rather than recycling facilities. Such gaps can be bridged by designing systems in which resources flow in closed loops (EMF, 2012).

Processes have emerged to operate systems that produce closed-loop resource flows. For example, reverse logistics is an established process that involves the following operations: acquire resources from end-users; collect, inspect and sort resources; and position resources for reuse or disposal (Agrawal *et al.,* 2015). Reverse logistics enable closed-loop supply chains, which aim at maximising value creation over the entire life cycle of products and components with the dynamic recovery of value from different types and volumes of returns over time (Govindan *et al.,* 2015; Guide Jr *et al.,* 2003). Reverse logistics include processes to support the flow of materials, e.g., waste management (Blomsma, 2018), which are adopted especially by sectors urged to action due to their wasteful nature, e.g., the built environment sector (Pomponi and Moncaster, 2017) and the waste electrical and electronic equipment sector (Islam and Huda, 2018).

New business models, which offer better management of the flow of resources, are also emerging. These models, both in business-to-business (B2B) and in business-to-consumer (B2C) contexts (Breen, 2006), integrate products and services to deliver value rather than resources. They are commonly known as product-service systems (PSSs) and have been recognised to '*bring about changes in production and consumption patterns that might accelerate the shift towards more sustainable practices and societies*' (Mont, 2002, p. 239). Product-Service Systems (PSSs) are marketable sets of products and services that fulfil customers' needs (Goedkoop *et al.,* 1999). Nevertheless, PSSs do not necessarily lead to more sustainable consumption

(Beuren *et al.,* 2013; Manzini and Vezzoli, 2003; Tukker, 2015a; Tukker and Tischner, 2006). The opportunities for more sustainable resource consumption explored in this study involve business models that produce flows of resources following circular principles (Armstrong *et al.* 2015; Bakker *et al.* 2014b; Bocken *et al.,* 2016; EMF, 2013a; Stahel, 2016; and Tukker, 2015).

Circular principles propose narrow and slow flows, i.e., fostering reuse and extension of the service life of resources (Stahel, 2016). Such types of flow can be produced by PSSs either by offering access to resources rather than their ownership (i.e., use-oriented PSSs) (Tukker, 2004), or by offering the consumption of results rather than resources (i.e., result-oriented) (Mont, 2002; Pine II and Gilmore, 2013; Reim *et al.,* 2015; Stahel, 2010; Tukker, 2015a). Flows are slow if the service providers use resources efficiently, and they are narrow if the number of resources needed is minimised compared to individual resource-ownership (Bocken *et al.,* 2016). The dynamics between customers and service providers in these PSSs change as the ownership of resources in the system is repositioned (Baxter *et al.,* 2015; Tukker, 2004). The literature extensively discusses how to configure PSSs to have narrow and slow resource loops (Barquet *et al.,* 2013; Tukker, 2004), be accepted by consumers (Baxter *et al.,* 2017; Tonelli *et al.,* 2009), and be successful in slowing and narrowing resource flows (Kjaer *et al.,* 2018; Lindahl, Sundin, *et al.,* 2014; Romero and Rossi, 2017).

Circular principles also propose flowing resources in closed loops, i.e., managing to turn old goods into as-new resources (Stahel, 2016) by feeding resources back into the system after they are no longer used (EMF, 2013). PSSs produce this type of flow either by reusing products and components, e.g., refurbishment; or by recycling materials, e.g., waste management (Armstrong *et al.,* 2015; Corvellec and Stål, 2017; Mont, 2002; Romero and Rossi, 2017; Scheepens *et al.,* 2016). Despite the acknowledgement of the potential of PSSs to close the resource loops, there has been little exploration of the way in which PSSs can manage waste (Besch, 2005; Corvellec and Stål, 2017; Mishra *et al.,* 2018; Stål and Jansson, 2017) even though it has been pointed out that closing resource loops requires active decision-making (Boons and Howard-Grenville, 2009). In particular, the literature lacks a structured overview of the potential of PSSs to close loops and how this can be achieved.

This study aims, firstly, to explore the potential of PSSs to produce closed-loop resource flows by identifying elements of PSSs that enable such flows. We use the term PSS element to describe either a tangible or an intangible characteristic of a PSS. Examples of tangible characteristics are product features, service offering and contractual elements, whereas examples of intangible characteristics include stakeholder dynamics such as judgement of value and attachment to resources. The second aim is to provide guidance on how such PSS elements could be employed by PSSs to establish closed-loop resource flows.

The remainder of this chapter is structured as follows. In Section 2, we outline the current understanding of PSSs as plans to intercept resources and close resource loops. Section 3 explains how we identified PSS elements that enable closed-loop resource flows. In Section 4, we present a framework consolidating twenty-one PSS elements based on their contributions to four subfunctions to close resource loops. In Section 5, we discuss how and why PSSs satisfy these subfunctions and how to refocus research on PSS elements to close the resource loops. Finally, Section 6 discussess the limitations of this work followed by conclusions in Section 7.

5.2. Product-Service Systems and obsolescence

In the next three subsections, we outline the current understanding of the elements of PSSs, the potential of PSSs to close resource loops and the role of obsolescence in PSSs.

5.2.1. The current understanding of the elements of PSSs is fragmented

PSS elements are addressed in PSS design methodologies. The methodologies suggest designing the product and service elements in parallel, as services depend heavily on product design aspects (Morelli *et al.,* 2002) and PSS economics are related to product and service dynamics (Oliva and Kallenberg, 2003). Methodologies for integrated design have only recently emerged (Maussang *et al.,* 2009; Mestre and Cooper, 2017). Moreover, interest in the circular economy appears to further drive the development of specialised PSS design methodologies (McAloone and Pigosso, 2018; Vezzoli *et al.,* 2014), business models (Blomsma and Brennan, 2018; Bocken *et al.,* 2016; Lewandowski, 2016) and whole system design (Charnley *et al.,* 2011). The methodologies include suggestions to consider stakeholders and their needs (Charnley *et al.,* 2011; McAloone and Pigosso, 2018; Vezzoli *et al.,* 2014), construct meaningful relations and partnerships between stakeholders (Bocken *et al.,* 2016; Charnley *et al.,* 2011; Haase *et al.,* 2017; Lewandowski, 2016), and manage the impacts of resources (Mestre and Cooper, 2017) as well as the interest in resources (Blomsma and Brennan, 2018; Vezzoli *et al.,* 2014) throughout the lifecycle.

PSS elements also emerge from descriptions and characterisations of PSSs in the literature. Scholars have undertaken studies aimed at capturing their various complex characteristics at a detailed level (Annamalai *et al.,* 2010; Baines *et al.,* 2007; Beuren *et al.,* 2013; Boehm and Thomas, 2013; Haase *et al.,* 2017; Van Ostaeyen *et al.,* 2013; Pagoropoulos *et al.,* 2014). Nevertheless, the most commonly used classifications appear to revolve around just a single characteristic of PSSs – it is either about *when services occur* (Mont, 2002), e.g., at the point of sale, during use, and at the point of disposal, or *who owns the resources* (Tukker, 2004; Tukker and Tischner, 2006), e.g., product-oriented (owned by consumer/customer), use-oriented, and result-oriented PSSs. However, the architectural levels of PSSs as suggested by Müller and Stark (2010) constitute an easily interpretable and high-level structure for different types of characteristics, i.e., *services*, *products*, *stakeholders*, *contracts*, *integrated value delivery*, and *tools and systems*.

To sum up, PSS elements that emerged from design methodologies and characterisations include *stakeholders*, their needs and interrelatedness; *services*, their type and timing; ownership of resources; *lifecycle impacts* of resources; *value propositions* in business models; and *product design*. However, despite the proliferation of terminology regarding PSSs, there is no agreed list of elements of PSSs and their definitions (Haase *et al.,* 2017; Tukker, 2015a; Vasantha *et al.,* 2012). Instead, the current understanding of PSSs seems fragmented, as emphasised by the recognised needs for common PSS language, design methods and tools (Vasantha *et al.,* 2012), and a better account of PSSs in the circular economy (Blomsma *et al.,* 2018).

5.2.2. The insights on the potential of PSSs to close loops are sparse

A closed-loop resource flow contains and returns resources to preserve or restore their quality levels (Blomsma, 2018). A closed-loop material flow has environmental benefits, for example, when deferring plastics from landfill to recycling. Similarly, PSSs reuse resources and produce closed-loop product- or component-resource flows eliminating the environmental impact of producing new resources. A closed loop, however, risks being perceived as a continuous flow free of environmental impact in (re)production (Allwood, 2014; Zink and Geyer, 2017). It can also appear to justify accelerated consumption in a circular framework (Wieser, 2016) and feeding secondary resources into the economy, instead of substituting primary resources (Zink and Geyer, 2017). Therefore, the popular order of 'reduce, reuse, and recycle' must be followed to control environmental impact (Allwood, 2014). A closed-loop resource flow, thus, is an integrated consideration rather than an alternative to narrow or slow flows.

Producing closed-loop resource flows does not emerge as the primary reason to adopt a PSS. More likely, manufacturers are driven by the commercial and financial benefits that come with offering the consumption of services rather than resources (EMF, 2012; Stahel, 2013; Tennant, 2013; Tukker, 2004). The commercial benefits include gaining a competitive advantage (Mont, 2002) by offering added value (Reim *et al.,* 2015); exploring market trends (Mont, 2002); anticipating legislative threats (EMF, 2012; Goedkoop *et al.,* 1999; Mont, 2002; Peeters *et al.,* 2017); and gaining feedback and customer insights on resources (Hussain *et al.,* 2012; Oliva and Kallenberg, 2003; Pialot *et al.,* 2017). Financial benefits can be linked to the dematerialisation of consumption (Bakker, Den Hollander, *et al.,* 2014), for example, using fewer resources for longer by designing efficient, lasting and durable products (Besch, 2005; Manzini *et al.,* 2001; Tukker, 2004), which produce narrow and slow resource flows. In contrast, high costs and the complexity of reverse logistics challenge the commercials and financing of closed loops (Breen, 2006).

There is a paucity of research into the potential of PSSs to produce closed loops. Empirical work by Huang *et al.* (2017) and Mishra *et al.* (2018) has aimed at identifying enablers of closed loops in business models but has only produced insights for very specific product types. More commonly, the potential of PSSs has emerged through suggestions to embed specific PSS elements that enable closed loops, such as a revalorisation service (Mont, 2002) that reclaims used resources (Besch, 2005). Another common premise is to use centralised ownership. Despite the fact that ownership does not guarantee closed loops, it enables PSSs to close multiple successive product-resource loops through sharing models (Den Hollander *et al.,* 2017; Tukker, 2004), close the component-resource loop by intercepting components during centralised maintenance (Williams, 2007; Yoo *et al.,* 2016), and stress responsibilities to close resource loops when being subject to emerging legislative changes and encouragement by governments (Demirel and Kesidou, 2011; Goedkoop *et al.,* 1999; Tennant, 2013). As such, although PSS elements and their ability to enable closed-loop flows are mentioned frequently, they are not the main topic of PSS literature nor do they offer proven design solutions resulting in sparse insights on the potential of PSSs.

5.2.3. Employing obsolescence to close the loops of resource flows

The lifecycle of a resource typically consists of four sequential phases: origin, production, use and end-of-life (EOL). The end of the use phase, thus, is marked by the moment in which resources are disposed of and enter the EOL phase. A resource's lifetime, however, is defined as the period between the moment a resource leaves the production phase and the moment it becomes obsolete (Den Hollander *et al.,* 2017). The moment in which resources become obsolete thus emerges as significant. Many business strategies refer to this moment using terms such as 'required utility', 'time to failure', or even 'product death date' (Packard, 1960). Thus, it appears plausible that service providers know when resources will become obsolete. Interestingly, however, it is rarely disclosed when resources are planned to become obsolete.

The concept of 'planned obsolescence' implies a 'deliberate decision [made] by suppliers that a product should no longer be functional or desirable after a predetermined period' (Cooper, 2010, p. 4). Although the concept was initially introduced to stimulate consumption and boost the economy (Packard, 1960), it has been criticised for driving production at the expense of the environment (Burns, 2010; Packard, 1960; Papanek, 1985) and for justifying short lifetimes (Wieser, 2016). In practice, resources rarely become obsolete due to clear-cut factors such as technical unreliability. More commonly, obsolescence is the result of psychological, social, technological, economic, programmed, situational and environmental factors (Burns, 2010; Cooper, 2004; Packard, 1960; Zeeuw van der Laan and Aurisicchio, 2019a).

A service is commonly offered to address the needs of stakeholders at purchase, during use or at disposal. presents a timeline of the resource flow in the use phase, indicating when services are offered and the key stakeholders that access resources at those moments. Interestingly, services are not accurately timed to be offered at the moment in which resources become obsolete. Whether products, components and materials continue to flow, thus, depends on the response of the stakeholders to obsolescence. For example, despite the existence of services such as mobile phone recycling, obsolete mobile phones are often kept in drawers by consumers which stagnates this resource flow. More so, even if resources are owned centrally by service providers, there is a risk that resources continue to flow linearly. For example, in use- and result-oriented PSSs resource owners are often tempted to sell pre-obsolete resource to avoid disposal or repair costs. In fact, the response to obsolescence is, in

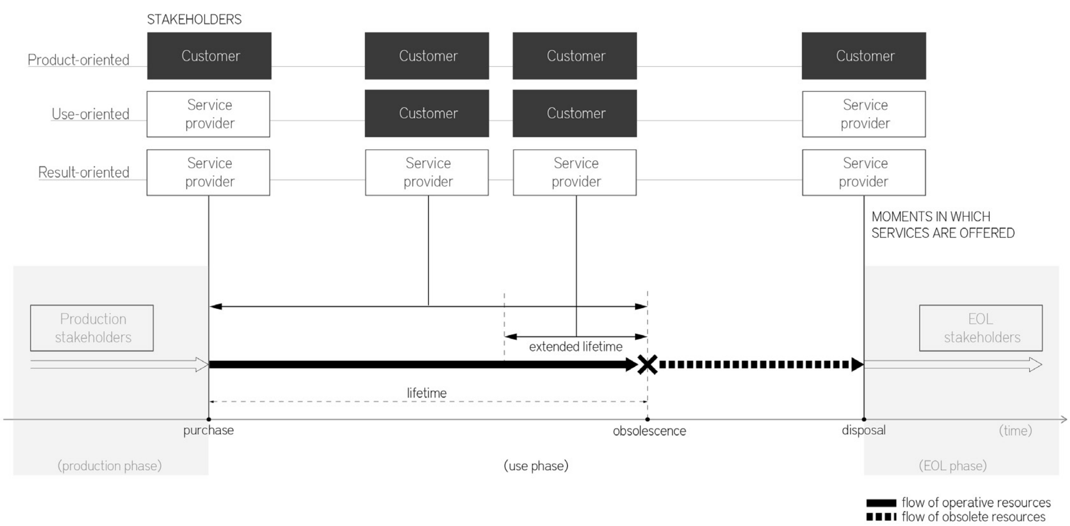


Figure 5.1 Timeline of the resource flow in the use phase, indicating when services are offered and the key stakeholders.

general, very often unpredictable (Breen, 2006; Burns, 2010; Daae and Boks, 2015; Macleod, 2017; Wastling *et al.,* 2018) challenging the flow of resources.

The significance of the moment in which resources become obsolete implies that obsolescence deserves consideration as a PSS element of interest. Employing obsolescence in PSSs implies 'planned-for obsolescence' (Burns, 2010) such as anticipating the moment in which resources become obsolete by designing a plan to intercept them (Zeeuw van der Laan and Aurisicchio, 2017). However, instead of obsolescence, scholars have studied resource lifetimes in PSSs (Bakker, Wang, *et al.,* 2014; Burns, 2010; Oguchi *et al.,* 2010; Stahel, 2013). For example, use-oriented and result-oriented PSSs benefit from designing durable products (Bakker, Den Hollander, *et al.,* 2014; Bocken *et al.,* 2016; Cooper, 2010) and planning regular maintenance and upgrades to extend lifetimes (Den Hollander, 2018; Pialot *et al.,* 2017; Yoo *et al.,* 2016). The defined lifetimes may be more appropriate for some resource types, even if that implies a shorter life (Burns, 2010). For example, this is the case for products that face rapid technological obsolescence (Bakker, Wang, *et al.,* 2014) or for components for which the regular replacement extends the life of the product (Thomsen *et al.,* 2016). Despite this interest in resource lifetime, the research on the relevance of obsolescence in PSSs appears limited.

5.2.4. Closing remarks

In the first section, we concluded that there is only a fragmented understanding of the elements of PSSs. The lack of a consolidated list of PSS elements limits our understanding of PSS elements and the ability to undertake research on their potential to close loops, because it is not guaranteed that all PSS elements have already been put forward. In the second section, we showed that the literature provides a sparse account of the potential of PSSs to close resource loops e.g., through specific and unconnected PSS elements. Nevertheless, there is no structured and comprehensive understanding, which limits our ability to develop and design PSS elements that unlock the potential to close loops. In the third section, we emphasised the need to focus on the use phase and the moment in which resources become obsolete. Despite being an element of critical interest, obsolescence has been largely overlooked. On this basis in the rest of the chapter we present a systematic literature review to identify PSS elements by integrating current fragmented understanding, structuring sparse insights on the potential of PSSs to close loops, and focusing on the use phase and obsolescence.

5.3. Methods

In this study we aim to identify PSS elements that enable resources to flow in a closed loop and provide guidance on how to embed such PSS elements to establish closed-loop resource flows. We use a systematic literature review to identify insights in the literature on PSSs that address the potential to produce closed-loop resource flows. Systematic literature reviews constitute a method that is distinctive, rigorous, transparent and has a reproducible procedure (Borrego *et al.,* 2014). The method is suitable to synthesise published knowledge on a particular subject (Borrego *et al.,* 2014; Møller and Myles, 2016). Systematic literature reviews have been previously used to study the characteristics of PSSs (Boehm and Thomas, 2013; Corvellec and Stål, 2017; Pigosso *et al.,* 2015). We use this method to understand which PSS elements enable closed-loop resource flows and how this is achieved. We used the broad definition of PSS elements presented in the introduction section to include tangible and intangible characteristics of PSSs.

5.3.1. Data selection

Table 5.1 Scopus search criteria.

Product-service system	Closed loop	
Product service system, product/service system	End-of-life	End of life, EOL
	Waste	Disposal
	Recovery	Reuse, refurbish, recycle, restore, re-use, circular, circulate, reverse logistics, extended supply chain
	Closed loop	Closing loops, closed-loop
	Revalorisation	Revalorization, return, take-back, takeback, retrieve, retrieval
	Use time	Obsolescence, utilisation time, utilization time, lifetime, lifespan, obsolete, time in use

We accessed the literature surveyed in this research via Scopus. The search focussed on the title, abstract and keywords. We experimented with the inclusion of several search words related to closed loops and the notion of obsolescence to gather a rich and relevant set of papers. We focussed on closing the gaps at the end of the use phase and therefore the selected papers include both reuse-oriented PSSs producing closed-loop product and component flows as well as recycling-oriented PSSs producing closed-loop material flows. The papers in the final dataset mentioned both a 'product-service system' and 'closed loop' or a set of variations of these keywords, as presented in Table 5.1. The search (conducted in May 2018) delivered 209 results; 3 publications were manually added as they were not picked up by the search engine due to the use of a different hyphen. Following this initial identification, we entered the details of the 212 publications into an Excel spreadsheet for further analysis.

A screening process that consisted of analysing the title and abstract of each publication to judge whether they were eligible for further review led to the shortlisting of 49 publications. We were cautious to select multiple papers by the same authors but included their work if the relevant PSS elements differed substantially. Eligible work investigated PSSs with closed loops or how PSSs produced closed loops and also discussed one or multiple elements of PSSs. We excluded work that did not discuss PSS elements, was solely aimed at slowing and narrowing loops, ruled out a flow of tangible resources as it studied only digital products, and merely proposed models to simulate or assess environmental impacts to reflect on the circularity of the PSS rather than its individual elements.

A total of 37 publications formed the final dataset. Selected publications either reviewed one or more PSSs case studies, in which the intention to close resource loops (e.g., manage waste, take-back products, plan disassembly) was clearly stated, or studied the specifics of a PSS in relation to closed loops. The final selection included publications that discuss how elements create both challenges as well as opportunities for PSSs to close resource loops.

5.3.2. Dataset statistics

The 37 papers (Table 5.2) were published between 2005 and 2018 with the majority having appeared in more recent years (i.e., 24 were published after 2014), indicating a growing interest in the topic. Nine were conference papers, whereas the remaining 28 were journal papers published in 19 different journals. All the articles except six presented case studies. In some articles, multiple case studies of products in various product categories were the subject. The case studies involved PSSs that were either busines-to-business (B2B) or business-to-consumer (B2C).

Table 5.2 Detailed list of the 37 selected papers.

Reference (J: Journal; C: Conference)			Case study/studies	
[1]	Anttonen (2008)	J	High maintenance goods (chemicals and resources)	B2B
[2]	Arabi *et al.* (2017)	J	Electronic goods (computers)	B2C
[3]	Armstrong *et al.* (2015)	J	Fashion (clothing)	B2C
[4]	Besch (2005)	J	Furniture (office furniture)	B2B
[5]	Bindel *et al.* (2012)	C	Electronic goods (electronic goods)	B2C
[6]	Bressanelli *et al.* (2018)	J	-	
[7]	Chang *et al.* (2017)	C	-	
[8]	Chattopadhyay and Rahman (2008)	J	-	
[9]	Corvellec and Stål (2017)	J	Fashion (apparel)	B2C
[10]	Costa *et al.* (2015)	C	Furniture (office furniture)	B2B
[11]	Gelbmann and Hammerl (2015)	J	Electronic goods (domestic appliances)	B2C
[12]	Gottberg *et al.* (2010)	J	Electronic goods (domestic appliances)	B2C
[13]	Hussain *et al.* (2012)	J	High maintenance goods (laser cutters)	B2B
[14]	Jensen and Remmen(2017)	C	High maintenance goods (automobile, aircraft and ship manufacturing)	B2B
[15]	Kamigaki *et al.* (2017)	C	Electronic goods (photo copiers)	B2B
[16]	Lee *et al.* (2007)	J	Electronic goods (computers)	B2C
[17]	Lindström (2016)	J	-	
[18]	Michelini *et al.* (2017)	C	-	
[19]	Peeters *et al.* (2017)	J	Electronic goods (electronic products)	B2C
[20]	Petersen & Riisberg (2017)	J	Fashion (baby clothing)	B2C
[21]	Pialot and Millet (2014)	J	Electronic goods (household appliances	B2C
[22]	Retamal (2017)	J	Electronic goods (builders' tools) Fashion (designer bags, apparel) Furniture (baby equipment)	B2B
[23]	Romero & Rossi (2017)	C	Electronic goods (parts and components)	B2B
[24]	Roy *et al.* (2014)	C	-	
[25]	Russo *et al.* (2016)	C	High maintenance goods (cranes)	B2B
[26]	Sinha *et al.* (2016)	J	Electronic goods (mobile phones)	B2C
[27]	Sousa-Zomer *et al.* (2017)	C	Electronic goods (white goods)	B2C
[28]	Stål and Corvellec (2018)	J	Fashion (apparel)	B2C
[29]	Stål and Jansson (2017)	J	Fashion (apparel)	B2C
[30]	Suckling and Lee (2015)	J	Electronic goods (mobile phones)	B2C
[31]	Sundin and Lindahl (2008)	C	High maintenance goods (forklift trucks, soil compactors) Electronic goods (white goods, cameras)	B2B
[32]	Sundin *et al.* (2009)	J	High maintenance goods (forklift trucks, soil compactors) Electronic goods (white goods, cameras)	B2B
[33]	Tasaki *et al.* (2006)	J	Electronic goods (various equipment)	B2B
[34]	Thomsen *et al.* (2016)	J	High maintenance goods (aeroengine components)	B2B
[35]	Williams (2007)	J	High maintenance goods (automobile)	B2B
[36]	Wilson *et al.* (2017)	J	Electronic goods (mobile phones)	B2C
[37]	Yoo *et al.* (2016)	J	High maintenance goods (car batteries)	B2B

5.3.3. Data analysis

The dataset was created by collecting quotes from the 37 papers. To remain open to possible directions and definitions that could emerge, we used open-ended initial coding to identify quotes of interest (Saldaña, 2013). We selected quotes that introduced or explained elements of the PSS and their relation to a closed loop system. Rather than looking for specific terms or concepts, we identified PSS elements based on the definition stated in the introduction section i.e., the tangible and intangible characteristics. The quotes were organised in an Excel spreadsheet, see Appendix B for the full dataset. The data was analysed to identify PSS elements; identify the contributions of PSS elements to closing loops; and how We used abstractions to continue to build depth into the analysis by simplifying the complexity of intermediate results and intensify our focus (Hoover *et al.,* 1991). The analysis process is illustrated in Figure 5.2.

5.3.3.1. Identifying and organising PSS elements

All quotes were coded descriptively (Saldaña, 2013) i.e., based on the aspects of the PSS that they addressed. Some papers discussed multiple elements, for example, if they compared various case studies. Others studied only one or two specific elements of a PSS but provided a more in-depth definition. We clustered the codes in categories, based on six architectural PSS levels (Müller and Stark, 2010). We renamed Müller and Stark's 'products' level as resources to include elements related to products as well as components and materials. Services are intangible products offered to customers. Stakeholders include elements related to the service provider, one or multiple customers and other parties in the extended supply chain. Resources, services and stakeholders together produce an integrated value delivery, which is enabled by supplemental systems and tools. Further, a contract is included in which stakeholders make agreements on value delivery. The process of coding and categorising was iterative and led to the synthesis of twenty-one PSS elements. Table 5.3 provides examples of the simplified coding process. From the categorisation of the PSS elements the first version of a framework was constructed in which the elements are defined and categorised by the six architectural levels of PSSs. The six levels are mutually exclusive, i.e., each element was always categorised by one level, precluding co-occurrence on the other levels.

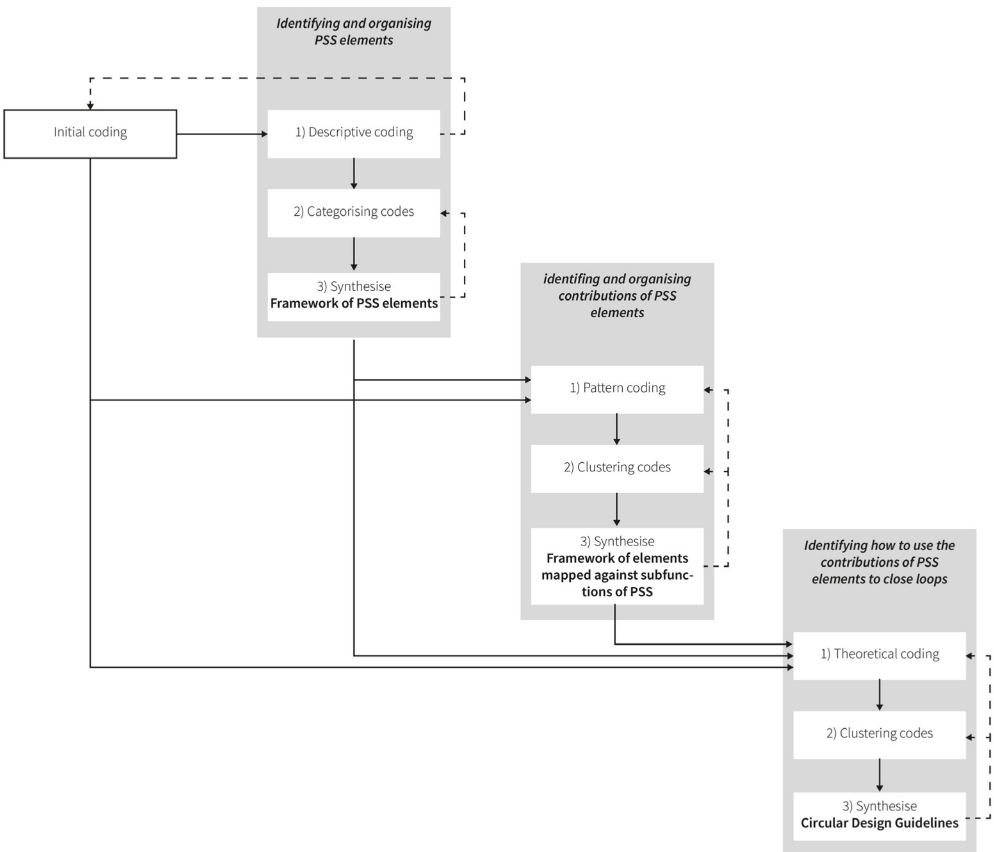


Figure 5.2 Diagram of the data analysis process.

Table 5.3 Examples of quotes and how they have been coded

Quote	Interpretation	Coded element
A part of customers prefers purchasing (or leasing) remanufactured products, and such customers are increasing, however, still such demands are limited. Remanufactured products are often bundled to newly manufactured products when a large-lot customer purchases (or leases) products (Kamigaki et al., 2017, p. 647).	Describes that the demand of customers is linked to the uptake of cycled resources.	Demand
The valuation of a ship as it ages is complex but the European Commission states that 'freight rates determine when to scrap; labour costs determine where to scrap; steel prices determine the size of the ship owner's profit' (Jensen and Remmen, 2017, p. 379).	Explains how the value of resources can be impacted and implies a link to the EOL.	Value
The baby equipment rental business explained that some baby equipment items need to be replaced after a certain period of time due to safety concerns. For example, a car seat needs to be retired after 5-6 years. Accordingly, they tend not to repair their equipment and often sell equipment to friends before it becomes worn. In this situation, repair of rental goods is not desirable, but professional recycling may still be possible (Retamal, 2017, p. 897).	Illustrates how external factors can determine when a resource becomes obsolete and how this limits its continued flow.	Terms and conditions

5.3.3.2. Identifying and organising the contributions of PSS elements to closing loops

We continued to analyse the PSS elements and their subsets of quotes to identify how exactly they contributed to closing loops. 'Closing resource loops' was considered an overarching function satisfied by each of the PSSs studied. However, when we interpreted the contributions of the PSS elements to closing loops, the elements were not found to literally 'close resource loops'. Instead, several themes emerged which indicated that they enabled PSSs to satisfy numerous subfunctions that favoured or permitted the studied PSSs to close resource loops. We used pattern coding to group these contributions (Saldaña, 2013), followed by an iterative comparison and refinement of the patterns to identify the key contributions. Four subfunctions emerged from the analysis i.e., state resource lifetime; govern resource lifetime; intercept obsolete resources; transition obsolete resources. We structured the contributions under the following four subfunctions, for example, the element 'demand' illustrated in the example quote (Table 5.3) was linked to the subfunction 'transition obsolete resources' as it describes how this element contributes to moving resources into a successive life cycle phase. In the final framework, the identified PSS elements relate to both the architectural levels of PSSs and the four subfunctions. The subfunctions are not mutually exclusive to the elements, i.e., some PSS elements were found to enable one or more subfunctions.

5.3.3.3. Identifying how to use the contributions of PSS elements to close loops

Finally, we analysed the PSS elements and their contributions to closing loops, as well as their initial subsets of quotes to understand how we could purposefully embed PSS elements to close the loops of resources. The quotes in the dataset had been used to identify the contributions of a PSS element to one or multiple subfunctions. Many of the quotes also illustrated how the elements were designed, and designed to satisfy the subfunctions. This part of the analysis focused on this information. We used theoretical coding to integrate earlier results in order to abstract the results and explain how the contributions can be employed in PSSs (Saldaña, 2013). The quotes were clustered on how they enabled a single subfunction. For example, the following quotes were linked to governing lifetimes: '*(…) When the child outgrew the clothing, it was simply switched to a new packet in the next size via parcel post. (…)*' (Petersen and Riisberg, 2017); and '*(…) This schedule of upgrades, carried out by a support service that collects worn modules at the same time as it implants "improved" modules, facilitates* *the end-of-life processing of these modules (…)*' (Pialot *et al.,* 2017). These quotes illustrate a design solution to govern lifetime consisting of timely offered services at the moment in which resources change to the obsolete state. The clustering process involved grouping and abstracting the codes to synthesise a final set of coherent design guidelines. The guideline for the example used here is '*Align changes to the obsolete state with moments of interaction*'. The guidelines are exclusive to the subfunctions but are independent of the specific PSS elements and the six PSS element categories.

5.4. A Framework of PSS elements that enable closed-loop resource flows

The first result of this study is a two-part framework. The first part consolidates and categorises the twenty-one PSS elements and organises them on six architectural levels; the second relates the PSS elements to both the architectural levels as well as to the four subfunctions that describe the contributions of the PSS elements to closing loops.

5.4.1. PSS elements that enable closed-loop resource flows

Table 5.4 presents the twenty-one PSS elements identified and defined in this study categorised by six architectural levels. Relationships exist between the PSS elements on a single architectural level as well as between PSS elements on different levels. For example, contracts on component lifetime defined by ***obsolescence*** are offered for ***maintenance services*** (Lindström, 2016) and ***ownership*** is a central topic in ***access and performance services*** (Bindel *et al.,* 2012; Corvellec and Stål, 2017). Further, the concept of ***obsolescence*** was also used to sell products under a service life guarantee without obtaining ***maintenance services*** (Jensen and Remmen, 2017), and ***ownership*** was found to be independent of the waste effect (Corvellec and Stål, 2017). It is unlikely that embedding one single PSS element is sufficient to enable PSSs to produce closed loops. Rather, multiple PSS elements configured together will enable the overarching function. However, in this study, we have identified the elements separately and interpreted their individual and independent contribution to closed loops.

We found that PSS elements exist on all six architectural levels. Some PSS elements are commonly studied in PSSs, e.g., ***ownership*** or ***logistics***, whereas others are less explored, e.g., ***judgement of value*** or the ***volume of resource flow***. At least two PSS elements were identified for each of the levels. PSS elements at the service level are similar. However, more commonly, there are differences in the nature, complexity and capacity of the PSS elements at the same level. At the resource level, for example, we identified the ***value*** as a complex PSS element influenced by factors such as labour and transportation costs. However, at the resource level, we also identified PSS elements that seem self-contained, such as ***architecture*** (e.g., assembly-planning) and ***features*** (e.g., colour schemes). The stakeholders level has the most PSS elements. The diversity of these elements reflects the complexity of this level as they address stakeholder needs (e.g., ***demands*** and ***incentives***), contributions that they are expected to make (e.g., ***participation*** or ***operation***), and behaviours (e.g., ***attachment*** that consumers may express towards a resource or how they ***judge its value***). PSS elements at the contract level include agreements on ***ownership*** and ***obsolescence*** of resources. For example, obsolescence reflects the scheduled replacement of a product, including agreements on the

Table 5.4 First version framework presenting the PSS elements and their definitions categorised by six PSS architectural levels.

Services	*Access and performance*	Services that intensify the use of products through leasing, renting or pay per service units.
	Maintenance, repair, upgrade	Services that extend the life of products by component or material replacements.
	Take-back	Services that accept obsolete products, components and materials for further processing.
	Warranty	Services that cover unexpectedly incurred costs related to product performance during a predefined utilisation time.
Resources	*Value*	The value of products, components and materials during lifetime or afterlife, subject to labour costs, transportation costs, commodity prices, etc.
	Architecture	Structural organisation of product systems, sub-systems and components e.g., modularity, ease of access, ease of disassembly.
	Features	Aesthetic, geometrical and functional characteristics of products, components and materials, e.g., colours, shape, size, weight, working principles.
Stakeholders	*Attachment*	The emotional bond between a resource and a customer.
	Demand	The quantity of (obsolete) resources that customers are willing or able to acquire for various prices over a given period.
	Judgement of value	Assessments of the value of resources based on experience, cultural and contextual dimensions, e.g., brand image, the extent to which a recycled content is appreciated, personal preferences.
	Incentive to participate	Encouragement to engage in PSSs e.g., monetary rewards or access to use an expensive product; or lack of encouragement e.g., costs, education, awareness.
	Incentive to operate	Encouragement to operate PSSs e.g., flexibility in resource management and practices, extended producer responsibility.
Contract	*Ownership*	Possession of (obsolete) products, components and materials and associated responsibility and liability for their state and flow.
	Obsolescence	Dynamics of various social, technological, economic and environmental factors that determine the end of the lifetime.
Value delivery	*Terms and conditions*	Conditions that influence the delivery of value, e.g., legislation, resource availability.
	Pace of flow	The time it takes for products, components and materials to complete a single loop.
	Volume of flow	The number of products, components and materials that move through a single loop.
System and tools	*In-use data collection*	Sensing, recording and monitoring the context, state and quality of a resource during its lifetime, e.g., through RFID and IoT sensors and devices.
	Data on origin	Transparency on material usage and product structure including systems, sub-systems and components, e.g., material passport, disassembly instructions.
	Data interpretation	Responding to available data, e.g., assessing the state and quality of a resource, planning the servicing, predicting obsolescence, deciding on EOL.
	Logistics	The organisation of the operational activities to move obsolete resources, e.g., location, accessibility, time of collection.

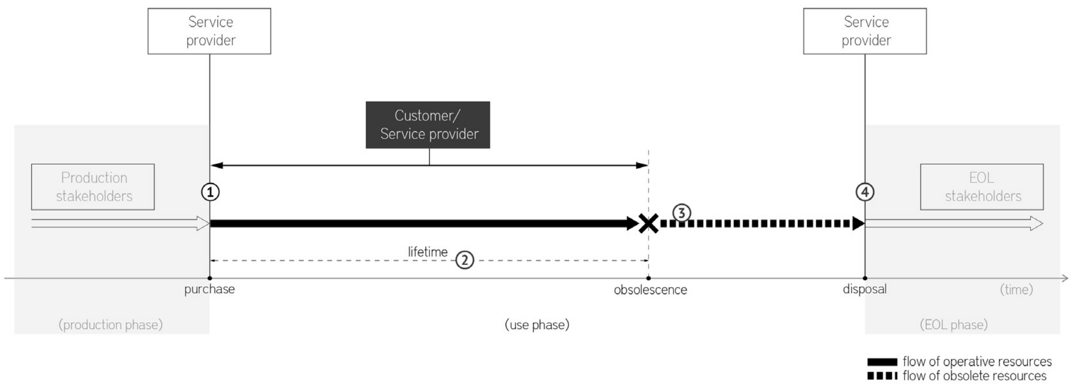


Figure 5.3 Timeline of resource flow in the use phase, indicating stakeholders and the four subfunctions:
1: State resource lifetime;
2: Govern resource lifetime;
3: Intercept obsolete resources;
4: Transition obsolete resources.

Table 5.5 Final framework presenting the contributions of PSS elements to closed loops (see Table 5.2 for references) structured under four subfunctions and categorised by six architectural PSS levels.

	PSS Element	State resource lifetime	Govern resource lifetime	Intercept obsolete resources	Transition obsolete resources
Services	*Access and performance*	Define use time. [4, 9]	Off-set lifetime. [33, 34]	Specify location. [10]	Value resource release. [18, 22, 35]
	Maintenance, repair, upgrade		Value lifetime. [21, 34]	Plan intervention. [21,37]	
	Take-back			Provide location. [1, 3, 4, 9, 12, 16, 29]	Establish volume. [11, 19, 35]
	Warranty	Define lifetime. [2, 8]			
Resources	*Value*				Raise interest. [4, 10, 11, 14, 19, 32, 36]
	Architecture				Purify resource flow. [7, 19, 21, 27, 32, 35]
	Features	Impact duration of the lifetime. [20, 23, 30]			
Stakeholders	*Attachment*			Coerce resource release. [31, 36]	
	Demand				Pull resources. [1, 3, 4, 9, 11, 15, 17, 26, 29, 30]
	Judgement of value		Resource retention. [36]		Raise interest. [3, 9, 29]
	Incentive to participate			Lure resources. [2, 3,9, 10, 28, 29, 30, 36]	
	Incentive to operate				Push resources. [9, 16, 28]
Contract	*Ownership*		Value lifetime. [5]	Navigate resources. [9, 10, 29]	Agree on responsibilities. [9, 10]
	Obsolescence	Agree on service life. [14]	Anticipate resource release. [17, 21, 23, 34]		
Value delivery	*Terms and conditions*	Determine the lifetime. [12, 14, 22, 23]			
	Pace of flow		Plan duration of the lifetime. [22, 26, 36]		Stabilise flow. [19, 30]
	Volume of flow				Stabilise flow. [4, 10, 17, 26]
System and tools	*In-use data collection*		Trace resource conditions. [7, 13, 14, 17, 32, 37]	Track resource location. [6]	Value resources. [5, 6, 16]
	Data on origin				Purify resource flow. [14, 19, 27]
	Data interpretation		Intervene timely. [7, 14, 23, 24, 25, 34, 37]		Automate interventions. [1, 7, 31]
	Logistics	Notify the lifetime. [9]		Move resources. [1, 4, 9, 10, 11, 26]	

minimum or the guaranteed lifetime. The value delivery level includes the ***pace*** and ***volume*** of the flow of resources, as well as ***terms and conditions***. The latter element includes contextual factors, such as legislation that set boundaries for practitioners. On the system and tools level, the PSS elements appear structural, such as ***logistics*** and ***data interpretation***.

5.4.2. Four subfunctions to close loops enabled by PSS elements

PSS elements were found to contribute to closed loops by enabling PSSs to satisfy four specific subfunctions that affect the resource flow in the use phase, see Figure 5.3. Two of the subfunctions occur from the early to the late stages of the use phase, i.e., state and govern resource lifetime. PSSs that *state resource lifetime (1)* aim to clearly define the lifetime of resources. PSSs that *govern resource lifetime (2)* monitor and maintain resources in use. Clarity on the lifetime of resources and the current state of resources can be used to make a plan for when resources become obsolete. Although enabling these subfunctions is no guarantee for closed loops, these two subfunctions favour closed loops as they appear to increase the probability to gain control over resource flows.

The two other subfunctions align with later stages of the resource's life. PSSs that *intercept obsolete resources (3)* aim to gather resources from the moment resources become obsolete at the end of the use phase. PSSs that *transition obsolete resources (4)* ensure that resources enter a successive lifecycle after the use phase. In contrast to the first two, these subfunctions are a hard requirement for PSSs that aim to close loops. Without physically capturing resources and ensuring their destiny, resources cannot flow in a closed loop.

The framework in Table 5.5 presents the contributions of PSS elements to the four subfunctions. Although the PSS elements are not new, the novelty of this framework is that they are presented based on their contributors to closing loops. For example, access and performance services are widely studied for their ability to extend the lifetime of resources. This study suggests that using them to simply specify a location to return resources is a key contribution to closing loops. PSS elements and their contributions to each subfunction are discussed in depth in the next Section.

5.5. Guidelines to design Product-Service Systems to Close Loops

The second result of this study is a set of 'Circular Design Guidelines' that explain how to design and employ PSS elements to enable PSSs to satisfy the subfunctions to closing loops. The guidelines are mutually exclusive to the subfunctions, see Figure 5.4. The guidelines influence the design of PSSs in three ways, i.e., the clarification of overall design requirements (e.g., make lifetime specific, understand value of obsoletes); the composition and organisation

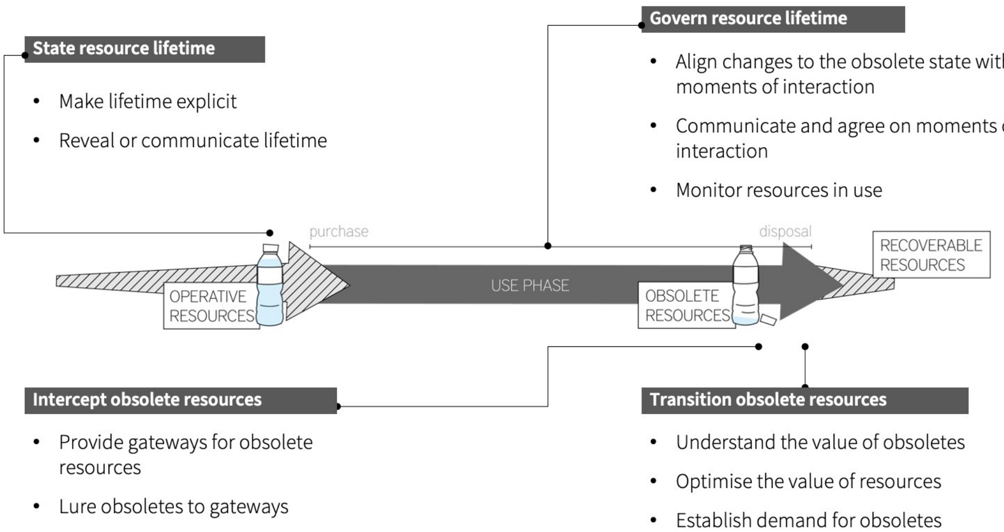


Figure 5.4 Circular Design Guidelines.

of the elements (e.g., planning moments of interaction, providing gateways); and the operating mechanisms (e.g., monitoring resources, luring obsoletes). This section is structured by the four subfunctions. We first discuss the importance of the subfunction, followed by the related guidelines and contributions of PSS elements that emerged from the literature.

5.5.1. State resource lifetime

PSSs that *state resource lifetime (1)* acknowledge the impermanence of resources, for example, by making the resource lifetime specific, which increases awareness to respond to the obsolete state of resources amongst manufacturers and consumers. This favours closed loops because uncertainties on lifetime are likely to disrupt the flow or make it unlikely for a resource to reach successive lifecycle phases (Sinha *et al.,* 2016; Suckling and Lee, 2015; Wilson *et al.,* 2017). In PSSs, stating the lifetime of resources has been suggested to increase the awareness of customers to return obsolete products (Sinha *et al.,* 2016; Suckling and Lee, 2015).

Make lifetime specific

Obsolescence is an inevitable event in a product's lifetime. By making lifetime specific, a plan for how to respond to obsolescence can be prepared. Methods already exist to calculate the economic lifetime of products and components that are subject to service offerings. These could easily be used to make lifetime specific to favour closed loops. Stating resource lifetimes involves being clear about the durability of resources. We identified two types of services, which specify the length of lifetime. First, ***warranty services*** aim not to exceed the technical life of a product (Chattopadhyay and Rahman, 2008). Arabi *et al.* (2017) proposed methods to optimise the warranty of a product and the cost endured by the provider of the service, such as defining the lifetime by estimating the out-of-warranty time. Second, ***access or performance services*** define the utilisation time explicitly, e.g., agreeing on a rental period (Besch, 2005; Corvellec and Stål, 2017), which removes uncertainty regarding how long to use or when to return resources.

Reveal or communicate obsolescence

To ensure the required response to obsolescence, PSS can be designed to clearly communicate obsolescence to users. The most explicit way to communicate is via a contract, e.g., a written agreement that includes a predefined service life and thus ***obsolescence*** of products or components. This is common for large, high-maintenance products mostly because retaining idle assets is expensive (Jensen and Remmen, 2017). Sometimes ***terms and conditions*** can define the lifetime of resources, e.g., retaining resources for a minimum time to justify the economics of a PSS (Gottberg *et al.,* 2010). Legislation may mandate the communication of the exact lifetime of resources, for example, due to safety concerns a car seat needs to be retired after 5-6 years (Retamal, 2017). Finally, the availability of replacement or upgraded resources is an essential condition for the length of the lifetime; for example, if component lifetimes are shorter than product lifetimes (Romero Rojo *et al.,* 2012).

There are also less explicit ways to communicate obsolescence. Some resource ***features*** directly impact or define the duration of the lifetime. For example, colour schemes for rent-out garments have been introduced to retain customer interest by mitigating aesthetic obsolescence (Petersen and Riisberg, 2017). Moreover, highly simplified hardware for electronics with rapidly developing software has been used to mitigate technological obsolescence (Suckling and

Lee, 2015). Another way to make users aware of the mortality of resources is using a ***logistic*** tool, such as the 'Rag-bag'. This tool is offered at the point of purchase is a used to return the obsolete product to the manufacturer (Corvellec and Stål, 2017). Although this does not explicitly state the length of the lifetime, it notifies consumers of the finite lifetime of resources.

5.5.2. Govern resource lifetime

PSSs that *govern resource lifetime (2)* monitor and maintain resources and their condition during the use-phase. Lifetimes are subject to complex contextual variables (Burns, 2010) and are influenced by use and user behaviour (Costa *et al.,* 2015). Monitoring resources allows to make better predictions of their change to the obsolete state and influence this change. The provision of adequate and topical information on the state of products, components and materials is favourable to closed loops for two reasons. Firstly, it is an opportunity to optimise lifetime and better predict when resources become obsolete (Jensen and Remmen, 2017; Kamigaki *et al.,* 2017; Retamal, 2017; Romero Rojo *et al.,* 2012; Wilson *et al.,* 2017). Secondly, it allows assessing the value of a resource in time by interpreting its prevailing condition. Governing lifetime, thus, provides opportunities to plan interventions to intercept resources effectively and identify those in valuable conditions.

Align changes to the obsolete state with moments of interaction

If stakeholders ***judge the value*** of resources higher or lower than expected, resources may not flow as intended. Interventions can be planned if the resource lifetime is governed. For example, in a study to understand consumer behaviour towards obsolete products, participants were found to retain several 'spare' mobile phones beyond what one would assume to be useful (Wilson *et al.,* 2017). Participants indicated that they kept the devices as they were unsure whether they would need them in the future. Uncertainty on value can, thus, result in resource retention and disrupt resource flow.

Instead, services can be planned in alignment with the change to the obsolete state. The ***pace of resource flows*** provides insight into the adequacy of the lifetime duration. Resource lifetimes can easily be disrupted or misunderstood, which decreases their likelihood of flowing into a closed loop. Disruption occurs, for example, if service providers sell their goods in anticipation of high maintenance investments, such as with rental vehicles (Retamal, 2017). This relieves the responsibility of disposal (Williams, 2007), and it may extend the life of resources in a second use cycle. However, the resources that prematurely leave a PSS now have a low probability of flowing in closed loops. Furthermore, misunderstanding can occur if resources are retained longer than necessary, such as mobile phones hibernating in drawers (Wilson *et al.,* 2017). Hibernated obsolete resources affect the efficiency of resource flow (Sinha *et al.,* 2016).

Instead, PSS elements such as ***maintenance*** or ***upgrade services*** can provided appropriate moments of interaction to align with obsolescence of components.For example, worn modules are collected while scheduled upgrades take place (Pialot *et al.,* 2017). The ***access and performance service*** that leased baby clothes, provided a postal service was offered to return the clothes at the moment they were outgrown (Petersen and Riisberg, 2017). As such, providers of these service can control the flow of these resources.

Communicate and agree on moments of interaction

To ensure an action of the resource owner, moments of interaction must be made apparent. ***Access and performance services*** often agree with consumers on times and locations to return their resources (Costa *et al.,* 2015). A contract can be used to specify who is responsible for the environmental management of resources at the EOL, e.g., as is done for aircrafts (Jensen and Remmen, 2017). Service providers with ***ownership*** of resources value lifetime and govern it intending to extend it (Bindel *et al.,* 2012). Contracts can include a schedule for the preservation of assets (Romero Rojo *et al.,* 2012). These interventions can be used to intercept replaced components ahead of ***obsolescence*** (Pialot *et al.,* 2017) and anticipate when the obsolete resources are released to flow. There is a risk, however, that, scheduled activities could tempt service providers to use short-lived components, where more durable components could be used (Bindel *et al.,* 2012; Lindström, 2016; Pialot *et al.,* 2017; Romero Rojo *et al.,* 2012).

Monitor resources in use

There are several approaches to observe and track the conditions of resources in use. They are used by providers of ***services*** who retain ownership of resources. For example, providers of ***maintenance, repair or upgrade*** services typically govern lifetime to extend it (Pialot *et al.,* 2017). In the case of ***access and performance*** services, providers own fleets of resources and have incentives to monitor their state to maintain the resources (Costa *et al.,* 2015). To optimise the costs of products used in access and performance services, the expenses to govern resource lifetime are sometimes off-set against cheaper and shorter-life components (Tasaki *et al.,* 2006; Thomsen *et al.,* 2016), which risks to accelerate a flow of obsolete components.

The conditions of resources can also be documented by ***collecting in-use data*** in a passport that accompanies products throughout the use phase, a method commonly used for ship recycling (Jensen and Remmen, 2017). Monitoring can also be automated by equipping products with sensor-technology that automatically collects in-use data, for example, by tracing the conditions of resources during service life (Jensen and Remmen, 2017). Adaptive systems use sensors to monitor product states, such as temperature and maintenance data (Chang *et al.,* 2017; Yoo *et al.,* 2016). Additionally, IoT can be used to measure prevailing properties of artefacts (Yoo *et al.,* 2016), and other frameworks have been proposed to collect consumer needs data (Hussain *et al.,* 2012). The second element at this level is ***data interpretation***, which enables timely intervention (Thomsen *et al.,* 2016; Yoo *et al.,* 2016). This involves the analysis of the collected data to diagnose damage and failure (Roy *et al.,* 2014; Russo *et al.,* 2016), predict EOL (Romero Rojo *et al.,* 2012), and inform service providers about EOL decisions (Hussain *et al.,* 2012; Sundin *et al.,* 2009; Yoo *et al.,* 2016). Data interpretation can advance further if monitoring systems can automatically direct maintenance services (Chang *et al.,* 2017).

5.5.3. Intercept obsolete resources

PSSs that *intercept obsolete resources (3)* reclaim, collect or receive the resources that either can no longer be used or are no longer needed. Resources are tangible matter and they can only be revalorised if they can be accessed by the stakeholders providing this service. Intercepting obsolete resources is, therefore, required to close loops. Intercepting resources involves directing resources to dedicated locations where they can (re)enter recovery systems. Successful interception is a requirement for closing loops for two reasons. Firstly, because it ensures that obsolete resources get the chance to be a supply in consecutive lifecycle phases. Secondly, because commercial logistics and recovery are volume dependent.

Provide gateways for obsolete resources

A designated location where obsolete resources can be intercepted is critical to enable PSSs to intercept obsolete resources. Obsolete resources can be intercepted in the form of materials, components e.g., worn out modules in electrical goods (Pialot *et al.,* 2017), or products e.g., brands like the Swedish Boomerang that offer to take-back obsolete apparel and furniture in-store to sell second-hand (Corvellec and Stål, 2017). We use the term gateways to indicate entry points for resources into the system. Several PSS elements were used to provide gateways.

The most obvious one is a ***take-back service*** that provides a location where obsolete resource are gathered (Armstrong *et al.,* 2015; Lee *et al.,* 2007; Stål and Jansson, 2017). However, ***access and performance services*** specify to users when and where to return resources (Costa *et al.,* 2015), allowing for a designated yet more flexible and impermanent location. ***Maintenance, repair or upgrade services*** provide a recognised opportunity to intercept resources during planned interventions (Pialot *et al.,* 2017; Yoo *et al.,* 2016). The ***logistics*** of ***take-back services*** are an important factor with regards to their economic feasibility (Besch, 2005). The economics appear to depend on who manages the collection of the obsoletes, as well as where the collection takes place. In product-oriented PSSs, take-back is typically optional and the manufacturer or service provider is rarely committed to intercepting obsolete resources (Williams, 2007). However, there are examples in which manufacturers make contracted commitments (Costa *et al.,* 2015). Some businesses choose to decouple this activity from their organisation through outsourcing or internal separation (Costa *et al.,* 2015; Stål and Corvellec, 2018; Stål and Jansson, 2017). This can be beneficial if a company is unequipped to store or process obsolete products (Costa *et al.,* 2015) or when a company is reluctant to take responsibility (Costa *et al.,* 2015; Retamal, 2017).

Lure obsolete resources to gateways

Once gateways are introduced, PSSs must ensure that obsolete resources will reach them. The destiny of resources, thus, is likely to strongly depend on the actions of the stakeholders who use and possess the resources at the moment they become obsolete. To ensure that obsolete resources reach gateways, the journey to gateways must be made appealing, or even insistent.

The journey can be made appealing by considering an appropriate location. We derived numerous locations where interception could take place, e.g., at the point of purchase (Corvellec and Stål, 2017), by means of a collect-and-return product (Anttonen, 2008; Costa *et al.,* 2015), or by reclaiming directly from users (Anttonen, 2008). The strategies for gateways thus seem to be operating in close proximity to where resources become obsolete; situating them next to common gateways such as bring banks; or positioning them where replacement purchases are made. The accessibility of gateways seem to be one of the largest contributors to efficiently closing loops, such as was found for obsolete mobile phones (Sinha *et al.,* 2016). More appealing locations can be imagined when PSS elements such as ***in-use data collection*** are embedded in the PSSs, for example, using IoT for real-time product location (Bressanelli *et al.,* 2018). This could provide an opportunity to fetch the resources from users by offering flexibility in locations.

The probability of resource interception could be increased if the PSS was more insistent on making the journey. At the foremost, the journey is sensitive to the ***behaviour of stakeholders*** owning the resources (Gottberg *et al.,* 2010; Suckling and Lee, 2015; Wilson *et al.,* 2017). Our studies showed that gateways were found to be used more if owners of obsoletes were educated on their use, informed of their existence or incentivised to use them. Therefore, PSSs embedded ***incentives to participate***, including discounts on new purchases after returning obsolete resources (Corvellec and Stål, 2017; Sinha *et al.,* 2016; Stål and Corvellec, 2018), access to expensive products (Armstrong *et al.,* 2015), and education to increase awareness (Armstrong *et al.,* 2015; Suckling and Lee, 2015; Wilson *et al.,* 2017). PSSs can use contracts to further increase the probability of interception. For example, ***ownership*** of resources could be used to clarify the responsibilities of resource owners to intercept and recycle resources (Costa *et al.,* 2015; Lee *et al.,* 2007; Michelini *et al.,* 2017). The proper management of resource flows was even found to be more critical to return resources back into systems than who owns the products (Corvellec and Stål, 2017). The responsible stakeholders, then, bring resources to designated locations, such as those where components are intercepted during planned-for maintenance (Lindström, 2016). In some PSS, stakeholders could become emotionally ***attached*** to the resources (Sundin and Lindahl, 2008) and tactics may be required to coerce release tangible resources from emotional bonds (Yoo *et al.,* 2016). To insist strongly on the return of resources, consumers could be charged per use time which is often the case in ***access and performance services*** (Costa *et al.,* 2015). Hibernation of obsoletes then becomes an expensive practice and consumers have stronger incentives to return resources they do not use.

5.5.4. Transition obsolete resources

PSSs that *transition obsolete resources (4)* push the resources into a successive lifecycle phase, e.g., EOL, production or a new use phase by developing demand for resources after an interception. Enabling this function is a must to close loops, because intercepted resources must have a destination to be fed-back into systems. Transitioning obsolete resources necessitates a commercial interest such as satisfying a demand. As with any supply-and-demand dynamic, supplies are more likely to satisfy demand if they meet quality standards and their volumes are consistent and sufficient. Demand for these resources could arise in the EOL phase, for example, by harvesting components from obsolete products for reuse in new products or if recycling materials to become building blocks for new products. Demand can also arise in the use phase, for example, if PSSs can revalorise obsolete resources without additional processing. Transitioning obsolete resources, therefore, is required to physically achieve closed loops.

Understand the value of obsolete resources

First, we suggest obtaining a good understanding of the (potential) value of the intercepted obsolete resources. This is critical to understand if the resource could satisfy demands of potential stakeholders. The value depends, firstly, on internal factors such as features that influence costs for take-back services and recovery processes, e.g., ease of disassembly (Peeters *et al.,* 2017). Clever ***architecture*** of resources involves the optimised and strategic positioning of components for ease of access and disassembly (Chang *et al.,* 2017; Sousa-Zomer *et al.,* 2017; Sundin *et al.,* 2009), which has advantages efficient maintenance, repairs and upgrades (Pialot *et al.,* 2017; Thomsen *et al.,* 2016). It is also essential to efficiently recover components and materials. Product ***architecture*** should, therefore, be an early consideration and relate to service elements, component durability and obsolete resource value (Lee *et al.,* 2007; Peeters *et al.,* 2017; Romero Rojo *et al.,* 2012; Sundin *et al.,* 2009; Williams, 2007).

Secondly, the value depends on external factors, which include timing, market expectations and market preferences. The resource ***value***, for example, is subject to the costs of obsolete resources, which can decrease with optimised ***architecture*** as this reduces complexity and disassembly time (Jensen and Remmen, 2017; Peeters *et al.,* 2017; Williams, 2007). The value of obsolete resources depends on many such contextual factors, such as commodity prices (Jensen and Remmen, 2017) and labour costs (Besch, 2005; Jensen and Remmen, 2017; Peeters *et al.,* 2017). It can also be impacted by the availability of newer products (Wilson *et al.,* 2017); thus, a key factor relates to when obsolete resources are transitioned. Stakeholders may be reluctant to use recycled materials because of uncertain quality standards (Sundin *et al.,* 2009), which may be mitigated by introducing quality criteria for cycled resources (Gelbmann and Hammerl, 2015). Stakeholders may also worry that cycled resources compete with their offer of virgin resources (Costa *et al.,* 2015; Gelbmann and Hammerl, 2015).

Optimise the value of obsolete resources

The ***value*** of obsolete resources can often be optimised in PSS. Providers who own products or are held responsible for EOL costs, they have incentives to optimise the value and lifetime of products. Value can be optimised by reducing complexity. For example through ***architecture***, e.g., through accessible positioning of replaceable components; designing full disassembly plans and sequences; and simplifying disassembly processes through standardised components or features e.g., active fasteners (Peeters *et al.,* 2017) or modularity (Pialot *et al.,* 2017). Information on resources can further reduce complexity.

A lack of data on products and components can disrupt or disable disposal routes (Lee *et al.,* 2007; Suckling and Lee, 2015). Systems and tools include PSS elements such as ***data on the origin***, which can be used to purify resource flows to optimise resource value effectively. For example, using information on product architecture to optimise expensive disassembly and dismantling processes (Jensen and Remmen, 2017; Peeters *et al.,* 2017; Sundin and Lindahl, 2008), or using information on material contents to recycle more accurately (Anttonen, 2008) and optimise the value of the recovered material (Jensen and Remmen, 2017). The data could be stated in material passports or dismantling instructions provided at product purchase (Jensen and Remmen, 2017; Peeters *et al.,* 2017; Sousa-Zomer *et al.,* 2017). PSSs can also ***collect in-use data*** to inform stakeholders on the current state of resources at the EOL (Bindel *et al.,* 2012; Bressanelli *et al.,* 2018; Chang *et al.,* 2017), which can be used to value the resources better. PSSs may then automatically ***interpret data*** such as to automate disassembly planning and to transition obsolete resources (Anttonen, 2008; Chang *et al.,* 2017; Sundin and Lindahl, 2008).

Value can also be optimised by reducing uncertainties on the volume of obsolete resources. Economic feasibility can be achieved if resources can piggyback on the flow of another, more valuable, resource. For example, the recycling of materials in mobile phones is a by-product of the collection of mobile phones for reuse (Suckling and Lee, 2015). Services should be used to establish flows and ensure volumes such as through ***take-back services*** (Gelbmann and Hammerl, 2015; Peeters *et al.,* 2017; Williams, 2007). A sufficient ***volume of resource flow*** is needed to manage interception and recovery costs. This stabilises flow and favours the profitability of obsolete resources (Besch, 2005; Lindström, 2016). The consistency of the volume is also important because aftermarkets need the stability of supplies (Sundin *et al.,* 2009). Flows can be inconsistent due to uncertainties in terms of resource quality (Besch, 2005). Uncertainties related to the number of reclaimed resources relate to the (lack of) customer incentives (Costa *et al.,* 2015). Uncertain quantities can also be a consequence of inconsistent ***pace of flows*** caused by loop leakage (Sinha *et al.,* 2016) and hibernation (Wilson *et al.,* 2017).

Establish demand for obsolete resources

Finally, customers for obsolete resources need to be found. If a provider has ***demand*** for its own obsolete resources, incentives to optimise value are stronger. Indeed, ***ownership*** can be used to flow back into the providers own value chain, for example, to benefit from using components for an extended period (Michelini *et al.,* 2017). In that case, declared and consistent demand comes from the service provider who already owns the resources (Anttonen, 2008). The demand can also come from a provider offering second-hand products alongside their original product offering (Armstrong *et al.,* 2015; Corvellec and Stål, 2017; Kamigaki *et al.,* 2017). The use of recovered resources is then integrated in the PSS e.g., by selling used product mixed with or next to original product, e.g., FilippaK sells used garments of its own brand (Corvellec and Stål, 2017).

Nevertheless, despite the strategic use of ***ownership*** in PSSs it is often unclear what happens to resources that are centrally owned. For example, a lease-model for baby clothing has been used to send a new package with larger sizes after receiving the customer's prior package with outgrown clothes (Corvellec and Stål, 2017; Petersen and Riisberg, 2017). Although in this case obsolete resources are intercepted but what happens to those that cannot be repaired or reused is not discussed. In another example, vehicles used for ***access and performance*** were strategically sold ahead of economic obsolescence, releasing them to flow further and avoiding maintenance and repair costs (Retamal, 2017) because service providers are financially responsible for EOL costs (Williams, 2007). Although this could ensure a longer life for the products, it reduces the chances for a responsible closed loop.

If providers cannot use their own obsolete resources, it is necessary to proactively establish a ***demand*** to create the aftermarket needed to responsibly transition obsolete resources (Jensen and Remmen, 2017; Sousa-Zomer *et al.,* 2017). A ***demand*** is a crucial to move resources into successive lifecycle phases (Anttonen, 2008; Besch, 2005; Corvellec and Stål, 2017; Stål and Jansson, 2017; Suckling and Lee, 2015). Demand for used and remanufactured products can be uncertain (Stål and Jansson, 2017) and some markets are less receptive to cycled resources than others (Kamigaki *et al.,* 2017; Lindström, 2016; Sinha *et al.,* 2016). Economic benefits seem to be the strongest ***incentive to operate*** a PSS that closes resource loops (Corvellec and Stål, 2017). If the costs of intercepting and transitioning are too high, landfill and incineration will be more economically attractive (Besch, 2005).

How stakeholders ***judge the value*** of resources can raise interest and establish demand. Customers can feel positively about take-back services and recycled content (Armstrong *et al.,* 2015; Corvellec and Stål, 2017; Stål and Jansson, 2017). This seems especially true when it is apparent how the obsolete has transitioned into the next cycle, for example, using an increased share of intercepted fibres in new clothing, rather than cascading them to a rug (Stål and Jansson, 2017). Such high appreciation by customers of activities to intercept and transition resources could even be another ***incentive to operate***.

5.6. Discussion

Although PSSs have been reported to produce closed resource loops (Armstrong *et al.,* 2015; Mont, 2002; Romero and Rossi, 2017; Scheepens *et al.,* 2016), this potential is only sparsely reported in the literature. This study explored how PSSs can be used to establish a closed-loop resource flow, identified PSS elements that enable it and proposed guidelines to design PSSs that produce closed-loops.

5.6.1. The potential of PSSs to produce closed-loop resource flows

This work positioned 'closing resource loops' as an overarching function of PSSs. In PSS research the notion of function has occasionally been put forward to explore the complexity of PSSs beyond standard classifications (Van Ostaeyen *et al.,* 2013) and suggestions have been made to use functional analysis in designing and modelling PSSs (e.g., Haber and Fargnoli, 2017). However, the abilities of PSSs are rarely studied from a functional perspective. Conventional design approaches predominantly focus on the ability of PSSs to meet customer demands (e.g., Vezzoli *et al.,* 2014) and construct meaningful partnerships (McAloone and Pigosso, 2018). Providers are incentivised to manage durable products and reduce service costs, and as such design methodologies have evolved to design products with extended lifetimes (Bakker, Wang, *et al.,* 2014). Although these involve important PSS elements, focussing exclusively on them risks ranking the circular and sustainable aspects of the resources and their flow as secondary objectives.

Instead, identifying and formulating key subfunctions allows taking a top-down approach to designing PSSs that meet a specific overarching function or operational requirement, i.e., what the system fundamentally has to do (Burge, 2006). The subfunctions can then be positioned as requirements, which break down the operational requirement (Burge, 2006) and have to be considered early in the design process (Boons and Howard-Grenville, 2009; Haber and Fargnoli, 2017). The subfunctions include both demands and wishes (Pahl *et al.,* 2007). The former must be met under all circumstances to achieve an operational solution, e.g., producing closed-loop resource flows demands to intercept and transition obsolete resources. The latter should be taken into consideration whenever possible and, if met, warrant operational improvements, e.g., PSSs want to state and govern lifetime to optimise the operations to produce closed loops.

At present, PSSs are more commonly used to foster reuse by extending the service life of products and components (e.g., Mont, 2002; Pine II and Gilmore, 2013; Reim *et al.,* 2015; Stahel, 2010; Tukker, 2015) and the value that can be extracted from these resources, than to foster recycling by recovering materials. PSSs, thus, rarely produce a fully circular resource flow. Therefore, there appears to be a gap in the structural deployment of PSSs to enable the recovery of resources beyond the use phase. Despite this, we found that the same subfunctions can be used to close loops through reuse as well as through recycling, although how the requirements are positioned and with what purpose must be considered for fully circular flows.

Intercepting and transitioning resources results in closed loops. In reuse-oriented PSSs, service providers intercept resources from users, such as when a furniture-lease expires (Costa *et al.,* 2015). They are then incentivised to transition resources, either by flowing product-resources back to the start of the use phase to repeat a use cycle (Den Hollander *et al.,* 2017), or by disassembling products to flow component-resources back into the production phase (Michelini *et al.,* 2017). As such, by satisfying these requirements PSSs produce closed loops by exerting control over resources, and enabling the extension of resource lifetime (Den Hollander *et al.,* 2017; Stahel, 2016). Nevertheless, resources will eventually and inevitably become obsolete, such as when the upkeep of high-maintenance goods becomes too expensive (Retamal, 2017) and poses economic obsolescence. In such case, obsolescence is likely to encourage service providers to reject resources out of PSSs, which reduces the chance to ultimately flow resources in a closed loop. Even though resources should remain accounted for at all times to achieve circularity (Den Hollander, 2018), the flow of obsolete resources typically remains unplanned.

The implication of this study is that the interception and transition of obsolete resources are positioned as demands to produce closed-loop resource flow both for reuse- and recycling-oriented PSSs. The use of their respective design guidelines allows to design appropriate 'plans for obsolescence'. Obsolescence of provider-owned resources is not dissimilar to obsolescence of resources owned by consumers. Unless we consider the complex factors that cause obsolescence (e.g., Burns, 2010; Cooper, 2004; Zeeuw van der Laan and Aurisicchio, 2019a) and intentionally select and embed specific PSS elements to enable the interception and transition of obsolete products, components and materials, it is unlikely that resources will flow in a closed loop and successfully substitute the inflow of virgin equivalents. Providers who monitor resources in use can easily predict and influence obsolescence. It is not unlikely that various forms of obsolescence could be useful in the design of PSSs e.g., the aesthetic obsolescence of baby clothes. Although understanding of obsolescence is suggested to be powerful to close resource loops (Burns, 2010; Den Hollander *et al.,* 2017) further research is needed to understand how obsolescence is to be integrated PSSs to close loops.

Further, stating and governing resource lifetime result in exact lifetimes. Stating resource lifetime positions time as a variable in the value equation, which links it to economic success (Gottberg *et al.,* 2010; Morelli *et al.,* 2002; Pine II and Gilmore, 2013; Stahel, 1982). Governing resource lifetime allows an even more precise lifetime estimate subject to change due to usage patterns, decisions made by resource owners and contextual factors that influence the stay of resources in the use phase (Burns, 2010; Cooper, 2004; Daae and Boks, 2015; Wastling *et al.,* 2018). Exacter resource lifetime, thus, seems a requirement to foster reuse and produce narrow and slow resource flows (e.g., Bakker *et al.,* 2014b) where lifetime quantifies the value of the time resources spend in the use phase.

The implication of this study is that the lifetime of resources acquires a new strategic purpose. Exact lifetimes are wanted as they can optimise the interception and transition of obsolete resources in two ways. First, they support timely interceptions, i.e., interceptions taking place at prevailing locations and convenient times, therefore benefitting customer compliance (Breen, 2006). For example, the specification of lifetime and the alignment of moments of interaction with the obsolete state can improve gateways and lure obsoletes as consumers are informed of imminent obsolescence and enabled to action through moments of interaction. Second, they support topical interceptions, i.e., interceptions that account for aspects such as the conditions of the resources at the time of interception, and can be used to avoid contamination of resources (Baxter *et al.,* 2017), inferior resource quality (Zink and Geyer, 2017) or obsolescence beyond recovery (Den Hollander *et al.,* 2017). Timing the interception with the depreciation of resources by embedding specific PSS elements can, thus, not only enable but also optimise resource transition. As such, although 'planning-for obsolescence' (Burns, 2010; Zeeuw van der Laan and Aurisicchio, 2017) appear to intercept pre-obsolete resources, it also increases the likelihood to intercept and transition them.

5.6.2. Using PSS elements to plan the flow of resources

In Section 2.1 we argued that though various PSS elements are discussed in the literature, current understanding of PSS elements is fragmented. In Section 2.2 we concluded that only very few PSS elements and their contributions to the circular economy are studied in-depth, e.g., ownership (Baxter *et al.,* 2015; Stahel, 2013; Tukker, 2004). Furthermore, the investigated contributions typically revolve around slowing and narrowing resource flows while further circular potential is merely implied (Blomsma *et al.,* 2018). This is regrettable as the knowledge of PSSs consequently spirals around very few PSS elements and unlocks only a fraction of the full potential of PSSs in a circular economy. Moreover, such narrow research focus is not unlikely to compromise PSS development and slow their adoption by industry (Ceschin, 2013; Vezzoli *et al.,* 2012).

This study identified twenty-one PSS elements; categorised them by six architectural levels; consolidated them in a framework based on their contributions to producing closed-loop resource flows; and proposed new circular design guidelines to use the framework to design PSSs with closed loops. These results address gaps in PSS research and design methodology (Tukker, 2015a) as the framework articulates why specific PSS elements should be embedded in PSSs to achieve full circularity to guide designers of PSSs. The framework and guidelines give new meaning to PSS elements. First, because they explain why certain PSS elements are useful to close loops, and second because it explains contributions required to close loops and how common and less explored PSS elements can make these contributions.

Underexplored PSS elements are, for example, those that influence, measure or assess resource value (e.g., judgement of value, in-use data collection, the volume of flow, or resource architecture) are found to have a significant role to close resource loops. Some circular product design strategies do aim to address resource value at specific moments in the lifecycle, for example, recovery costs can be minimised by maintaining the purity of resource flows or designing product architecture for ease of disassembly (Bocken *et al.,* 2016; EMF, 2012; Mestre and Cooper, 2017). However, the value of resources is complex and changes throughout the lifecycle. Understanding this is essential to produce closed-loop resource flow because intercepted obsolete resources will have different conditions, and will only transition if stakeholders recognise commercial benefits in acquiring them (Lüdeke-Freund *et al.,* 2018).

There are also PSS elements that influence resource value. For example, data on origin provides transparency on resources, enabling cost-effective recovery. The resource value is also dependent on whether quality is compromised compared to virgin resources (Zink and Geyer, 2017). PSS elements such as in-use data-collection can be used to measure actual quality of resources. Current efforts to study resource value tend to focus on singled-out aspects of the resource, such as consumers' willingness-to-pay for a material with a particular origin (Magnier *et al.,* 2019) or the fractions of valuable materials in residual municipal solid waste (Rada and Cioca, 2017). Instead, this study implies that PSSs and the value of resources are related, and PSS elements can impact value positively or negatively. Using the supply of resources to satisfy a demand inside or outside the PSSs requires anticipating the value of resources over time. This puts forward a need to study the resources in PSSs over time, for example, through a multi-dimensional characterisation (Karana *et al.,* 2015) to interpret both the value of obsolete resources and the ability to manipulate resource value to enable their successful interception and transition.

A number of PSS elements in the framework are commonly studied. Despite this, only very few explicit contributions of these PSS elements to closed loops are found in the literature, e.g., using ownership to agree on responsibilities related to resource management (Den Hollander *et al.,* 2017; Tennant, 2013; Tukker, 2004). Not surprisingly, many of the common PSS elements identified in this study appeared at the stakeholder level. PSSs are typically customer-oriented (e.g., Vezzoli *et al.,* 2014), making stakeholders, their needs and the dynamics of their relationships undeniably important (Bocken *et al.,* 2016; Charnley *et al.,* 2011; Lewandowski, 2016; McAloone and Pigosso, 2018). The framework expands on these elements with implied roles for stakeholders, such as participating in PSSs or operating (parts of) the PSSs, and possible behaviours of stakeholders, such as attachment to resources or their judgement of value. Understanding what is expected of stakeholders in PSSs (roles) and whether they meet these expectations (behaviours) is essential to produce closed-loop resource flows. For example, we can intercept obsolete resources only if the stakeholders who have access to them carry out activities that position resources in accessible locations (Zeeuw van der Laan and Aurisicchio, 2019a, 2019b). Once we have an understanding of this role, the meaning and weight of other PSS elements, such as incentives to participate, can be defined to effectively lure the owners of resources to designated locations (Zeeuw van der Laan and Aurisicchio, 2019d).

5.7. Limitations and further work

In this study we conducted a systematic review of existing literature on PSSs. Producing closed loops is rarely the primary aim of PSSs, and thus the identified PSS elements are sparse and not systematically covered in the literature pertaining to close loops. Other relevant elements are likely to exist that did not emerge from this study. Additionally, our ability to identify elements bottom-up may have been impacted by our knowledge of existing PSS elements. Further, we selected literature for this review using strict criteria focusing specifically on PSSs. Because the data was not exhaustive, some of the results emerged through abstraction. This was necessary to identify contributions to closed loops which were found to mostly be implicitly discussed in the literature. We are confident that the results are representative of our investigation, but do not rule out that they can further evolve. For example, a broader selection of literature could lead to including specific or common types of PSSs using different search terminology e.g., car sharing, sharing platforms or building-related services. PSS elements appear to be resource-specific, and the products in the selected papers could only be placed in four categories. Thus, the dataset could be expanded by studying PSSs in other product categories. To extend and develop the framework and the guidelines we, therefore, suggest conducting empirical research to investigate PSS elements in specific industries (e.g., case studies). We also recommend prioritising research on specific PSS elements to deepen our understanding of their contribution to producing closed-loop resource flows (e.g., through focused literature reviews). Finally, the guidelines find their bases in a review of the literature and could be validated in practice.

5.8. Conclusions

We found that the literature reports sparse insights on how to use PSSs to produce closed-loop resource flows but lacks a structured and comprehensive understanding. This limits the use of PSSs in a circular economy and the ability to guide practitioners to design for fully circular resource flows. Using a systematic literature review this study identified twenty-one PSS elements that can unlock the potential of PSSs to close resource loops.

The study makes important contributions to PSS research and design methodology. First, it presents a novel framework, which consolidates relevant PSS elements. The framework can inform, educate and encourage practitioners to use elements beyond those commonly considered in design practices. Second, it categorises PSS elements by six architectural levels, demonstrating that PSS elements are available across levels of services, resources, stakeholders, contracts, value delivery, and system and tools. Third, it structures the contributions of PSS elements to close the resource loops under four subfunctions. Closing the loops demands of PSSs to intercept and transition obsolete resources and wants PSSs to state and govern resource lifetime. The framework can, therefore, suggest how and why to embed specific elements into PSSs to produce closed loops. And finally, this work proposes a set of guidelines for the design of closed-loop PSS, contributing to the literature on CE and PSSs in the CE. This result guides designers in how to design, organise and operate PSS elements to deliver closed-loop PSSs. Further empirical work is suggested to validate these guidelines.

These results call for a functional and systematic approach to PSS design. The approach implies positioning the four subfunctions of PSSs as requirements on the flows of resources and considering obsolescence of products, components and materials in their entire lifecycle. The PSS elements in the framework deserve further study. Some elements such as those that appear to influence the assessment or measurement of resource value are significant but appear to be underexplored in the literature. Other elements are commonly studied but their research can be extended to better explain and understand the contributions they make to closed loops. Empirical research is suggested to extend and develop the framework and validate the guidelines.

6. Explaining the Systems that Produce Resource Flows

This chapter presents a modelling method developed to explain how systems produce closed-loop recourse flows. The method is based on the analysis of nine empirical case studies of closed-loop systems in the FMCGs sector.

6.1. A need for systems solutions

Producing closed-loop resource flows, such as through reuse or recycling, requires that the FMCGs sector makes systemic changes to and redesigns the current linear consumption systems. Designing system solutions requires a broad range of design skills, including deep knowledge of materials science, engineering techniques, operational processes, service design and human behaviour (De los Rios and Charnley, 2017). Currently, however, industry's common methods to investigate environmental issues and resource flows are based on life cycle thinking. Life cycle thinking emerged to understand the wider impacts associated with a product throughout its lifetime (Heiskanen, 2002). It attempts to see the product life cycle as a system and to understand and act on its impact (De los Rios and Charnley, 2017). Life cycle thinking implies that environmental impacts are the result of the systemic elements that enable and influence a specific journey of resources. This emphasises the importance of this journey and how it is made. The actual physical journey of the materials and products, however, is typically simplified in four life cycle phases (e.g., Vogtländer, 2010). Rather than considering the entire resource flow, assumptions are made for critical moments in the journey, such as if consumers fulfil their role when resources become obsolete (Zeeuw van der Laan and Aurisicchio, 2019a). Limited understanding of resource flows poses a risk by allowing resources to lag or prematurely abort their journey. For example, despite improvements to recycling infrastructure, the flow of recycled materials will not be closed loop if there is no demand for the recovered material (Zink and Geyer, 2017).

Instead, to overcome the issues of a linear economy, systems thinking is often suggested to be a valuable approach to designing solutions for the CE (e.g., Charnley *et al.*, 2011; EMF, 2012, 2013, 2014). Systems thinking is a way to look at systems by seeing things as a whole with interrelated parts (Senge, 2006), allowing explanation of the operations and behaviour of a system rather than of its single parts (Richmond, 1993). Systems thinking, thus, firstly, involves looking at both system elements and their interconnected whole (Meadows, 2008; Sterman, 2014), which implies that all (un)intended consequences of changes to system elements are investigated. Secondly, the approach focuses on how elements interrelate (Richmond, 1993; Seiffert and Loch, 2005; Senge, 2006) and integrates all the elements of a system that are part of a complex problem (Charnley *et al.*, 2011; Miser and Quade, 1985). This ensures that all elements that play a role in the solution can be identified and included in the solution. Thirdly, systems thinking provides a holistic view of a system and is a means to understanding the behaviour, abilities and impacts of both its elements and the system as a whole (Gedell *et al.*, 2011; Senge, 2006; Stahel, 2010). Lastly, it is often used to review and inspect solutions over time which can be challenging (Richmond, 1993; Stahel, 2010), for example, because there can be delays between implemented solutions and their effects in the new behaviour of the system (Sterman, 2002).

Although systems thinking could indeed be suitable for designing systems for the CE, the use of this approach for the physical production of resource flows over time seems limited in practice. Rather, FMCG manufacturers and their partners aspiring to transition to the CE are integrating systems spanning sourcing, manufacturing, distribution, retail, consumption and waste management. Integrated systems can optimise the throughput of resources, which in turn generates value for individual stakeholders such as reduced material losses and energy savings. However, there are limitations to this approach in supporting the design of systems for the CE.

The first limitation is that system boundaries considered for integrated problems are often too narrow, focusing primarily on the interfaces between systems rather than the structural problem of linear resource flows. With narrow boundaries there is a risk that only parts of the whole journey of resources are covered and disproportionate attention is given to such parts. In addition, the number of system elements considered is reduced, increasing the likelihood that significant behaviours of the system are omitted or erroneous assumptions are made (Liu *et al.*, 2015). What is considered the whole depends on how and where system boundaries are set (de Weck *et al.*, 2011). Therefore, to (re)design the systems that produce resource flows stakeholders must frame the system accordingly, i.e., neither too narrow nor too loose but covering all parts of the system that influence the flow of resources.

The second limitation is that systems are integrated without stakeholders' alignment on the overarching requirement of the system to create circular flows. Circular resource flows most likely involve multiple stakeholders who will have to collaborate to architect, design and integrate the system. Collaboration is considered a key enabler for adopting a CE (Ellen MacArthur Foundation, 2016; Kraaijenhagen *et al.*, 2016; Prendeville *et al.*, 2014) and gathering multiple perspectives is essential for a good understanding of a system (Charnley *et al.*, 2011). In systems thinking stakeholders can aim to understand the operational requirement of the system to be designed, aligning themselves on what the system has to do. Nevertheless, stakeholders typically have individual agendas on what they want the system to do, aiming to achieve their own objectives rather than the shared objective to flow resources.

Therefore, despite the recognised value of systems thinking in the transition to the CE, it does not appear to be easily adopted by the FMCGs sector for the purpose of redesign of systems. Although systems thinking is an established field, its methods are abstract and complex (e.g., De Haan and De Heer, 2017). If industry does revert to cross-organisational models of resource flows, they commonly use Material Flow Analysis (MFA). MFA aims to capture the entire volume of a single material resource within the boundaries of a (geographical) system (Brunner and Rechberger, 2004). Although MFA models the flow of resources as a sequence of processes that partition the volume of the flow, it does not model the structure that delivers the operation of the system, i.e., the interrelated elements that determine whether resources flow or not. The system structure spans across sociotechnical domains, requiring integrating elements such as behaviour, design and infrastructure (Charnley *et al.*, 2015; Grant and Banomyong, 2010), There is, however, little knowledge on the relation between such elements. Together with inappropriate boundaries and misalignment on the function of systems, stakeholders struggle to develop shared mental models of the system structure and, therefore, to visualise solutions (Charnley *et al.*, 2011), collaborate (Senge, 2006) and explain how the systems work.

This work addresses the gap of methods that use systems thinking to frame a system based on the flow of resources it produces and enables one to identify the structure to explain how the system operates. The aim, thus, is to develop a method to explain how systems produce closed-loop resource flows. Such a method can then be used to model FMCG systems and to understand their whole as well as their interrelated elements. A structural and consistent approach to look at these systems, would also allow comparison between systems, which provides opportunities deepen insights on the relations between certain elements.

The remainder of this chapter is structured as follows. In Section 2, key concepts of systems thinking are reviewed and used to conceptualise the Resource Flow-System, as the system of interest. Section 3 outlines how research on case studies of nine closed-loop FMCG systems was used to develop a method to explain these systems. The two key results include, in Section 4, 'Flow Functions' which provides a function tree for and a functional model of the RFS; and, in Section 5, the 'Flow-Causality Diagram' which is a novel method to model the RFS using a Library of System Elements. Section 6 discusses the implications of this work followed by limitations and further directions for future work in Section 7 and conclusions in Section 8.

6.2. Thinking in systems

Systems can be seen as a collection of elements that together deliver a certain function or purpose (Buede, 2009). Setting the right boundaries to study or design systems is key to ensure all its relevant parts are included. Further, understanding what the structure of a system entails is essential to be able to explain how a system works. This section explores the literature on systems thinking on these two approaches and uses the insights to further conceptualise the system of interest.

6.2.1. Setting the right system boundaries

Setting the boundary of a system adequately is important as it determines which elements are considered part of the system, and which elements are considered a part of the environment or context of the system (de Weck *et al.*, 2011). There are different ways to set boundaries, which range from focusing only on system elements that can be influenced by the stakeholder (s) to including elements that could directly or indirectly be affected or influenced by the system solution (de Weck, *et al.*, 2011). One way to determine the boundaries of a system, is by looking at what the system does or has to do. As a whole, any system delivers a high-level objective, which can be interpreted as its overall function. The overall function is sometimes also referred to as an operational requirement (Burge, 2006), objective (Gedell *et al.*, 2011), goal (Dwyer, 2015), stakeholder objective (Buede, 2009), desired or intended output of a system (Ullman, 2016), or, in human-focused systems, a purpose (Halbe *et al.*, 2014; Kasser and Mackley, 2008; Meadows, 2008). Generally, however, what the system does or *how it behaves* can be interpreted as its function (Meadows, 2008). Behaviours of systems can be visualised as patterns that can be used to assess whether the system is functioning as intended (Senge, 2006). Accordingly, the function of a system describes what products or systems do, or are proposed to do (Burge, 2006; Maier and Fadel, 2009; Ullman, 2016), which is fundamentally different to a description of what products or systems look like or how they perform (Aurisicchio *et al.*, 2012).

Functions are used to describe processes, i.e., operations or actions that transform a certain input into a certain output (Burge, 2006; Maier and Fadel, 2009; Pahl *et al.*, 2007). The recipients of the functions are objects such as a materials, energy or signals (Stone and Wood, 2000). Functions are typically expressed as verb-noun structures, in which the verb is used to express the process and the noun expresses the recipient (Burge, 2006; Stone and Wood, 2000). Therefore, a functional view of a system can be used to describe a system without reference to its structural elements (Kasser and Mackley, 2008). This has several benefits for systems thinking. Using a function rather than technical requirements as a starting point, for example, pushes design teams to obtain a clear collective focus (Burge, 2006). It also supports and encourages designers to imagine different solutions that deliver the same overall function (Aurisicchio *et al.*, 2012; Halbe *et al.*, 2014; Maussang *et al.*, 2007). Reasoning *from* or *to* functions provides the designers with a consistent approach in comparing functions and developing various solutions to functions, as well to compare and assess different solutions (Aurisicchio *et al.*, 2012; Stone and Wood, 2000).

Since any system has a specific overall function (Senge, 2006), this can be used to identify the boundaries of the system. Elements are considered part of the system if they relate to what the system has to do. Setting boundaries turn a system into a subsystem of another system (Buede, 2009). The boundaries should then encompass that portion of the whole system, which includes all important variables relevant to address the problem (Bala *et al.*, 2017). Boundaries that are too tight can limit the ability to study the overall function of a system, while boundaries that are too loose can distract from reviewing the overall function (Forrester, 1968b). Therefore, the overall function of the system can be used not only to determine its objective but also its scope. Despite its importance in understanding and defining systems, the overall function of the system is rarely explicitly expressed (Meadows, 2008). Rather, functions of systems are derived from user needs or other stakeholders' objectives (Buede, 2009; Halbe *et al.*, 2014). As a result, different stakeholders may think they understand the same or a similar system, but their respective systems have different (albeit sometimes overlapping) content (Gedell *et al.*, 2011). In addition, the parts of a system that do not address a stakeholder's objective are easily overlooked or not considered at all. Instead, setting system boundaries more appropriately can be achieved by redefining the overall function of the system, for example, by including 'basic human needs' to ensure social aspects are covered (Halbe *et al.*, 2014), or by combining stakeholder objectives and environmental needs to cover environmental concerns (Moreno *et al.*, 2015).

6.2.2. Explaining the operations of systems

To deliver the function and do what it has to do, a system operates in a certain way due to the *system structure* (Buede, 2009; Hughes, 1987). The structure of a system can be seen as the architecture that organises its elements (Stone *et al.*, 2000). System elements are the most likely parts of the system to be noticed (Meadows, 2008). However, a random collection of system elements does not characterise a system, as elements alone do not describe how a system operates (Seiffert and Loch, 2005). Rather, the way in which the elements interrelate and are organised results in what the system does. Therefore, the structure of the system is sometimes interpreted as the mechanism contributing to the operation of the system and the delivery of the overall function (Meadows, 2008; Richmond, 1993). A lack of understanding of these inner workings of a system may lead to assumptions about its function and a poor performance (Toba and Seck, 2016). Studying both the elements and how they interconnect is, therefore, required to explain the workings of a system (De Bruijn and Herder, 2009; Kasser and Mackley, 2008; Meadows, 2008).

6.2.2.1. Elements

Elements of systems are the physical and non-physical parts of a system that can be seen, felt, counted or measured at any given time, such as the location or quantity or resources, an individual's self-confidence, or money in the bank (Meadows, 2008). System elements are also referred to as stocks (Meadows, 2008), quantities (Gedell *et al.*, 2011), aspects (Toba and Seck, 2016) or factors (De Haan and De Heer, 2017). Changing an individual element can influence the ability of a system to deliver its overall function. System elements are important in understanding the foundation of a system because they represent a core part of the structure (Meadows, 2008).

Structures of systems can be modelled using non-variable domain-specific elements. Several taxonomies exist that divide common elements in a specific domain based on what they are. One example being a taxonomy that organises the types of containers, vehicles and collection methods used in waste collection systems (Rodrigues *et al.*, 2016). Taxonomies like these are useful in identifying system elements, that relate to each other and influence the performance of the system. For example, the taxonomy for waste collection systems can be used to understand the level of automation of the system which is then used to understand the costs for manual operations (Rodrigues *et al.*, 2016). Systems become increasingly complex, however, when they span across multiple disciplines or domains (De Haan and De Heer, 2017). Consequently, taxonomies become increasingly difficult to organise as they must combine multiple domains (Buede, 2009) and terminologies (Hughes, 1987), rather than isolating a group of similar type of elements. In addition, the elements in taxonomies are usually constant factors reviewed in isolation, which limits the interpretation of their contribution to the behaviour of a system.

Structures can also be modelled using variable elements to understand more dynamic relations in systems, such as changes in theamount of water in a tub or money in a bank, or an individual's self-confidence (Meadows, 2008). Dynamic models explain non-linear behaviour of systems over time (Senge, 2006; Sterman, 2001). In System Dynamics, an element can be a 'stock', which is a quantity that can change due to the workings of the system (like the water in a tub) (Meadows, 2008). The actions or processes that change the stocks, also referred to as 'flows', are also part of the system (e.g., the inflow of water) (Meadows, 2008). The flows define the rate at which the element changes. Other variable and constant elements are included in the model based on whether they cause changes of stocks or flows, which together portray the operations within systems (Richmond, 1993). In contrast to taxonomies that present a finite number of fixed elements, this approach to defining elements is qualitative as it focuses only on those elements present in the system instead of listing all possible elements. It can be used to identify and define both constant and variable elements across domains based on the data and insights available to the investigator. However, translating abstractions of system elements as variables is not a straightforward exercise (De Haan and De Heer, 2017).

6.2.2.2. Interconnections

Interconnections are the relations between the elements of a system (Meadows, 2008; Senge, 2006). These relations explain how system elements work together to operate the system and can, therefore, be used to explain how the system delivers the overall function (Sushil, 2012). The interconnections between elements are sometimes explained as flows (Forrester, 1968b; Meadows, 2008), interactions (Sushil, 2012), dependencies (Gedell *et al.*, 2011) and internal interfaces (Stone *et al.*, 2000; de Weck *et al.*, 2011). Elements that are interconnected are seen as the most important property of a system in forming its complex structure which then delivers its overall function (Seiffert and Loch, 2005). We can explain the behaviour of systems by understanding this structure (Meadows, 2008) i.e., reviewing how the elements interact with each other to deliver the overall function of the system (Hughes, 1987).

Understanding the interrelations of a system requires both structural as well as functional thinking, such as thinking about what constitutes the system and how it operates as a system (Kasser and Mackley, 2008; Richmond, 1993). A structural model of a system is helpful in representing the elements and their interconnections (Sushil, 2012). To model the structure of a system, elements must be of a consistent type (e.g., in objectives, activities, events, parameters, properties) (Sushil, 2012), and maintain similar levels of granularity (Gedell *et al.*, 2011).

Structures with non-variable elements can be modelled using linear relations. For example, a function-means tree can be used to model the hierarchical break-down of functions and indicate relations between the means to realise a function (Hubka and Eder, 2012; Robotham, 2002). A function-means tree can thus be used to model the relationships of subfunctions to elements of a technical system (Pahl *et al.*, 2007). There are examples of extending this approach to more complex systems, particularly in Product-Service Systems (PSSs) (Van Ostaeyen *et al.*, 2013). This is a suitable approach for organising non-variable elements such as the ones presented in a taxonomy. These interconnections can be given more depth using an interpretive structural modelling methodology, which uses pairing between elements to quantify the relations between them (Attri *et al.*, 2013). The relationships can be illustrated in level-hierarchies using rankings and directions (Kuo *et al.*, 2010). Although these methods help to structure interconnections and in some cases their specific directions, they provide a limited understanding of how system elements interact to deliver the overall function of the system (Engelhardt, 2000).

Dynamic relations involve the effects of individual elements on other elements, such as imagining them changing one by one (Meadows, 2008). If the elements in dynamic structures represent quantities, such as energy, materials or signals, the interconnections can be considered transformational processes (Gedell *et al.*, 2011). Subsequently, system elements become the output for one process and the input for another (e.g., Stone and Wood, 2000). Alternatively, the elements may represent non-physical quantities, e.g., an individual's level of motivation, in which case the interconnections imply causalities between one element and another. In this case, system elements are linked to each other in causal loops which explain the effect of one variable element on another (e.g., Forrester, 1968; Haan, 2017; Meadows, 2008), or even the mathematical dependence of elements (Sushil, 2012).

6.2.3. Defining the Resource Flow-System

Resources are the tangible matter that take the form of materials, components, and products. A resource often is an input and output for several familiar systems, such as a business model, PSS or waste management system, see Figure 6.1. In a CE, these systems can be joined to form an industrial symbiosis, in which the resource outputs by one system are used as inputs in another system (Chertow, 2000). Realising this requires progressing from technocentric approaches that consider the material, product and component levels to more human-centric approaches that include societal changes supporting the transition to new sociotechnical systems (Ceschin and Gaziulusoy, 2020). The boundaries of such sociotechnical systems in practice appear to be the result of subsumed systems, as depicted in Figure 6.1. To make the journey, the resource has to move from system to system. Although there can be overlap between these systems, often there are gaps between them, in which case the resource journey is likely to be poorly facilitated. Here, the work introduces the Resource Flow-System (RFS), which encompasses all the parts of the system in place to produce the flow of resources. Therefore, it uses the resource flow – the journey of the resources – to set the boundaries of the system. Conventional systems, or parts thereof, can then be considered subsystems of the RFS.

The RFS can be designed to produce a certain type of resource flow, such as a circular flow circular e.g., a slow or narrow flow, or a closed-loop flow (Bocken *et al.*, 2016). This work focuses on closed-loop resource flows, which is the most needed type of flow for the FMCGs sector. A closed-loop flow is the type in which a resource immediately repeats its journey after completion in an identical journey, see Figure 6.2.. The processes that involve initial raw material extraction and final disposal are beyond the scope of the closed-loop resource flow.

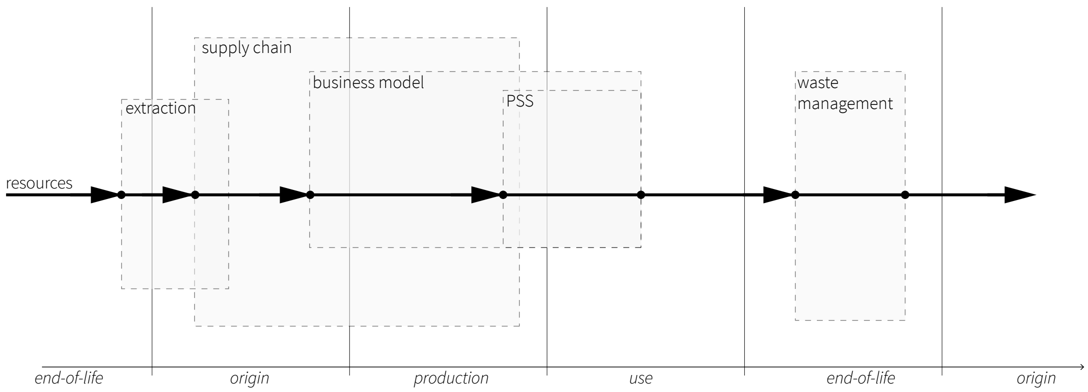


Figure 6.1 Abstract and conceptual visualisation of a linear resource flow through conventional systems.

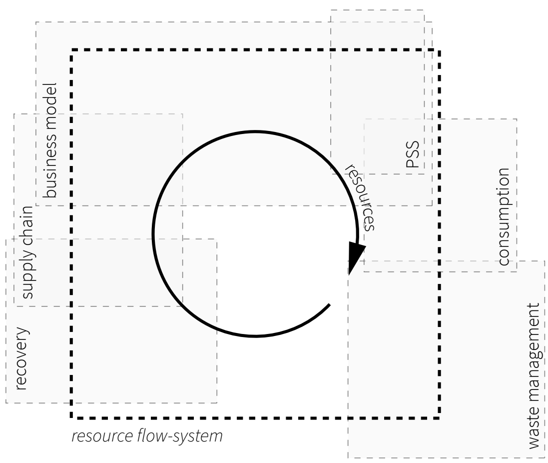


Figure 6.2 Abstract and conceptual visualisation of a RFS for a closed-loop resource flow.

In the remainder of this section, we further conceptualise the overall function and the structure of the RFS that produces closed-loop resource flows.

6.2.3.1. Using the operational requirement to set the boundaries of the RFS

The overall function of the RFS is 'to flow resources'. In this study, the overall function is further defined as 'to flow resources in a closed loop'. Although many stakeholders could benefit from flowing resource in a closed loop, it rarely appears to be their primary objective. Rather than addressing the objective of a stakeholder, this function addresses the needs of a resource in the context of a CE. From this perspective, the preservation of the resource would be favourable to the resource itself, as this allows for it to be used longer (EMF, 2015). Flowing resources is thus within the interest of society as it allows to increase the value gained from natural capital.

Function-based methods can favour the design of systems that require a broader system boundary (Halbe *et al.*, 2014). For example, functions have been used to combine the technical and aesthetic functions of a product (Aurisicchio *et al.*, 2011). Functions have also been used to combine the product and service domains of PSSs, and define the functional requirements of a PSSs (Maussang *et al.*, 2007). Similarly, functions have been used to organise both stakeholder needs and environmental needs and translate them into the requirements of engineering systems (Halbe *et al.*, 2014). However, there are, to our knowledge, no known studies that position the flow of resources as the overall and prime objective of a system. In prior work we studied the potential of PSSs to deliver this function (see Chapter 5). However, the four subfunctions of PSSs that emerged did not relate specifically or exclusively to the physical flow of resources (Zeeuw van der Laan and Aurisicchio, 2020). Only one of the four functions directly implied the physical movement of resources ('intercept obsolete resources'). The other functions carried implications for the ability of physical movement and emphasised that there is a commercial need to satisfy in order to produce resource flow. For example, 'transitioning obsolete resources' is defined as pushing resources into the successive life cycle phase which necessitates a stakeholder demand.

In the current study we position the sole and primary overall function of the RFS as flowing resources, which are interpreted as the physical movements and transformations of a resource in a system. However, we do not disregard the need to understand the non-physical processes that the resource could be the recipient of, such as the commercial activities that are likely to be significant to solutions for the CE (Blomsma *et al.*, 2018; Bocken *et al.*, 2016). Rather, we suggest that the main goal of the RFS is to flow resources. By positioning the flow of resources as the overall function of the system, anything that is important or required to deliver this function, such as commercial activity or stakeholder needs, will emerge as the structure of the RFS.

6.2.3.2. Explaining the operations of the RFS

The RFS overlaps several domains and can be seen as an integrated system. Based on an integrated life cycle approach, we can expect that the RFS includes a resource flowing in an extended supply chain, human behaviours and interactions with the resource, business management and the impacts of the resource (Acaroglu, 2018). Thus, the RFS is a sociotechnical system consisting of elements which belong to social domains such as people and their communities, and elements which belong to technical domains such as resources (Hughes, 1987). The system is multifaceted, and this necessitates the consideration of multiple domains (Charnley *et al.*, 2011).

There are researchers who have studied sociotechnical domains independently and have crossed over the structures to see how they interrelate (Cherp *et al.*, 2018; Toba and Seck, 2016). This approach builds on the theory that the domains might be semi-autonomous, which makes it essential to study both the relatively independent development of each domain and their interdependencies, their loss of integration, and their integration (Freeman, 2001). The domains of the RFS can be identified through the conventional subsystems that it overlaps with and are subsumed by (see Figure 6.2). For each domain, it is possible to identify taxonomies that could serve as checklists for possible elements in the system, based on, for example, the architecture of a PSSs (Müller and Stark, 2008), or the physical elements of a waste collection system (Rodrigues *et al.*, 2016). There often is, however, little consensus on taxonomies and whether they are all-encompassing, because they only include known elements and cover only subsystems of the RFS.

Regardless of the taxonomies' conclusiveness, we see limitations in their ability to identify the elements of the RFS based on the scope of a domain. One limitation is that the subsystems may only be partly included in the system, or overlap each other, and are unlikely to represent the RFS in its entirety. Consequently, elements outside the conventional boundaries can be easily overlooked. Another limitation is that this approach poses the risk of being biased when identifying elements of the subsystem elements. Therefore, it may result in identifying elements that are relevant only to the objective of the subsystem, rather than to the overall function of the system, which could assign unmerited importance to some elements. For example, in previous work we studied elements that emerged in relation to closing loops in PSSs, but we did not review the relevance of these elements to other subsystems such as reverse logistics (Zeeuw van der Laan and Aurisicchio, 2020). Taxonomies of non-variable elements would also limit the ability to model the dynamics of the RFS. To clarify how the system works, we need to understand the variability of elements in the system (De Haan and De Heer, 2017).

Instead, we aim to create specific and precise definitions of the system structure, creating a new vocabulary in descriptive terms (Forrester, 1968b). A consistent language to model the elements would allow to use it consistently to develop comparable models. The boundaries of the RFS are defined by the journey of the resource and include all elements that are part of delivering the overall function of the system (Bala *et al.*, 2017). Thus, the multifaceted RFS may entail elements belonging to various social, technical, political and economic domains (Hughes, 1987). This will allow to develop a new sector-specific taxonomy for the elements that exist in the RFS. Organising elements based only on what they are may pose a limit in understanding the dynamics of the systems (De Haan and De Heer, 2017). Thus, it is important to define elements of a consistent type (Sushil, 2012) and use a consistent level of granularity to describe its elements (Gedell *et al.*, 2011), which should allow for the interpretation of the relations between elements that explain the workings of the system.

6.3. Methods

The aim of this study is to develop a method to model the RFS for FMCGs, providing a means to explaining how it produces resource flows in order to support the design of such systems. To achieve this, systems theory was used to analyse empirical data on several RFSs, collected through cases studies of closed-loop systems in the FMCGs sector. Each case involved one RFS, and each system has the same overall function, i.e., to 'flow resources in a closed-loop'. Data was collected through focus groups and insights were obtained through extensive analysis per case. The insights were used to model the RFS for each case. This process was iterative and various theoretical frameworks were used to interpret and compare the insights from the cases to develop the method. In the remainder of this section, the methods used for this study are described in detail.

6.3.1. Case study research

Case study research is a qualitative research method in which one or multiple cases are studied. The method is highly suitable for explanatory purposes, especially for asking 'how' questions focused on a contemporary phenomenon (Yin, 2018), which in this case is RFSs in the FMCGs sector. Case study research is useful for studying events that are difficult to control, such as if they include behavioural elements (Yin, 2018). The research method offers a suitable way of studying complex and multifaceted systems that may span over various domains and may include behavioural elements. Studying and comparing multiple cases provide broad insights and can capture variations and similarities that can be used to generalise learnings across systems (Gioia *et al.*, 2013; Robson, 2011). RFSs produce different types of closed loops including recycling and reuse. Any of these systems is unique depending on the product, the services offered and the society in which it operates. Therefore, multiple systems were studied whose overall function was considered the same, as this allowed to compare case studies and synthesise qualitative data to discover commonalities and develop a robust understanding of the common structure of RFSs (Jurisch *et al.*, 2013).

6.3.1.1. Case eligibility

Systems were considered eligible for this study if they produced a resource flow that involves the reuse of components or products, or the recycling of materials. Services were eligible if they applied either to a few specific FMCGs (e.g., Coca Cola bottles) or a category of FMCGs (e.g., drinks bottles). FMCGs are defined as products that conveniently and temporarily satisfy continuous consumer needs, which can include less conventional categories of FMCGs (Zeeuw van der Laan and Aurisicchio, 2019a) such as products used at events. Both reuse or recycling services offered by FMCG manufacturers and by independent service providers were considered eligible, as long as the services were offered to consumers. Reuse and recycling in the FMCGs sector are becoming more widespread, which is why different maturity levels were considered, e.g., operational services or trials of services, as well as services offered by different sizes of enterprises, e.g., small/medium enterprises (SME) and multinationals. Finally, for practical reasons, only systems in Europe, the United Kingdom and the United States of America were invited to participate.

6.3.1.2. Case selection

Based on the criteria above, an initial list of companies of interest was developed. The twenty-six companies that were deemed the most feasible to connect with were shortlisted. These companies were approached by reaching out individuals employed by these companies through the researchers' networks (i.e., through phone or email, if contact details were available). Alternatively, individuals were approached through events, mutual connections, LinkedIn, or company websites. A script was used in all communication to explain the context and purpose of the study and why they were invited to participate. To develop a broad set of data on closed-loop FMCG systems, aimed to study between five and ten cases. Fifteen of the shortlisted companies replied to the request. A total of nine companies agreed to participate in the study. The companies varied in terms of type of product, enterprise size, type of closed-loop, maturity of the company, and maturity of the service, see Table 6.1. All cases strived for a closed-loop resource flows in which either components or materials were recovered to an as-new state. Nevertheless, some of the recycling cases acknowledged that the use of recovered materials was still an ambition rather than a reality, due to technology or commercial challenges. These cases were still included as understanding these challenges was expected to provide valuable insights into system elements that explain how the RFS work. Companies were given the opportunity to request a non-disclosure agreement to further guarantee the confidentiality of their data.

Table 6.1 Characteristics of the 9 cases included in this study.

Case	Product category	Enterprise size	Maturity of enterprise	Closed loop	Maturity of service	Service provider
A	Home care	Multinational	Mature	Reuse	Pre-launch trial	Independent
B	Personal care	SME	Start-up	Reuse	Pre-launch trial	Manufacturer
C	Food and beverage	National	Mature	Reuse	Operational	Manufacturer
D	Personal care	SME	Start-up	Recycle	Operational	Independent
E	Personal care	Multinational	Mature	Recycle	Operational trial	Manufacturer
F	Food and beverage	SME	Start-up	Recycle	Operational	Independent
G	Event	SME	Start-up	Recycle	Operational	Manufacturer
H	Event	SME	Start-up	Recycle	Terminated	Manufacturer
I	Personal care	Multinational	Mature	Recycle	Operational trial	Independent

6.3.2. Data collection

Empirical data was collected on the case studies through focus group, supported by visualisations of the RFSs. A focus group is a group of individuals who meet in an informal setting to talk about a particular topic set by the researcher (Longhurst, 2003). Focus group research was used to gather descriptive information on RFSs. The focus group provided a useful way of facilitating a guided and structured interactive discussion that addressed all relevant topics (del Rio-Roberts, 2011).

Focus groups present several benefits to researchers that were taken into consideration for this study. First, focus groups allow researchers to gather multiple and different views on a topic. Although the system has overlap with familiar subsystems, the RFS as a defined system is not conventional. Understanding a whole system requires the view of experts from multiple disciplines (Charnley *et al.*, 2011). It is therefore unlikely that a single individual can be found with a deep and comprehensive understanding of the system. In addition, the overlapping subsystems relate to familiar knowledge domains (e.g., marketing or production), even though the system itself is multifaceted, and therefore impossible to link to one domain. Instead, gaining a deep understanding of a system requires insights from different perspectives and knowledge from multiple domains (Miser and Quade, 1985). Brainstorming with experts is a recommended technique for identifying variables and their relations (Attri *et al.*, 2013). Therefore, gathering different views on the RFS through focus groups is a suitable approach in addressing these issues.

Second, focus groups allow participants to build on each other's knowledge. As participating individuals are likely to be experts only on specific domains, it is possible that there are gaps between their explicit knowledge. In addition, elements that are irrelevant to some stakeholders might be important to others (De Haan and De Heer, 2017). In focus groups, participants can make comments in their own words while being stimulated by the thoughts and comments of others in the group (Robson, 2011). As such, participants complement each other's insights like a brainstorming exercise, which itself is a recommended approach in solving complex problems (Camillus, 2008). Although there is always a risk that power dynamics or personalities may affect the discussion in a focus group (Robson, 2011), this risk in this study is deemed low because the participants had worked as a team previously and were mostly involved in recent and celebrated solutions.

Third, focus groups enable researchers to gather data efficiently and effectively. Because several views are needed to gather a comprehensive picture of the system (Miser and Quade, 1985), interviewing multiple individuals is necessary. Not only do focus groups allow researchers to collect data from several individuals at the same time (Robson, 2011), the interactive nature serves as a natural quality control on data collection, as it allows participants to immediately check one other's points, allowing the most important topics to emerge naturally (Robson, 2011; Sharken Simon, 1999).

Finally, focus groups can be compelling for participating companies. Not only are focus groups typically experienced as enjoyable, they, also provide an opportunity for both the facilitator as well as the participants to learn (del Rio-Roberts, 2011). This is appealing for larger enterprises who are now investing more in learning more about the CE, as well as for smaller and less mature enterprises who have fewer resources to review and optimise with their systems.

To increase the level of engagement, exercises other than oral questions were used (Krueger, 2014). In systems thinking, a mental model is a rough, crude and usually incomplete version of the system (Forrester, 1968b; de Weck *et al.*, 2011). Visualising the mental model limited the focus of the discussion and organised the descriptive information provided by the participants based on the discussion structure of the researcher. This gives control over the scope and direction of the participants' discussions, without directing them (Krueger, 2014).

6.3.2.1. Participants

As reuse and recycling services are an emerging phenomenon in the FMCGs sector, recruiting participants based on their job description was an unreasonable expectation. Based on observations of the sector, it was reasonable to assume that the development of the services begins in departments such as marketing, supply chain, R&D, strategy or process engineering. To gather rich and broad understanding of the system as a whole, the strategy was to recruit groups of participants with diverse perspectives on the system. Heterogenous groups tend to stimulate and enrich the discussion. However, there is a risk that using a heterogenous group may negatively influence the group dynamic if hierarchical, personal or confidential topics appear (Robson, 2011). To ensure that a suitable group was assembled, the lead contact was invited to propose the participants for the focus group, after informing them on the aims of the study and criteria for selecting 'suitable participants', i.e., 'participants who have knowledge of, understanding of, or experience with, the design, functioning, operating or managing of the system, and are employed by the company or by a relevant third-party partner company'. The lead's proposal was reviewed to assess whether they could expect to provide diverse perspectives, see Table 6.2. The participants could be employed by manufacturers or independent service-providers. In cases A and I, the services were offered by independent providers, whilst the participants were employed by the manufacturer. In these cases, the manufacturers had been intimately involved in the development of the services. Participants often had expertise stretching over one or more of the areas of expertise (as shown in Table 6.2), especially when the enterprises happened to be smaller.

The facilitation of a focus group can be challenging because there may be multiple tracks of conversation or interruptions, and a general need to keep everyone engaged (Sharken Simon, 1999). To allow for the mapping of the initial model during the session, small group sizes were preferred. Smaller groups are more comfortable for participants (Krueger, 2014), but carry the risk of provoking less discussion (del Rio-Roberts, 2011). However, if participants each have in-depth knowledge on the topic and are, if necessary, required to speak at length, small groups are ideal (Krueger, 2014). Therefore, a maximum of three participants was applied. One exception was made for case B which involved a very young SME with several external advisors. In general, however, there was only a small number of eligible participants, either because the company was young, or the service was still very immature.

Table 6.2 Domain of expertise of participants per case. In some cases, participants also had good knowledge of additional areas of expertise, indicated with *

Case	Service provider	Total participants	Participant employment	Management	Design	Technical	Commercial	Operational	Legal
A	Independent	3	Manufacturer		1	1	1		
B	Manufacturer	4	Manufacturer	2	1			1	
C	Manufacturer	3	Manufacturer	2			1	*	
D	Independent	2	Independent	1		*		1	
E	Manufacturer	3	Manufacturer			1	2		
F	Independent	2	Independent	1		*		1	
G	Manufacturer	2	Manufacturer	1	*		1	*	
H	Manufacturer	1	Manufacturer	1	*		*	*	
I	Independent	3	Manufacturer				2		1
		23							

6.3.2.2. Setup and facilitation

All the focus-groups were conducted between October 2019 and January 2020. Focus groups were conducted at companies' premises, unless otherwise requested by the participants. The sessions were held in a meeting room in which one of the walls was used to map the initial model. Each session lasted between 60-120 minutes. All sessions were facilitated by the lead researcher, who has industrial experience in the FMCGs sector and knowledge on the topic, which are both useful to her role as a facilitator (Sharken Simon, 1999). A session plan was prepared to structure the sessions, which was refined after a test in a pilot. As answers are typically more elaborate in focus groups than in regular interviews (del Rio-Roberts, 2011; Robson, 2011), questions only focused on two areas: 1) 'What are the movements and transformations of the resource?'; and 2) 'How and why are the movements and transformations enabled?'. A flexible structure to questions was adopted to encourage discussion in combination with an open-ended interviewing style (Robson, 2011), using questions that gradually became more specific in order to obtain a deep and comprehensive understanding of the system (Krueger, 2014; del Rio-Roberts, 2011). For example, starting the conversation by talking holistically about the company, the system and the resource flow to understand how resources moved and transformed, and then asking specific questions about why they occurred. The session plan was used to manage time and a script to structure the discussion (Sharken Simon, 1999). The visualisations also provided guidance in the discussion and indicated which parts of the system had been discussed in depth. Both warm-up questions (e.g., questions about the company and the expertise of each participant), and research questions (e.g., 'tell me about the resource in this situation, what happens after this, and why does this happen?') were used (del Rio-Roberts, 2011).

6.3.2.3. Session structure and outcome

Pre-focus group

The focus of each session was the respective RFS, with system boundaries based on the closed-loop resource flow that the system produces. Rather than using conventional life cycle phases, a more specific, tangible and transient view of the resource flow was adopted by using representations of the states of the flowing resource. Resource states were used to form a state model of the resource flow (i.e., a means to represent the states of interest and the transition from one state to another, working as a simplified representation of a constantly changing reality) (Gedell *et al.*, 2011). These representations of resource states were named 'snapshots' and defined as 'characterisations of the same resource (e.g., a product, component or material) at different moments in the flow'. The participants from each case were introduced to descriptions of four states (see Table 6.3) prior to the session to familiarise them with the boundaries of the system. The facilitator collected images of each case to serve as snapshots, ensuring they always had a rich context to clearly communicate the specific moment in the flow. In a few cases, services were pre-launch and images were not yet available on the internet. In this case, the lead contact provided the images, and they were reviewed by the facilitator. The participants received the snapshots at least one week prior to the main session and were invited to suggest alternative images in case they found that they were not representative or insufficient in capturing the key transformations of the resource.

Table 6.3 Descriptions of the four snapshots and example images to illustrate them.

Snapshot 1	**Snapshot 2**	**Snapshot 3**	**Snapshot 4**
			
Products purchased or offered for purchasing	Products that consumers are using	Products that are no longer used or that are no longer needed	Products that can be accessed to undergo recovery processes

Focus group

The groups focused on the function, structure and performance of the system as understood by the participants. The snapshots were hung on the wall in chronological order, visualising the journey of the resources in time and serving as a starting point for the discussion. The snapshots served as the basic scope and structure of the system and were intended to encourage the participants to think about the flow of resources as the *overall function* of the system. The goal of this was to encourage the participants to think of the flow of resources as an 'effect' and the structure of the system as the object that 'caused' it. The visual model brought about an understanding of the structure and causal loops, as demonstrated in this excerpt: *[C:23] "It's the other way around. So, the fourth picture—because the customer leaves the empty [product] outside and then the [person] picks it up and takes it back to the [location]"*. In addition, the model was used throughout the session to structure the discussion and refer to different points in the system, as demonstrated in this excerpt: [A:8] "They go to consumers, which is the part that you see here".

Although the focus group was structured two sequential parts based on the two focus areas, in practice the two parts overlapped and naturally occurred in parallel. This seemed to happen because participants described or implied system elements when they were explaining the movements of transformation of flowing resources. For example, *[D:29] "But you have to be aware that it's quite a step for consumers because the consumer cannot throw the [product] s in the normal waste bin outside. Now, they have to collect it in a special bag and that special bag needs to be stored somewhere, and then when they go to the [location] then they have to bring it."* describes resource movement and transformation in phrases such as 'saving up resources' and 'storing resources', as well as the enabling structure in phrases such as 'a special bag', 'somewhere to store it', 'somewhere to take it' and 'a reason to go there'. Despite this, the facilitator led the session or sections of the session with the first part and followed with the second for discussion, encouraging participants to think first about the flowing resource (the changes), and then about how and why it is flowing (the causal loop).

For the first part, the movements and transformations of resources between snapshots were discussed and mapped to the initial model. The functions emerged by questioning the

Figure 6.3 Example of the initial model mapped for Case C.

participants on the journey of the resources and specifically the changes between the resource states. The functions were written as verbs on arrow-shaped post-it notes, which allowed to clearly distinguish it as a functional description of the system (see Figure 6.3). For example, when a participant said *[C:68] "So you take it from [location] (…)"*, the facilitator captured this as 'take resources'.

For the second part, system elements that enable the movements and transformations of resources were discussed and mapped to the initial model. The elements emerged during discussions on functions, as well as through questioning the participants on the causes of specific resource changes. In particular, by repeatedly asking participants 'why' processes worked in a specific way and 'what' it meant, provided deeper insights in the structure of the system (De Haan and De Heer, 2017). Rough descriptions of elements or their indication were captured, for example, when a participant said *[C:139] There's visual cues in your house to remind you of this, right? It will always be in the [context] in that [product]. So therefore, the night before, when you're making a coffee or whatever, oh, I'll leave my [product]s out. That visual cue is there in their [context]. So, there is an easy way to remind you to get into that habit".* This was captured by the facilitator as 'visual cue'. Elements were captured on square post-it notes to differentiate them from the functional description. Although the relations to specific functions were not mapped in the initial model, the descriptions of elements were roughly placed in proximity to the functions that they seemed to relate to.

6.3.3. Data analysis and system modelling

All the focus groups were audio recorded and transcribed verbatim in Word documents and photographs were taken of the models built during the focus groups. All participating companies and individuals were granted anonymity using the search function in Word to change any words that could disclose the identities of individuals, companies, brands or products to generic pseudonyms. The removed words included branded elements of infrastructure, branded services, product branding, companies, customers, partners, competitors, names, revealing contexts, materials, products, characteristics of products and locations. Additionally, both the participants and the cases were given a code. As the cases were built to develop an understanding of the RFS of closed-loop FMCGs, the aim was to understand, identify and organise their main components that could be used to model an RFS. Therefore, the anonymised transcripts were imported into coding software (ATLAS.ti) and anonymisation and desensitising of the transcript was furthered in the course of coding where synonyms were found. The transcripts were coded by the lead researcher; codes were used to assign attributes related to the system's elements or functions to the data (Saldaña, 2013). Coding is a suitable method by which to analyse qualitative data that is commonly used in case study research (Yin, 2018). Cases were coded one by one, using the same codes consistently throughout all the cases in order to develop rigour in the results (Jurisch *et al.*, 2013). The coding process was explorative, and highly inclusive of any possible variables (Saldaña, 2013).

The analysis of each case had several stages, see Figure 6.4. Each case went through all stages, but the stages were not completed for each case before continuing to the next stage. This is because after completing the first stages for a few cases, commonalities between cases became apparent and more defined codes and clusters of codes emerged (Saldaña, 2013). By working on stages both in parallel and iteratively, insights from later stages could be used

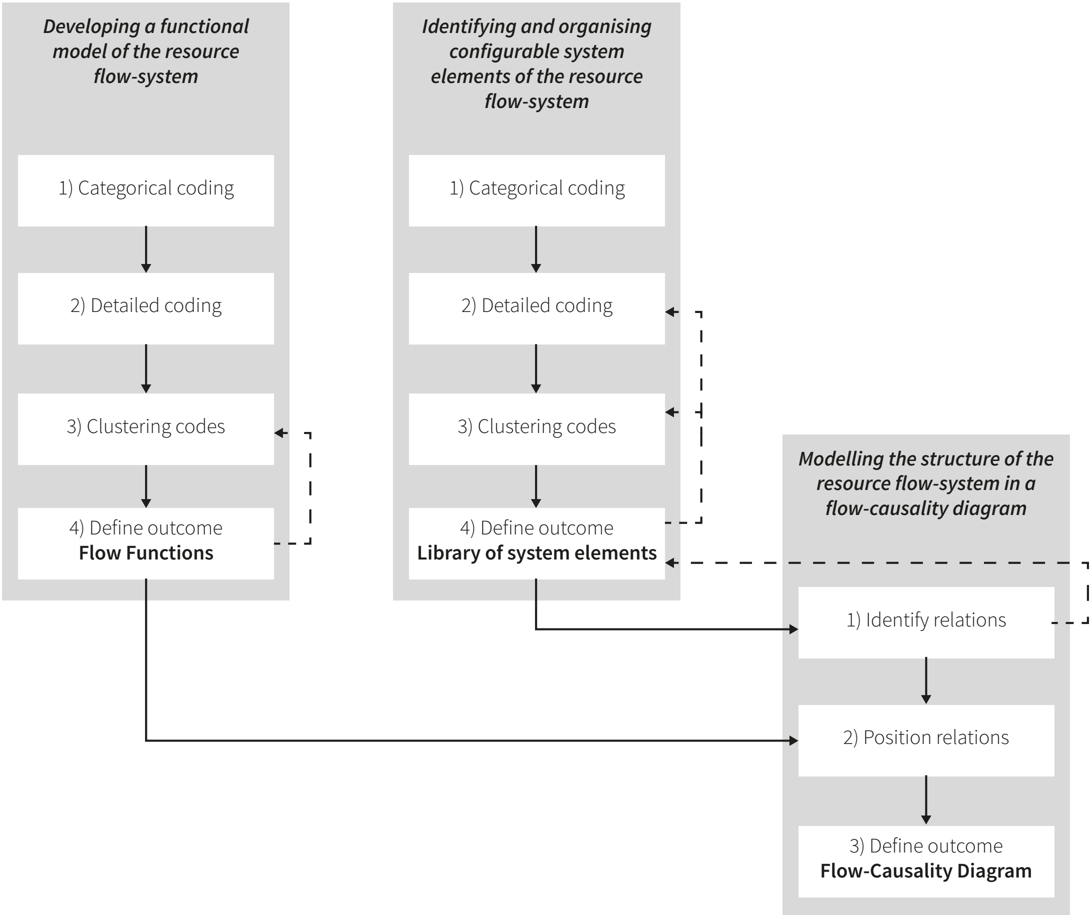


Figure 6.4 Key stages of the analysis.

to delineate the coding from the earlier stages (Gioia *et al.*, 2013). Codes for quotations were refined, merged and removed; approximately 75–150 quotes per case were used.

In some focus groups, the participants only provided insights on a section of the resource flow, resulting in comparatively fewer codes. The first stage of the analysis focused on the functions of the RFS and resulted in a set of Flow Functions, i.e., the most commonly occurring processes that move and transform resources. The second stage focused on the system, resulting in a set of system elements that were then organised into a library. The final stage focused on the overall workings of the RFS, using the first two results to develop a method whereby a flow-causality diagram that visually and qualitatively represents the RFS could be modelled.

6.3.3.1. Developing a functional model of the RFS

Function-based modelling methods find their roots in value engineering (Stone and Wood, 2000) and have two common purposes. The first is analysis, which involves studying a system to define its purposes and discover how it works (Miser and Quade, 1985). Functional analysis typically aims to derive the function(s) of a product or a system (Kasser and Mackley, 2008). The analysis arrives at the function of a subject through meticulously observing the behaviour of the system over time (Meadows, 2008) or dismantling a product to understand the purpose of each part (Stone and Wood, 2000). The second purpose is design and synthesis, such as modelling systems to produce an operational model or plan of a product or system (Burge, 2011). Functional modelling, then, aims to develop product or system solutions based on the desired function (Pahl *et al.*, 2007). In this case, the function, often broken down in subfunctions, is the departure point of modelling (Stone and Wood, 2000).

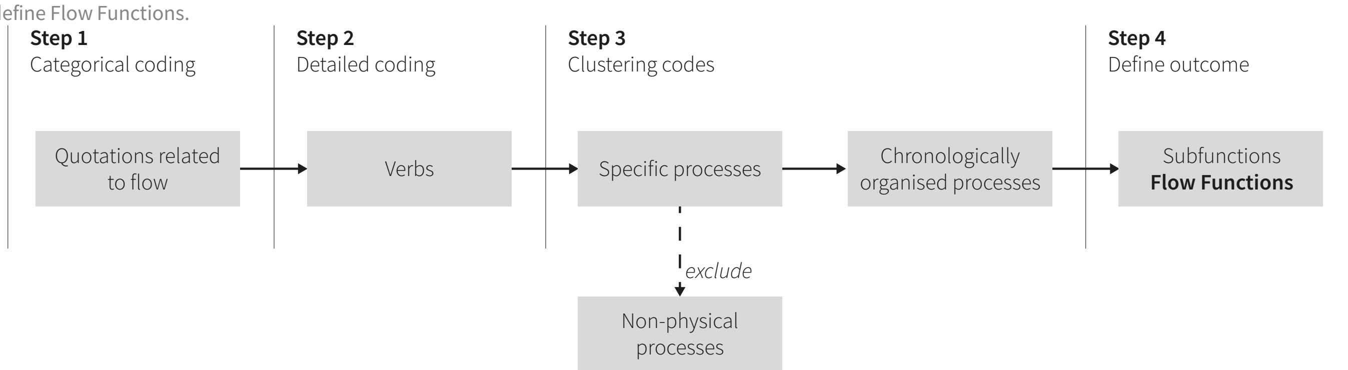
To develop a method to model the RFS, function-based modelling was used to analyse existing systems and develop a deep and specific understanding of the function and subfunctions of the RFS. Function-based modelling was used deduce the necessary system functionality by breaking down the overall function into simpler and easy-to-solve subfunctions (Burge, 2011; Stone and Wood, 2000). The subfunctions (or functional requirements) then form a functional model that specifies exactly what the RFS has to do (Burge, 2006; Kasser and Mackley, 2008), i.e., move and transform resources. Therefore, the functional model is a standardised notation that describes the system in terms of all the processes required to achieve its overall function, connected by the resources, which are the recipients of the processes (Stone and Wood, 2000). Standardised classes of functions provide a language with which to group processes for mechanical systems, however, processes cannot simply be assumed valid for any type of recipient (e.g., Hirtz *et al.*, 2002; Stone and Wood, 2000). Although 'materials' are a common recipient of these classes, they are not the same as 'resources', which is used in this work to bring materials, components and products into a single loop (Stahel, 2019). Although it is acknowledged that resources will be altered, but 'resource' is used as the general recipient when developing a generic function structure (Stone and Wood, 2000).

Subfunctions are simpler to solve as they are more concrete than the overall function and can therefore easily be used to identify underlying causes (Halbe *et al.*, 2014). The case data was analysed to develop the functional model; processes were identified, defined and grouped as subfunctions bottom-up (Figure 6.5). First, quotes were coded that described anything that was done to the resource and categorised it as 'flow'. For example, *[D:14] "You just bind—you fix the [product], you bind it in such a way that it becomes a package—let's say it in this way—in such a way that the outer side of the package is still very protected"* describes something that consumers do to a resource. To ensure the entire physical journey was captured, codes were used to describe anything done or happening to resources.

Second, the initial coding was detailed to express the doings and happenings as verbs. For example, [D:14] was coded as 'package resources'. This allowed to interpret the happenings as processes i.e., operations or actions that move and transform resources.

Third, the codes were clustered to identify specific processes, viewing physical movements and transformations to be the dominant processes acting on the flow (Stone *et al.*, 2000). Some codes were excluded as they were non-physical, for example, *[D:2] "(…) the consumer is changing buying behaviour, is buying more and more online (…)"* was coded as the process 'purchase resources' but did not directly involve physical movement or transformation. Although these are important parts of the system, they do not fall into the scope of the functional model. Codes were first clustered based on their meaning (for example, 'accept

Figure 6.5 Steps taken to define Flow Functions.



resource delivery' and 'to find delivered resource' were clustered as 'receive resources'). Then, they were structured chronologically per case and, finally, based on both their meaning and the moment in the flow in which they occur. For example, both consumer 'receives resources' and consumer 'picks up resources' (both of which lead to a 'getting resources' outcome) occur after purchasing but before using the product.

A final set of subfunctions was defined based on the case comparison. The subfunctions were identified and generalised depending on the reoccurrence of processes in each system. Any of the subfunctions indicate the movement (or non-movement) and/or transformation (or non-transformation) of resources. Subfunctions, therefore, serve as an umbrella to processes that happen at a similar moment and which involve similar processes. However, the specific processes can differ depending on the case, for example, 'receiving' and 'picking up resources' are grouped as 'get resources' as they both result in consumers obtaining the resource. By standardising the language used to describe the functions in the functional model they can be used in further operational and structural analysis (Kasser and Mackley, 2008) and to serve as a blueprint when modelling systems with the same overall function (Stone and Wood, 2000).

6.3.3.2. Identifying and organising the configurable elements in the RFS

To understand the elements of the RFS i.e., to specify what constitutes the RFS, required to define them in such a way that allows the interconnecting relationships to be consistently expressed (Gedell *et al.*, 2011). As part of this process, the elements were identified and organised following the steps shown in Figure 6.6. First, quotes were coded that described anything that could be a tangible or nontangible characteristic of the system, categorising these as 'system', for example, *[I:23] "I'd say in terms of awareness probably only the very eco-conscious people know about [service]. It's still not, like a mainstream name,"* was coded as it tells something about consumers and their behaviour; while *[B:56] "And it's quite important from what I understood that it's someone on a bike. So, zero emission bike or electric. So, it's zero emission delivery. (…)"* was coded as it tells something about the company's infrastructure and strategy. To ensure all elements within the boundaries of the RFS could be captured, it was assumed that anything described by the participants could possibly affect the overall function, either directly or indirectly.

Second, the codes were detailed based on the meaning of the data to identify specific aspects of the system. The quotations were coded using descriptive themes based on what the information implied, see Table 6.4. These themes described the core attributes of the quotations, as descriptions of the same element could be given by more than one participant. Additionally, quotations often referenced more than one theme. Themes were merged, added and removed throughout, resulting in roughly 230 themes.

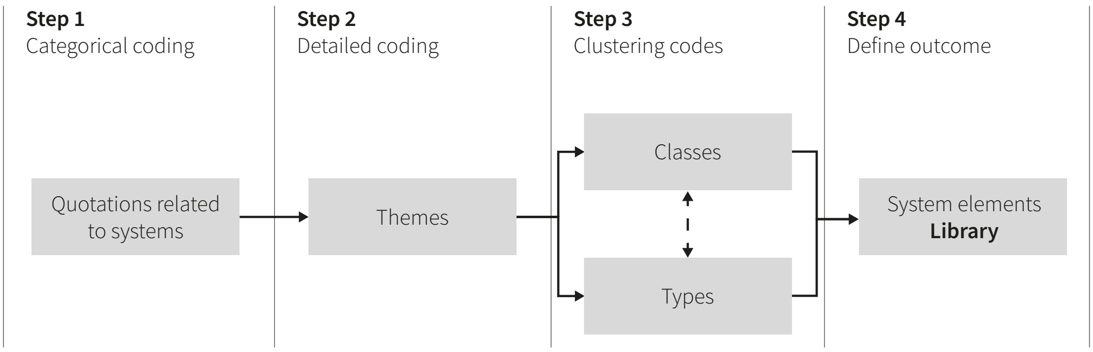


Figure 6.6 Steps taken to define System elements.

Table 6.4 Examples of quotations evolving into themes and elements.

Quote	Theme	Class	Element	Type
[A:26] The way we did it here is actually because it's [characteristic] it requires a twohanded opening and it also requires you to have big enough hands to open it, because—[A-P02]: So basically a finger span that is beyond the finger span of the group at risk, which are small children, and also the fact that it requires two different coordinated actions.	Exclusive users	Principles	Legislation & standard	Health & safety
[E:84] I think, if I'm not mistaken, and [E-P02] you can correct me, we can't have them like in schools with the younger kids, right? Like we can't have those public [aid]s near, just because of that, you know, safely—[E-P02]: [context] objects, yeah.	Exclusive users	Principles	Legislation & standard	Health & safety
[G:132] You cannot, like, just ask any transporter to deliver them to the waste treatment plant because they don't have a licence to do so.	Accepted waste	Principles	Legislation & standard	Waste management
[F:62] Frankly speaking, I think the fines for littering is also like it's non-existing here. I mean, if you go to Singapore you get I think a thousand dollar for littering and spitting. And there's nothing on the street. And they are really enhancing it. (…) [F-P01]: Yeah, thousand euro. I mean, I would also not—I would never put something—I mean, that's a big thing! That's like it's a huge amount of your monthly costs, right?	Consequence of not using the service	Principles	Legislation & standard	Societal

Third, the themes were clustered to identify different types and classes of elements. Pre-defined classes were avoided to limit bias from previous findings and a focus on specific subsystems. Instead, the clustering process was iteratively, see Figure 6.6. Themes were clustered bottom-up if they appeared to consider the same (type of) element, allowing to identify both the elements and different types of the same element. Themes were also clustered top-down, organised according to the elements' high-level meanings in different classes. Class definitions evolved until six remained: principles, value, actors, infrastructure, data and resources.

Fourth, a final set of system elements was compiled in a library, including descriptions, their organisation in six classes and inclusion of their various types in a library. System elements must have a consistent form and a similar level of granularity when they are modelled together in a system. Therefore, elements were not defined as objectives or other abstract forms; instead, they were consistently defined as 'features' of the system, such as qualities, parts or behaviours. Some elements might be considered small subsystems (Gedell *et al.*, 2011), however, they were still defined independently from other elements to represent meaningful and fundamental units. This provided a common language, which was necessary when forming a basis upon which to model elements as solutions to the subfunctions (Gedell *et al.*, 2011).

Table 6.5 Interpretations of relationships based on quotation elements and how they are expressed as causalities in the CFD.

Element {type} (class)	Quotation	Interpretation	Relation to…	Causality
Transportation means {electric vehicle} (infrastructure)	*[C:113] (…) So these vehicles that we've just brought in they have a wider range than those vehicles that you see on there. (…) the more this technology develops, the more options will become available for us. (...)*	Electric vehicles are used to deliver the resources	process i.e., 'deliver resources'	'deliver resources' causes the need for transportation means {electric vehicle}
Trait {authentic} (actor)	*[C:110] (…) So we have committed that future vehicles will be electric. [C-P02]: Yeah, we're aiming to have at least 90% of all of our routes by an electric vehicle. (…)*	Electric vehicles are used because the company has committed to zero waste	element i.e., transportation means (infrastructure)	Trait {authentic} causes more need for transportation means {electric vehicle}

6.3.3.3. Modelling the structure of the RFS in a flow-causality diagram

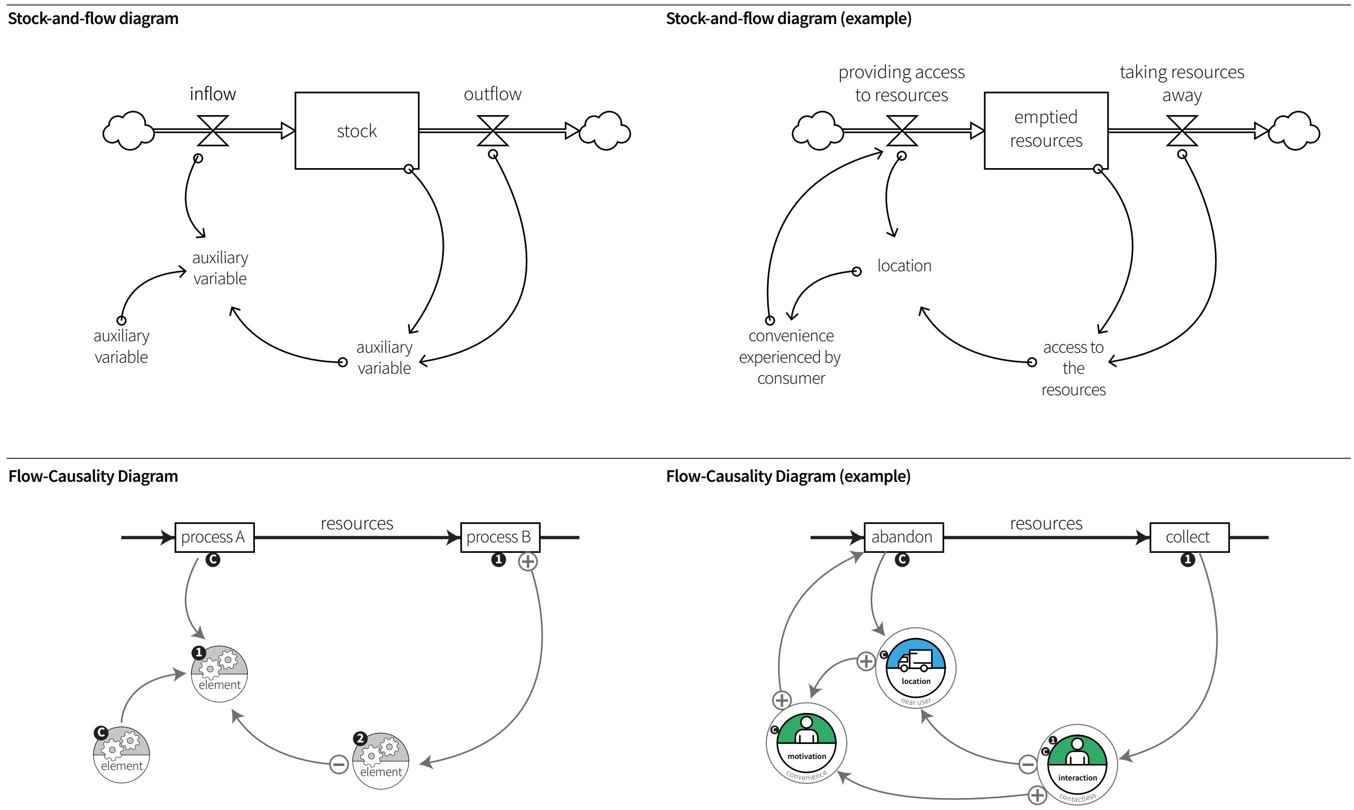
System elements work together to satisfy subfunctions and deliver the overall function (Gedell *et al.*, 2011). Therefore, it was needed to understand the relationships between elements, and between elements and processes, as this allowed to construct the RFS. By organising the elements, a causal-loop diagram can be used to qualitatively model a system and reveal its structure (Hirsch *et al.*, 2007). It can qualitatively structure elements from any domain, allowing to study their dynamics (Richmond, 1993). However, this type of diagram makes it difficult to distinguish between a stock variable and a flow variable (Hirsch *et al.*, 2007).

In comparison, a stock-and-flow diagram clearly makes this distinction; it is therefore seen as a more explicit method with which to quantitatively model a system as it typically expresses elements as measurable variables with consistent and compatible units of measure. However, the limitation of this diagram is that the elements have to have consistent units of measure and defined numbers (Richmond, 1993), whereas the aim of this work is to express the relationships qualitatively. Therefore, a combined diagram is proposed: the 'flow-causality diagram' (FCD). The FCD employs consistent units, as in the stock-and-flow diagram, to visualise a functional model, but also uses the causal-loop diagram to visualise the structure of the system. The design of the FCD evolved when modelling the RFS for each case. First, each case was reviewed to see if there were any relationships between their elements and any of the subfunctions. The library of elements was exported to an Excel sheet and used as a matrix to descriptively capture the relationships in each case. These relationships were interpreted case by case, reviewing all coded quotes and identifying relationships between an element and a subfunction, either directly (element–Flow Function) or indirectly (element–element–Flow Function), see Table 6.5. Only relationships that already existed in specific cases were captured; i.e., some elements were brought up by participants as examples in other systems or suggested as improvements to their current systems: *[I:35] "(…) the [customer] buyer was also asking us about what [competitor] do, where they have like a mini bin next to the [brand] machine (…)"*. This was used to define the infrastructure element of ***space***, however, this particular element did not exist in case I.

Second, functional models were prepared for each case, using the subfunctions as a standardised notation. This allowed to define what the system does without specifying the system itself (Galvao and Sato, 2005). These were used to construct a stock-and-flow diagram (Figure 6.7). In this organisation, subfunctions represent the diagram's 'flows'; that is, they are processes that change resources (over time): they move and transform the stock (i.e., resources). The model was further refined by including case-specific processes, indicating their owners and using them to represent the flows. The flow of resources represents the stock, which exists in quantities measured at a specific moment in time (Meadows, 2008; Richmond, 1993) and contains variables that change as a result of the flows (Chaudhary and Vrat, 2020). The resources were not expressed quantitatively (Sterman, 2002); rather, they were simply defined as 'resource' throughout.

Third, an FCD was developed for each case. The elements were interpreted as standardised auxiliary variables in a stock-and-flow diagram, see Figure 6.7. They were then visualised as icons and mapped onto the functional model, before being linked to processes and elements with which they have a relationship. For each element, the type and owner of each element were indicated. The FCD is a qualitative model; therefore, it does not consider

Figure 6.7 The stock-and-flow diagram compared to the FCD.



the quantifiability of the elements. Rather, the FCD models elements in causal loop: using arrows between elements to indicates that one thing 'causes the need for' something else, see the example in Figure 6.7. As with auxiliary variables, elements can be constant (i.e., they do not change) within a system, for example, to 'fill resources' *causes the need for* ***technology (processing)***. They can also be variable (i.e., they increase or decrease depending on the increases or decreases of other elements), for example, more ***motivation*** {environmental} *causes a need for more* ***space*** {bin}. The relation between variable elements can be positive or negative, similar to how they appear in causal-loop diagrams (Meadows, 2008; Forrester, 1968a).

6.4. Flow Functions

This section presents the Flow Functions, which form a set of subfunctions that decomposes the overall function of the RFS i.e., to flow resources in a closed loop.

A functional model of the RFS

Presented together, the Flow Functions form a functional model of the closed-loop RFS. The functional model presents the structure of the Flow Functions and emphasises their interdependency and ability to form a sequential function chain over time (Stone *et al.*, 2000). The Flow Functions consist of ten standardised functions that have been identified and defined based on their reoccurrence in nine RFSs. In this study, 'to flow resources' is interpreted as the physical movements and transformation of resources; therefore, the Flow Functions describe these processes.

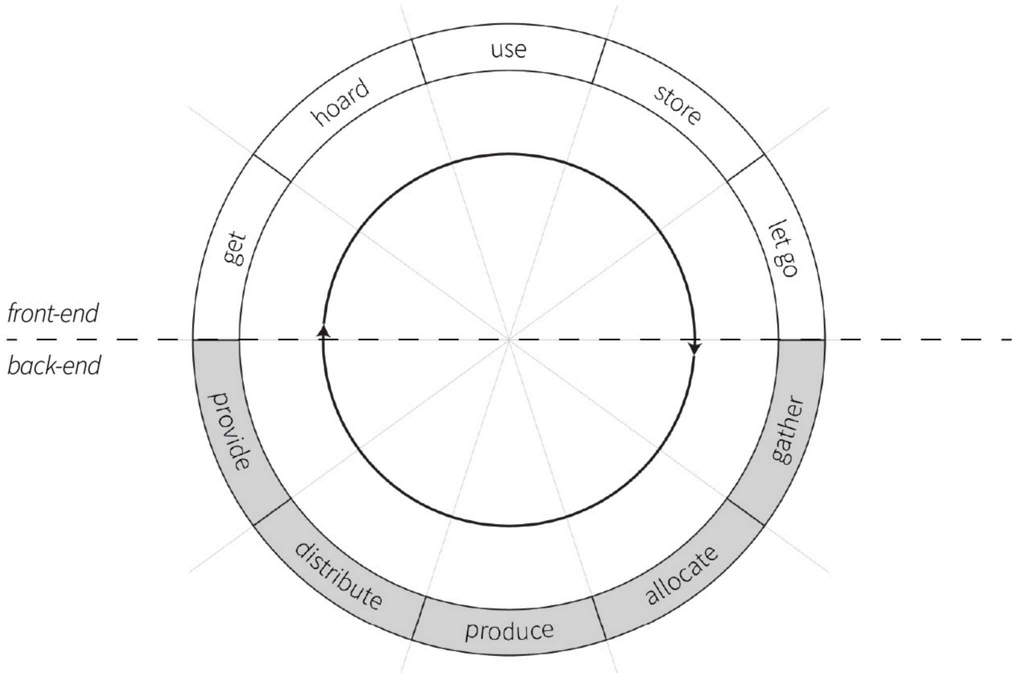


Table 6.6 The Flow Functions presented as a function tree of the movements and transformations to describe flow.

As a functional model, the Flow Function represents a blueprint for the RFS as it provides and structures the subfunctions that must be satisfied. For example, a consumer can only ‘get’ a resource if that resource has first been ‘provided’ by a stakeholder. Because the systems produce closed loops, the Flow Functions can be connected end-to-end (Figure 6.8). They describe what the system has to do to resources and how they are to be interpreted as processes with an input (a resource in a certain state) and an output (a resource in another state) that, together, deliver the overall function. This functional model exclusively focuses on the resource that is central to the RFS; the recipient of the Flow Function is always ‘the flowing resource’. Satisfaction of the Flow Functions is always the responsibility of a stakeholder, which allows the functional model to be divided into a front end (i.e., the consumer is responsible) and a back end (i.e., organisations such as manufacturers, service providers and [local] governments are responsible).

A function tree for the RFS

The Flow Functions also serve as classes of functions in a functional basis, in which the specific processes within each class can be seen as basis (Hirtz *et al.*, 2002; Stone *et al.*, 2000; Stone and Wood, 2000). Here, the Flow Functions serve as a function tree as they break down into more specific processes (Table 6.6); they can describe either a movement or transformation (or both, at the same time) while processes define more specific physical processes. For example, a consumer *storing* resources may involve both the *conditioning* (transformation) and *secluding* (movement) of resources. Therefore, processes are not always exclusively linked to a single Flow Function, for example, both *distribute* resources and *allocate* resources involve *transporting* resources. Processes specify the system’s functional description, going beyond how it appears in the functional model. These processes have emerged from the case studies, which focused on closed loops. Therefore, it is possible that additional processes can be identified.

Figure 6.8 The Flow Functions presented as a functional model of the closed-loop RFS.

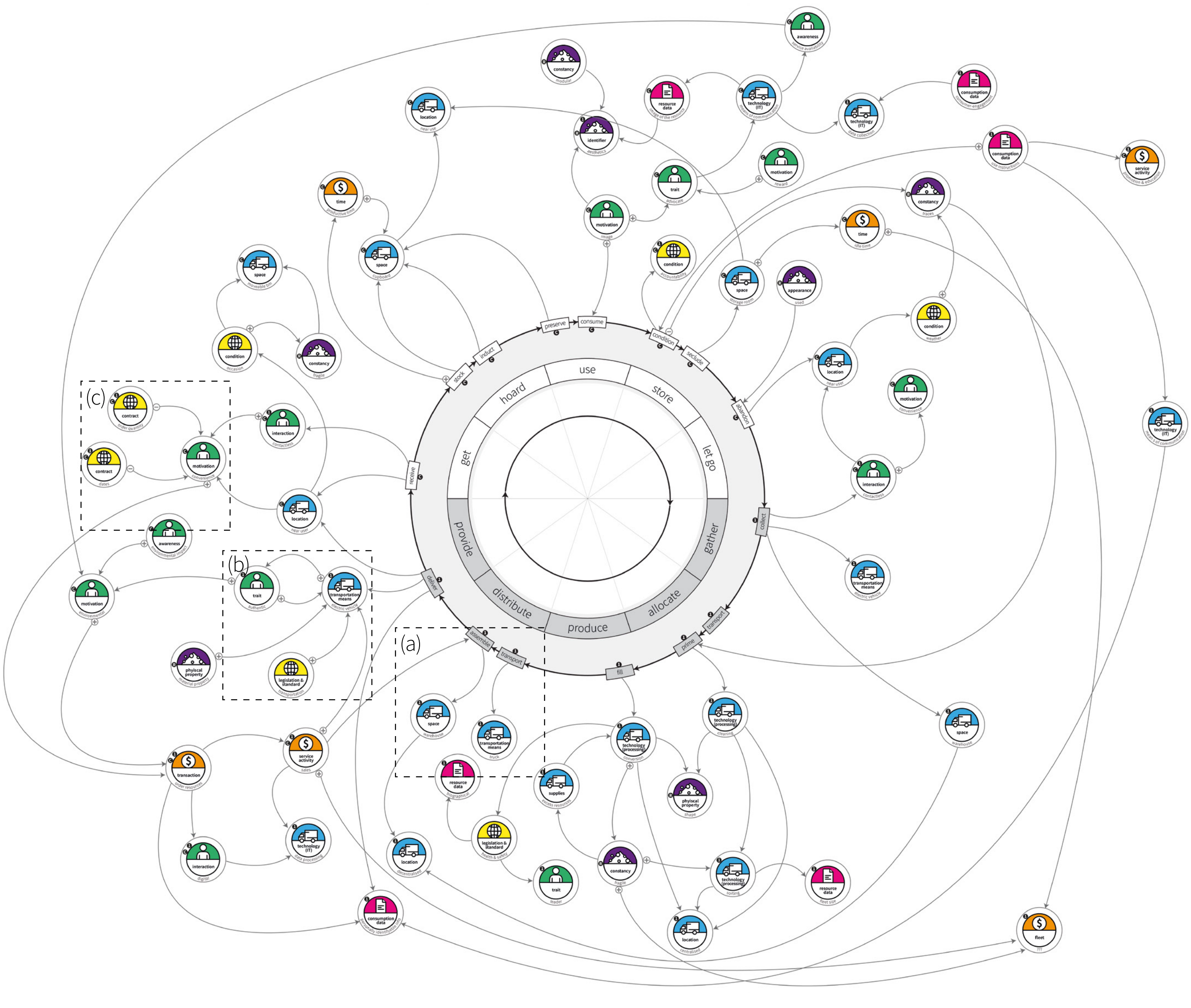
	Flow Function	Description	Process	Description
Front-end	*Get resources*	Flowing resources are taken (into) to consumers' homes or other consumption locations, in quantities based on specific consumer needs and sometimes in combination with other resources.	*Pick-up resources*	Flowing resources are taken by consumers in small quantities
			Receive resources	Flowing resources are accepted by consumers
	Hoard resources	Flowing resources remain stationary (near to) where they will be used, usually in quantities suitable to consumer needs.	*Induct resources*	Flowing resources are kept stationary in active use locations
			Stock resources	Flowing resources are kept stationary in storage locations
	Use resources	Flowing resources are taken in-use, sometimes in (deliberately) public or protective locations, and are (gradually) depleted or emptied.	*Abuse resources*	Flowing resources are used in unintended ways causing damage or decay
			Cherish resources	Flowing resources are (excessively) looked after
			Consume resources	Flowing resources are (gradually) depleted, emptied or saturated
			Exhibit resources	Flowing resources are exposed in private locations
			Preserve resources	Flowing resources are protected or conserved
	Store resources	Flowing resources remain stationary, often compacted and free from contaminants and usually secluded to be only with their own kind or with other combined with other resources.	*Condition resources*	Flowing resources are compacted, emptied, cleaned, decontaminated etc.
			Hold on to resources	Flowing resources are taken along by the consumer
			Save up resources	Flowing resources are kept stationary to accumulate
			Seclude resources	Flowing resources are separated from other resources
	Let go resources	Flowing resources are placed in locations where business stakeholders can reach them, sometimes in minimum quantities and sometimes combined with other resources.	*Abandon resources*	Flowing resources are left in a location
			Deposit resources	Flowing resources are dropped-off in locations
			Hand over resources	Flowing resources are given to someone else
Back-end	*Gather resources*	Flowing resources are taken from several locations to a single location, usually accumulating larger quantities and sometimes compacted.	*Collect resources*	Flowing resources are received or taken in larger quantities
			Condition resources	Flowing resources are compacted, emptied, cleaned, decontaminated etc.
			Sort resources	Flowing resources are put with the same type or same quality of resources
	Allocate resources	Flowing are kept stationary and sometimes modified until quantities suit specific stakeholder needs.	*Prime resources*	Flowing resources are processed to become as new, e.g., crushed, maintained, etc.
			Stock resources	Flowing resources are kept stationary in storage locations
			Transport resources	Flowing resources are moved
	Produce resources	Flowing resources are moved to manufacturing locations in which they undergo processing such as filling or manufacturing.	*Fill resources*	Flowing resources are replenished with new content
			Manufacture resources	Flowing resources are processed to become as new, e.g., labelled, assembled, etc.
	Distribute resources	Flowing resources are moved to several locations, usually in quantities suitable for customers (e.g., retailers) or single consumers and sometimes combined with other resources.	*Assemble resources*	Flowing resources are split and combined to form deliverable volumes
			Transport resources	Flowing resources are moved
	Provide resources	Flowing resources are placed in locations where consumers can access them, typically in small quantities and sometimes combined with other resources.	*Arrange resources*	Flowing resources are organised to be exposed in public locations
			Deliver resources	Flowing resources are brought (regularly) to consumers in small quantities

6.5. Flow-Causality Diagram

The FCD is a visual and qualitative model of the structure of the RFS which allows to explain its workings. The Flow Functions, used as a functional model, form a blueprint for the FCD. The FCD employs a refined functional description using the specific processes as presented in the function tree, see Table 6.6, creating a simplified stock-and-flow diagram to describe the physical movements and transformations of resources. Finally, the system's structure is configured using System Elements that emerged from the case studies, which are interconnected according to the relationships between elements and between elements and processes. An example of an FCD is presented in Figure 6.9.

The remainder of this chapter, presents the library of system elements, outline the method to model the FCD and demonstrate how the FCD can be used to explain the workings of the RFS.

Figure 6.9 Flow-causality diagram for Case C. The marked areas (a, b, c) are explained later in Figure 7.14.



6.5.1. Library of system elements

The structure of the RFS in the FCD is configured using system elements, of which a total of twenty-six emerged from case studies of RFSs based on their reoccurrence in the nine closed-loop FMCG systems. Elements are structural parts of the system and serve as auxiliary variables; they can be physical (i.e., a quantity, equipment, technology, place, area or object) or non-physical (i.e., a quality, rule, activity, duration, knowledge, contact, need, reason or piece of information). Elements emerge as critical parts of RFSs, in that they can (directly or indirectly) enable, facilitate, improve, hinder or worsen the flow of resources. Elements relate to different Flow Functions, for example, Case F involves the independent provider of a recycling service, in which the elements mostly concern *letting go* and *allocating* resources. Similar elements emerged throughout the cases, which could be grouped in classes and refined as different types of the same element.

These classes were then used to organise elements in a library (Table 6.7) and indicate what the elements are; as such, they provide the elements with immediate meaning and context. The six classes used here are as follows: '*principles*' (i.e., rules, agreements and circumstances that do not easily change); '*value*' (i.e., features and activities that suggest business value); '*actors*' (i.e., the actions and behaviours of and between stakeholders and resources); '*infrastructure*' (i.e., equipment and consumables); '*data*' (i.e., information gathered and provided); and '*resource*' (i.e., the qualities of the resource). It is worth highlighting this final class, as it implies that the qualities of resources are structural parts of the system. Resources, therefore, are not just the recipients of the processes, they may also have a role in enabling them.

The classes capture multiple facets of the RFS. When defining the classes and elements, language was used that can be understood across domains in a sociotechnical system (Hughes, 1987). In this way, it provides a common and consistent language with which to organise the features of elements that is interpretable by any discipline and thus allows the system's elements to be naturally integrated. This language also means that models can be developed consistently and allows to compare models in a way that deepens possible insights into RFSs. This library could also be used as a checklist to ensure that elements from all domains have been considered. In addition to their class, elements in the FCD are qualified according to their type and owner. An understanding of stakeholders and the exact types of elements offers important depth to the RFS. By considering the owners and types of elements separately, elements can form a more generic language in different FCDs. With the exception of ***condition*** and ***legislation & standards***, elements are always owned by a stakeholder. Ownership can be by one stakeholder (e.g., ***means of transportation***, ***trait*** or ***motivation***), by the resource (e.g., physical property), shared by two stakeholders (e.g., ***service activity***, ***interaction*** or ***transaction***), or shared by a stakeholder and the resource (e.g., ***interaction*** or ***identifier***).

Types are included as they provide the element with meaning and context. For example, the element ***awareness*** indicates that a stakeholder in the system has knowledge of the existence of something, while the type specifies what the stakeholder has awareness of, such as {service availability} or {environmental impact}. Using types to qualify elements allows to interpret them as variables when relevant (e.g., a ***location*** {near user} or {centralised} indicates a proximity variable). Generic language has facilitated the abstraction of certain types, for

Table 6.7 Library of system elements organised in six classes and presented with their various types.

Class	Element	Description	Type	Owner(s)
Principles	*Condition*	Qualities that are highly circumstantial yet not controllable	*Occasion; Weather*	N/A
	Contract	Rules defined by agreements between stakeholders	*Accountability; Partnership; Resource design; Order quantity; Dates*	2 stakeholders
	Legislation & standards	Rules defined by law, policy, industry or sectorial standards	*Certificates on resources; Health & Safety; Societal; Transportation; Waste management*	1 stakeholder
Value	*Service activity*	Activities by businesses for the benefit of consumers or of other businesses	*Use of a location; Data management; Logistics; Resource management; Promotion & education; Sales*	2 stakeholders
	Transaction	Activities that involve exchanging ownership of resources or other valuables	*Order resources; Service buy-in; Service pay-out*	2 stakeholders
	Fleet of resources	Total quantity of resources owned by a stakeholder	*N/A*	1 stakeholder
	Time	Duration that resources remain	*Idle time; Productive time*	1 stakeholder
Actors	*Awareness*	Knowledge of the existence of services and impacts	*Impact; Service availability*	1 stakeholder
	Interaction	Occasional contact between stakeholders or between a stakeholder and a resource	*Contactless; Face-to-face; Resource attachment, Digital*	2 stakeholder / stakeholder-resource
	Motivation	Needs or reasons of stakeholders for doing something	*Emotion; Environmental; Free time; Growth; Image; Reward; Convenience; Product quality*	1 stakeholder
	Trait	Qualities that shape stakeholders' identity	*Advocate; Authentic; Lack of interest; Leader; Maturity; Transparent*	1 stakeholder
Infrastructure	*Means of transportation*	Equipment to move resources and/or stakeholders	*Bicycle; Electric vehicle; Household recycling infrastructure; Mail; Public transportation; Personal vehicles*	1 stakeholder
	Location	Places that are geographical	*Centralised; Decentralised; Near use; Near user; Public*	1 stakeholder
	Space	Areas and objects that are available for resources	*Bin; Envelope; Moveable bin; Storage room; Smart bin; Warehouse; On shelf; Cupboard*	1 stakeholder
	Supplies	Substances used by the system as consumables	*Energy; Excesses; Zero waste*	1 stakeholder
	Information and communication technology	Technology to collect and process data	*Data collection; Data interpretation; Means of communication*	1 stakeholder
	Processing technology	Equipment to convert resources	*Cleaning; Conversion; Sorting*	1 stakeholder
Data	*Data on consumption*	Information on consumers and the consumption of resources	*Consumer-engagement; Personally, identifiable information (PII); Use instructions; Post label*	1 stakeholder
	Data on the problem	Information on the problem and its effects of the system	*Impact of the solution; Size of the problem*	1 stakeholder
	Data on the resource	Information on the resource and its existence in the system	*Biographical; Fleet size; Resource identifiable information (RII); Resource journey; Visual of the resource*	1 stakeholder
Resource	*Appearance*	Quality of a resource to look a certain way	*New; Used*	resource
	Identifier	Quality of a resource that provides recognition	*Branding; Labels; Logos; Aesthetics*	resource / stakeholder-resource
	Physical property	Quality intrinsic to the nature of the resource	*Material property; Mechanism; Shape; Size*	resource
	Constancy	Quality of a resource to stay the same	*Architecture; Modular parts; Traces; Wear & tear; Fragile*	resource

example, a ***location*** {centralised} could be a manufacturing site or a local recycling site, while a ***location*** {public} may indicate a supermarket or the location of a mailbox on the street. Some of the elements appear as obvious parts of the system, for example, a ***service activity*** or a ***means of transportation***, while some are typically studied in relation to one type of stakeholder, for example, the consumer's versus the company's ***motivation***, both of which could be relevant. Some surprising elements have emerged, in that they or some of their types are not always explicitly considered in systems: for example, a ***transaction*** or ***space***.

Because the elements have been determined using a bottom-up approach, it is probable that other elements can also be identified. In addition, other elements and types may be identified by analysing RFSs in other sectors. Indeed, there may be many different types of each element.

6.5.2. Modelling the RFS in an FCD

The FCD contains several components, which are described as nodes and arcs, see Table 6.8. The nodes represent the following: the Flow Functions (presented as a functional model that serves as a blueprint of the closed-loop RFS from which the modelling method departs); the processes, which are used to refine the functional model and make it case-specific (note that since the satisfaction of the processes that move and transform resources are the responsibility of a stakeholder, each process is qualified with an owner); and system elements, which form a core part of the structure of the system. System elements are qualified by class using icons, by type using descriptions, and by owner using numbered labels. Finally, the arcs represent the causalities between elements and between elements and processes.

Modelling the FCD starts at the centre of the diagram, i.e., at the blueprint formed by the Flow Functions, see Figure 6.10. Processes are selected from the function tree (Table 6.6) and are positioned against the respective Flow Function in order to describe the exact movements and transformations specific to the RFS. Both Flow Functions and processes are visualised as curved rectangular shapes. It is worth noting that, in contrast to the Flow Functions, there is no fixed sequence for processes, as their sequence and occurrence depends on the specific case. For example, when allocating resources, the resources may be conditioned either before or after they are transported. Short chains of processes may be quickly repeated or they may exist in parallel chains, for example, resources may be preserved and consumed over a short interval, or they may be exhibited while they are being consumed. To simplify the model, processes are always modelled sequentially, and short intervals are neglected. Owners of processes are labelled against each process; these might be the consumer (C) or other stakeholders (numbered). As can be seen in Figure 6.10 the consumer is always the owner of front-end processes, while back-end processes can be owned by one or more stakeholders.

Table 6.8 The components of the FCD: an overview.

Component	Annotations	
Nodes	*Flow Functions*	
	Processes	Owner
	System elements	Class
		Type
		Owner
Arcs	*Causalities*	+ / -

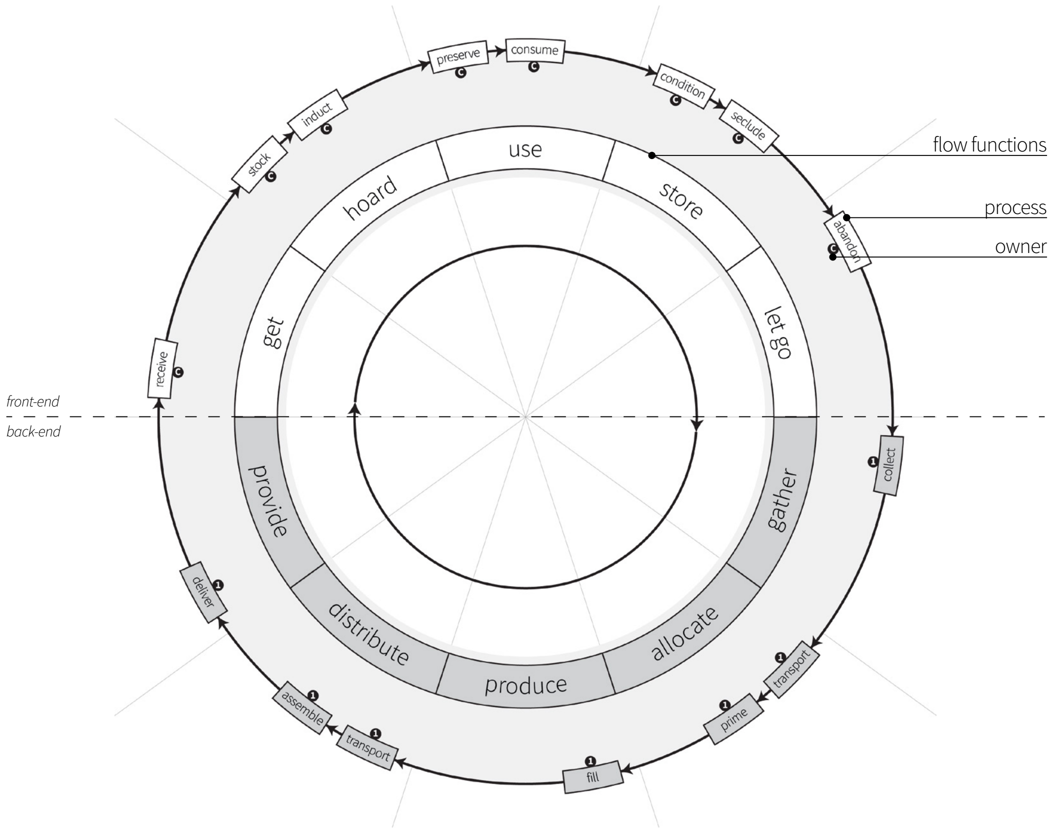


Figure 6.10 The Flow Functions used as the functional model of Case C, including case-specific processes.

Next, system elements are added based on their occurrence in the system, and nodes are visualised using circles. Different icons and colours are used for each of the six classes of element, see Figure 6.11, which ensures they can be easily recognised and provide a high-level understanding of the different facets of the RFS. To capture in-depth meaning and context, the nodes are also consistently annotated with the element, type and owner, see Figure 6.12. Just as for processes, consumers are always indicated by C, while elements belonging to resources are indicated by R and all other stakeholders are numbered. Several stakeholders emerged in the cases, including manufacturers, service providers, customers, competitors and several types of partners. In some of the cases, a single stakeholder fulfils more than one of the back-end roles, as is the situation in Case C in Figure 6.9. The stakeholders in the examples in this chapter are coded consistently as follows: 1: manufacturer; 2: service provider; 3: customer; and 4: other.

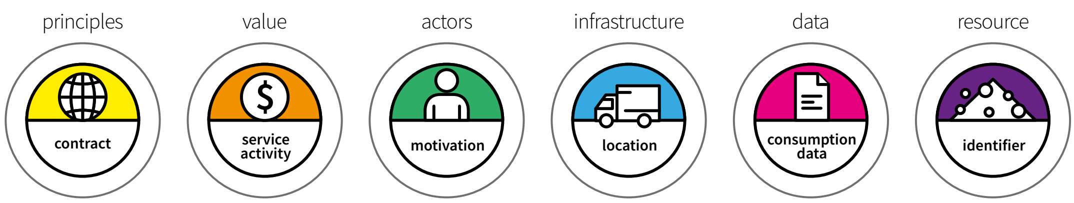


Figure 6.11 Visualisation of the six classes of elements.

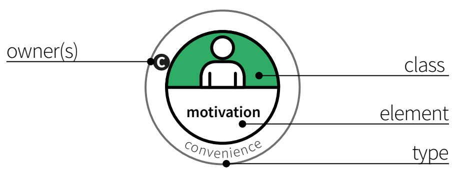


Figure 6.12 Annotation of system elements.

Finally, arcs are used to represent causalities between elements and between elements and processes. Elements themselves are direction-free (Meadows, 2008), i.e., they do not indicate whether they are increasing or decreasing, or whether they will have an increasing or decreasing effect. Instead, they can operate in more than one direction. For example, the element location {public} could cause less motivation {convenience} (e.g., if consumers have to make a specific trip there), however, it could also cause more motivation {convenience} (if consumers are already visiting this location). The exact contribution of an element, therefore, depends on the specific case; causalities provide information about these contributions. The arrows provide information about both the element(s) and the process(es) that it connects, as well as about their effect on each other. Three types of causalities are distinguished, see Figure 6.13:

- Neutral arrows indicate a constant element (i.e., the element does not change or vary in this system). It implies that element A causes (the need for) element B. The example in Figure 6.13 (a) reads as: stakeholder 1 *transporting* resources causes a need for ***transportation means*** {truck} owned by stakeholder 1.
- Positive arrows (annotated with +) indicate a variable element (i.e., the element can increase or decrease in this system). It implies that two elements change in the same direction. That means either that more of element A causes more (need for) element B; or that less of element A causes less (need for) element B. The example in Figure 6.13 (b) reads as: more of a ***legislation & standard*** {transportation} causes (a need for) more ***transportation means*** {electric vehicle} owned by stakeholder 1.
- Negative arrows (annotated with -) also indicate a variable element but imply that the two elements change in the opposite direction. This means that less of element A causes more (need for) element B, and vice versa. The example in Figure 6.13 I reads as less of a ***contract*** {order quantity} owned by the consumer and stakeholder 1 causes more ***motivation*** {convenience} owned by the consumer.

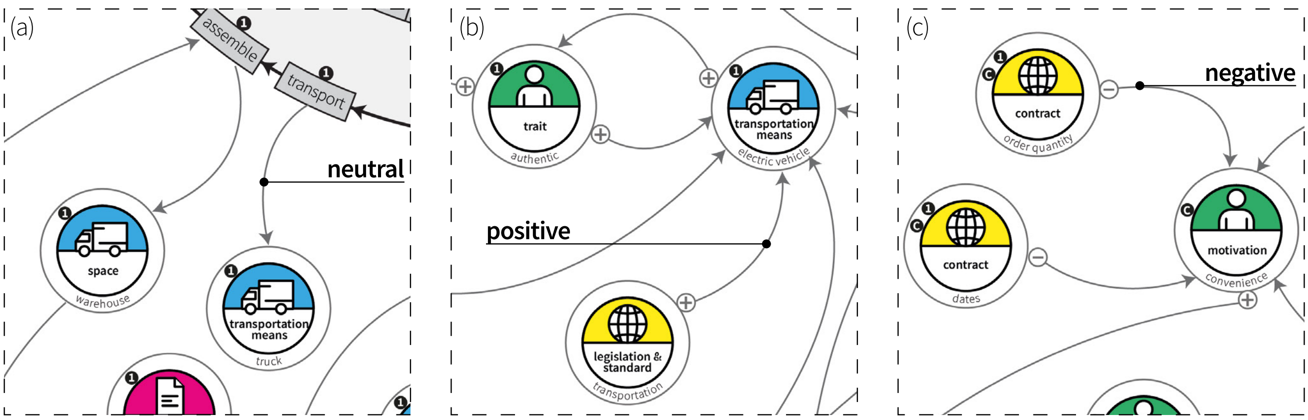


Figure 6.13 Three type of causalities selected from Case C in Figure 6.9.

6.5.3. Using the FCD to explain RFSs

This final section demonstrates how the FCD explains the workings of the RFS. Two examples are used, as highlighted in the FCD for Case C, see Figure 6.14. The highlighted nodes and arcs will be narrated to explain the working of the system.

Example 1

The ***motivation*** {image} of consumers boosts the *consumption* of this resource. If the ***motivation*** {image} increases further, this causes the consumer's ***trait*** {advocate} to increase. This ***trait*** {advocate} is also positively influenced by consumers' ***motivation*** {reward}. The consumers' ***trait*** {advocate} causes them to use ***technology*** {means of communication} which causes ***resource data*** {image of the resource}. This data causes an ***identifier*** {aesthetics} of the resource and company. This is also caused by the resource's ***constancy*** {modular}. The ***identifier*** {aesthetics} satisfies the need for consumers' ***motivation*** {image}, and the ***technology*** {means of communication} is used to cause ***awareness*** {service availability} which causes consumer ***motivation*** {environmental}.

This example indicates that consumption of this resource is highly driven by consumers' desire to maintain a certain image. The design of the product, which is recorded in a photo taken and shared by the consumer, has an important role in supporting their image. Image can be such a strong motivator (in addition to the reward for the friend-referral programme) that consumers will share these images on social media, thus increasing visibility and attracting the attention of environmentally motivated consumers. In this example, the processes get and use resources, which are satisfied by consumers, are strongly influenced by social elements, enabled through the branding of the resource.

Example 2

The *collection* of resources by the company needs an ***interaction*** {contactless} between company and consumer, which boosts the consumers' ***motivation*** {convenience}. It causes the need for a ***location*** {near user}, which is needed for consumers to *abandon* the resource. However, this ***location*** {near user} causes the need to consider a ***condition*** {weather}. More of this ***condition*** {weather} can affect more ***constancy*** {traces} in the resource. This ***constancy*** {traces} will be greater if consumers were to do less *conditioning* of the resource. Resource ***constancy*** {traces} results in the company needing to *prime* resources.

This example indicates that consumer convenience can be achieved through contactless interactions. However, this may involve using locations in which the weather plays a role, which could affect certain of the resource's features. Leaving the resource outside can cause traces on the resource, which will worsen if the consumer has not sufficiently or properly washed the resource. These traces are a cause of the processes needed to clean resources. In this example, the processes sort and let go of resources, satisfied by the consumer, might affect the features of resources due to the use of a certain infrastructure that aims to increase user convenience. As a result, these processes may hinder the manufacturer when it is priming the resource.

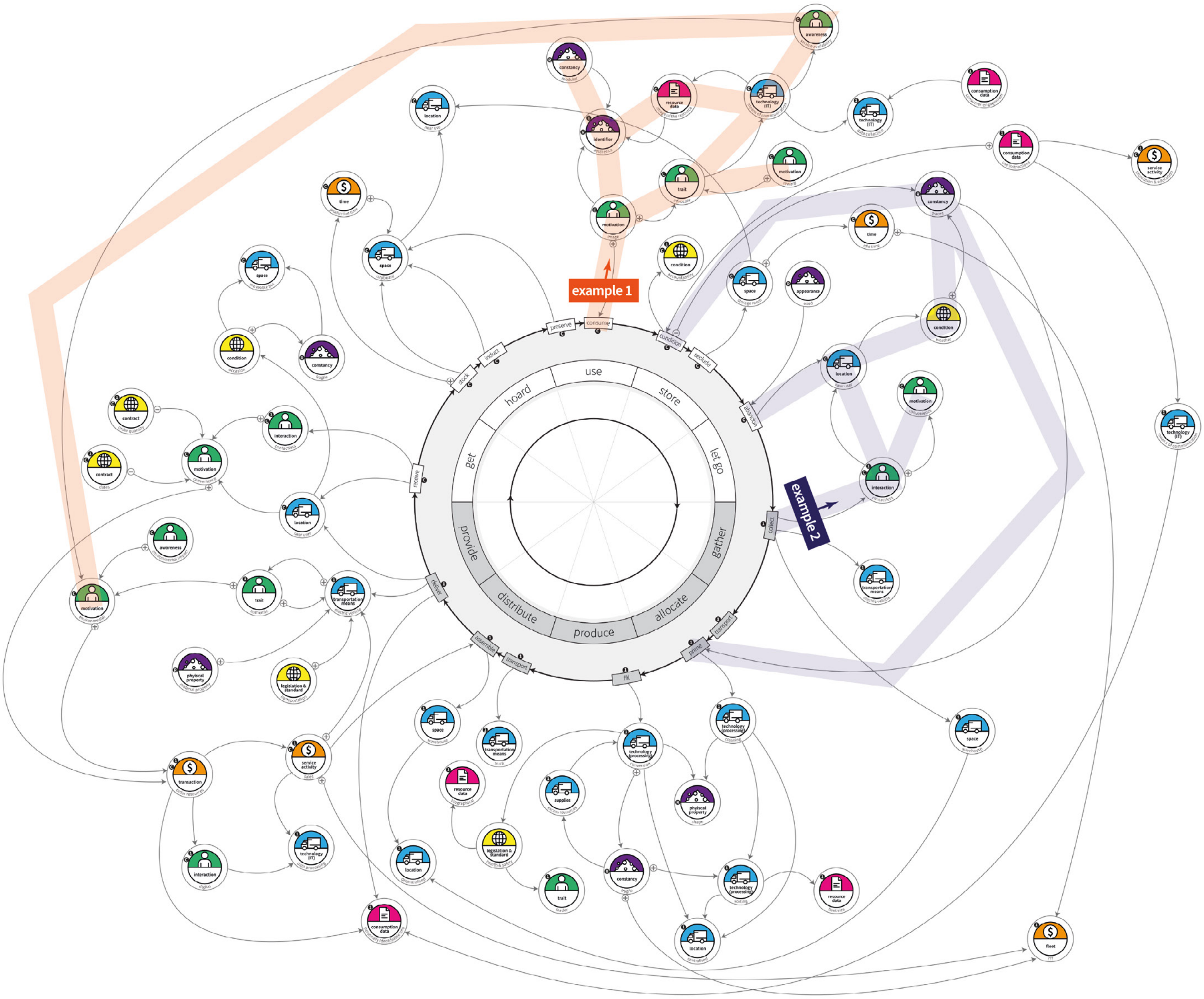


Figure 6.14 Indication of the two examples for Case C.

6.6. Discussion

This work involved an empirical study of nine RFSs in the FMCGs sector that produce closed-loop resource flows. The data generated was used to derive these systems' subfunctions (i.e.,' to flow resources') and their system elements (i.e., the physical and non-physical features that interconnect to form the system's structure). It was then used to develop a method to model RFSs in an FCD, which illustrates the workings of closed-loop FMCG systems. The method supports the FMCGs sector by modelling the FCD using language and visuals that can consistently be used across disciplines. Its consistency allows FCDs of different cases to be compared, furthering the understanding of the structures that enable FMCG resources to flow. The modelling method is based on the theory of system dynamics and function trees, and the results of this study have three key implications for research and design in the CE.

6.6.1. Expressing resource flows as functions

Transitioning to a CE challenges FMCG manufacturers to design and manage complex and multifaceted systems that produce closed-loop resource flows. The problems that these companies must now solve have innumerable causes and can be framed in different ways. There is no such thing as a right answer; rather, solutions are good or bad (Camillus, 2008), with RFSs posing wicked problems. Traditional design processes are not suited to solving wicked problems (Pourdehnad *et al.*, 2011; Rittel and Webber, 1973); instead, theorists aim to 'tame' them (Camillus, 2008). Systems thinking can be used to investigate these complex problems (Rittel and Webber, 1973), but methods are complex and there are no structured approaches that focus specifically on resource flows.

With the FCD, a novel method has been developed that expresses the flow of resources as functions. This approach provides several opportunities to manage the complexity inherent in designing systems solutions that entail resource flows. First, the functions provide a new level of granularity to the flow of resources. In design, resource flows are often interpreted as life cycles. However, life cycles typically only break down the journey of resources in high-level phases (e.g., origin, production, use and end-of-life [e.g., Vogtländer, 2010]). This work provides a novel method of describing the flow of resources, doing so more explicitly and with a higher level of granularity, and by using functions in verb–resource constructions. A functional basis for design is proposed that introduces and employs consistent language that can be used across methodologies in research and design to describe the functions of products and component engineering (e.g., Hirtz et al, 2002; Stone and Wood, 2000). Although functional bases exist, the novelty is a functional basis specifcically for resource flows.

In this work, functions are interpeted as problems that can be solved through design. Here, 'function' is used to describe the processes that move and transform resources; satisfying these is the responsibility of the system's stakeholders. These functions are derived from the analysis of several closed-loop systems, and specifically relate to resource flows. This is important because functions are not always valid for just any recipient (Stone and Wood, 2000). A resource flow in the CE places products, components and materials in the same flow (Blomsma and Tennant, 2020; Stahel, 2019) and thus benefits from a language in which functions can apply to any of a resource's states. Function-based methods provide designers with a clear objective and a consistent level of functional detail relating to the problem at hand (Hirtz *et al.*, 2002). Therefore, evolved and elaborated sets of Flow Functions could become a functional basis upon which our ability to consider the design of resource flows in a CE could be improved.

Second, functions were used in the current work to make the design challenge concrete. It is extremely challenging to grasp exactly what a system encompasses. More often, it is easier to identify independent elements within a system (Meadows, 2008), such as the presence of recycling bins or a recycling awareness campaign. Causalities in the system might be uncertain because the relationships between elements are non-deterministic (Steinder and Sethi, 2001) (i.e., elements can be interrelated to one or several other elements and processes in different ways). Therefore, elements alone provide little understanding of the system (Charnley *et al.*, 2011; Meadows, 2008), and it is unlikely that all the elements can be distinguished when analysing or designing a system (Gibson, 1977). Instead, functions provide a non-physical description of the system (Galvao and Sato, 2005) that provides a concrete definition of what it must deliver (i.e., the movement and transformation of resources) without specifying its structure. Functions can be broken down into smaller parts. This allows designers to deal with the complexity of RFSs (Burge, 2006). Understanding exactly what the system does, or has to do, makes it possible to align multi-disciplinary stakeholders with a system (Stone *et al.*, 2000) and to compare and assess solutions that deliver the desired function (Pahl *et al.*, 2007).

Finally, this work defined the overall function of the system ('to flow resources') which provided a means by which to define the scope and set the boundaries of systems of interest. Systems are typically defined as part of investigation and improvement and are bound by purposes defined by specific stakeholders (Charnley *et al.*, 2011). Different stakeholders define systems differently; additionally, systems are temporally dynamic and so their true effects might go unnoticed over the short term (Senge, 2006). This makes defining systems incredibly complex (De Haan and De Heer, 2017) in that it is difficult to understand which of a system's elements are relevant and satisfy the overall function (Senge, 2006). A great deal of the complexity of RFSs, therefore, seems to relate to uncertainty of scope. Clarifying the overall function of the design outcome allows designers to define an appropriate scope for the solution (Ullman, 2016).

6.6.2. Configuring RFSs

When considering systems with a high level of complexity, a designer would usually start with a mental model (Acaroglu, 2018; Senge, 2006). The abstraction of multifaceted systems and their elements is a difficult and time-consuming process (De Haan and De Heer, 2017), which makes it extremely difficult, if not impossible, to visualise systems and their solutions (Charnley *et al.*, 2011). The more designers are challenged with systemic innovations, the more their innovation teams must operate in synergy with experts from various disciplines (Ceschin and Gaziulusoy, 2020). A multi-disciplinary approach significantly improves the potential of systems thinking (Charnley *et al.*, 2011; Miser and Quade, 1985) because it facilitates a multifaceted understanding of a system (Charnley *et al.*, 2011; Senge, 2006). Modelling an RFS using FCD can be interpreted as configuring the system. The configuration process involves visually positioning and connecting elements from the library in around the Flow Functions until workings of the RFS can be explained. This type of visual modelling is not only a way to explain the workings of the system, but can also serve as prototyping means and improve communication and problem solving (e.g., Ryan, 2014; Lim *et al.*, 2008).

This work has two implications related to the design of systems in a CE. First, the library of elements provides multi-disciplinary teams with a means of communication. Multi-disciplinary collaboration is often challenged by how well the disciplines integrate (Ceschin and Gaziulusoy, 2020; Hughes, 1987; Toba and Seck, 2016; Forrester, 1968a). A plausible cause of such difficulty is uncertainty regarding the processes used to communicate between and to integrate the views of different disciplines (Charnley *et al.*, 2011). If a system is to be fully understood, it is essential that information can be shared between parties from different disciplines (Mishra *et al.*, 2019; Blizzard and Klotz, 2012), because better communication produces a more grounded understanding of the wicked problems systems present (Bofylatos and Spyrou, 2016).

The library of elements presented in this work provides a new type of taxonomy that includes cross-domain sociotechnical system elements. This library is specific to closed-loop FMCG systems, however, its strength is that it brings together elements from different domains in a form that allows them to be used as a systems vocabulary. Users can then communicate in the same language, addressing and overcoming communication barriers between disciplines. The library can also serve as a checklist to ensure that all relevant domains are represented in the model and to identify individual elements that require deeper investigation (Forrester, 1968a). It is easy to overlook parts of a system (Meadows, 2008), especially if domains are poorly represented within a team (Hughes, 1987). Additionally, the consistent visualisation of system elements makes interpretation and recognition of the elements easier, with the aim of making the language more accessible to less-experienced systems thinkers.

Second, the use of causalities facilitates innovative systems solutions, allowing to identify new opportunities. Elements alone do not tell much about a system, but their interrelated whole explains how a system works (Meadows, 2008). A lack of understanding regarding the relationships between elements and processes limits comprehension of the effectiveness of independent elements (Flood, 2010), for example, whether an awareness campaign has influenced recycling rates, or whether other system elements have had a role in consumer engagement (Steg and Vlek, 2008). A better understanding of the dependencies between system elements might enable more meaningful collaboration (Mishra *et al.*, 2019), for example, by using the functional model as a basis (Aurisicchio *et al.*, 2012; Stone and Wood, 2000) a team could configure system elements in order to discuss their relationship. This could lead to the identification of new opportunities (Galvao and Sato, 2005) and new areas for research regarding the effect of combinations of system elements (e.g., the effect of an awareness campaign on recycling rates). Relationships between elements and processes also emerged, and the inability of participants to discuss functions without explaining system elements indicates that people are aware of these relationships, even if they are difficult to articulate and explicitly define (Aguirre Ulloa and Paulsen, 2017). The FCD allows to configure variable and non-variable system elements, examine their relationship with processes and explore different solutions to the problems that are revealed.

6.7. Limitations and future work

The refill services in the dataset used sequential models (Muranko, *et al.*, in 2021) and the dataset did not include common recycling such as kerbside recycling. In addition, most of the services were still young and only served European and American markets. Furthermore, the modelling method focuses on as-is situations, rather than highly conceptual cases. Although more variety could be captured by investigating more cases, the recurrence of elements and processes indicates that the dataset was representative and allows to use the method to explain RFs for FMCGs, both in novel and in established systems. Further work is welcomed to complements the results, developing more generic frameworks and increasing understanding within the sector. It is very probable that more system elements exist, as such, the results will be valuable to other sectors and to other types of resource flows. However, they are currently based only on cases from one sector and on one type of flow. It is likely, therefore, that other blueprints can be made for other type of RFSs, that more elements will emerge. The scope of this work does not include the development of empirical knowledge of closed-loop FMCGs. However, valuable insights emerged during the analysis that relate to enabling system elements, their interconnections and their interconnectedness with processes. Future work to analyse the data using the method proposed in this chapter is suggested in the hope that it can capture and organise these insights. 'Flow' was defined as the physical movement and transformation of resources. Several commercial factors are intertwined with the physical flow of resources, such as demand (Zeeuw van der Laan and Aurisicchio, 2020); these commercial dynamics emerged as system elements in this study. Were the flow to be defined differently, or an additional flow introduced, other processes might come forward.

The FCD is used to model the as-is situation. Although the aim was to capture the complexity of the RFS as much as possible, elements had to be simplified for consistent use in the modelling method. The library and FCD are currently not able to model the non-existence of system elements (e.g., where there is a lack of legislation), nor can they distinguish between elements that are novel and those that already exist. Therefore, this modelling method would benefit from further development. This would allow the identification of new types of elements through a bottom-up approach and based on empirical data, and through a top-down approach by embedding elements in theoretical frameworks (such as the work shown in Chapter 5). This study was qualitative; as such, the results did not allow to express the structure of the system quantitatively. However, it can be envisionioned that the modelling method has potential to be extended in this direction.

6.8. Conclusions

Systems thinking is believed to be an appropriate approach to developing an understanding of systems and explaining their working. A gap exists in methods of applying systems thinking to explain how systems can produce resource flows. The system of interest in this work was conceptualised as the RFS, which encompasses all the structures put in place to produce this flow. Based on empirical data collected through case studies of nine closed-loop FMCGs, this work developed a set of ten Flow Functions. Used in a sequence, the Flow Functions form a functional model that serves as a blueprint for the closed-loop RFS. The Flow Functions also form a function tree, in which they are decomposed through processes that describe the specific movements and transformation of resources. The Flow Functions are used as the basis for the FCD, which is a visual and qualitative model of the RFS. The FCD models the structure of the RFS using annotated system elements that are organised in a library and connecting them with neutral, positive and negative causalities. The work provides a visual diagram of the structure of the RFS in order to explain its workings.

This research makes several contributions to the theory and practicalities of designing for the CE. First, it defines and scopes the system of interest in the CE using functions and suggesting more concrete and accurate system boundaries. Second, it provides the beginning of a functional basis for resource flows. This offers a language with which to describe the movement and transformation of resources that can be used across methodologies in research and design. This work uses functional bases to develop a blueprint for the closed-loop system, however, blueprints for other types of flows could be developed if the functional basis is extended. Third, the work consolidates system elements that are significant to the closed-loop flows of FMCGs. The library of system elements offers a language with which stakeholders can discuss RFSs. The library is sector-specific and, as such, more work is needed for an exhaustive library to be created. Fourth, the FCD provides a novel and straightforward method with which to consistently model RFSs. This allows different systems with the same function to be compared and to develop an understanding of the impact of isolated and interconnected system elements on flow. Further work is needed to apply the method to the nine cases and develop this understanding further. The modelling method also has the potential to support the design of systems, as it provides a means to prototype an RFS.

7. Developing a Tool to Support the Design of Products and Systems

This chapter discusses the development and evaluation of the Flow Mapper. The Flow Mapper is a tool that allows users to model a RFS to understand it holistically and in-depth, with the intention to support industrial users in designing closed-loop systems . This work was executed in parallel with the work in Chapter 6. Part of this chapter was presented at the PLATE Conference 2021 (Zeeuw van der Laan and Aurisicchio, 2021).

7.1. An urgent need for flowing resources

Methods and tools can be effective means to guide companies in innovation processes (Andrews, 2015). Certainly, there is no lack of tools aiming to support industry in its transition to the CE. The majority of tools focuses on upskilling designers and industrial decisionmakers, for example, by increasing awareness for business strategies that are needed for the transition to the CE (e.g., Blomsma *et al.*, 2019; Bocken *et al.*, 2013; Konietzko *et al.*, 2020), considering consumption behaviour right up until disposal (e.g., Selvefors *et al.*, 2019) and assessing the circularity of products (e.g., Saidani *et al.*, 2017). Seemingly, tools often focus on specific aspects of the CE, for example, consumer behaviour (e.g., Muranko, Aurisicchio, *et al.*, 2021; Selvefors *et al.*, 2019) or product features such as disassembly (e.g., Favi *et al.*, 2019; Vanegas *et al.*, 2018) and recyclability (WRAP, 2019a).

These specific aspects may indeed improve the circularity of a product but do not typically address the system as a whole. This is problematic, as it is acknowledged that a linear economy is caused by the whole system rather than its isolated parts (Dewberry and Monteiro de Barros, 2009; Senge, 2006). Redesigning isolated parts of the consumption system to solve the problem of linear flows, therefore, limits what can be achieved. In fact, consideration of incomplete solutions seems to easily compromise the ability of resources to flow in a full circular journey and lead to built-in disruptions (e.g., leakage, losses or hibernation) of resource flows. This is well illustrated by the following examples: supplying FMCGs to emerging markets without considering the country's poor waste management infrastructure, thus amplifying leakage of resources into nature (Jambeck *et al.*, 2015); designing beautiful FMCGs that structurally end up as waste because technically they cannot be recycled (De los Rios and Charnley, 2017); or celebrating the cascading of post-consumer recycled materials into inferior applications but facing volatile prices in procuring these resources (EMF, 2017b; Zink and Geyer, 2017). Based on these examples it seems obvious that a more holistic consideration of the consumption system, such as the RFS, could prevent such environmental and business issues.

Effective transition to the CE is also challenged by the generally poor uptake of tools by industry (Bocken *et al.*, 2019; Peters *et al.*, 2020; Vallet *et al.*, 2013). One reason for this could be that the outcome of tools may not sufficiently resonate with the needs of industrial users. Most CE tools provide outputs on conceptual and strategic levels while there is a scarcity of methods and tools that support the later phases of innovation, such as implementation (Baldassarre *et al.*, 2020; Norman and Stappers, 2015). This is problematic as businesses seek for evidence for the success of new business models to be convinced to make changes (Murray *et al.*, 2017; Yong, 2007). Generating evidence for the success of solutions, thus, seems a more promising enabler for a transition to the CE. It is plausible that current CE tools do not sufficiently provide the in-depth and practical insights on solutions that businesses need to evidence their success and grow their confidence in implementing them. In addition, if stakeholders using the tools only focus on the aspects that directly affect them, evidence will likely link to their business objectives rather than the circular success of a solution. Stakeholders may have an interest or something to gain along a specific part of a resource flow, such as in the production and use phase but not the end-of-life (EOL) phase. This narrow view can disrupt resource flows. For example, if obsolescence is not anticipated and planned-for, consumers may not be sufficiently aware or incentivised to respond appropriately to this inevitable event (Burns, 2010; Zeeuw van der Laan and Aurisicchio, 2017). Similarly, if there is no anticipated market for recycled materials, they will probably come to exist as secondary materials rather than substituting the demand for virgin materials (Zink and Geyer, 2017).

Supporting the transition to a CE, thus, requires tools that provide both a holistic and in-depth understanding of systems. Firstly, a holistic view is essential to understand the wider implications of changing specific aspects. Seeing a system as a whole gives understanding of both systems and processes and enables users to critique the systems (Jackson, 2006). A holistic understanding of systems can be built through mental models or visual models, which are often challenging to create due to the complexity of systems and the need for multi-disciplinary perspectives from all involved stakeholders (Charnley *et al.*, 2011). Secondly, understanding why the system fails or succeeds in flowing resources requires an in-depth understanding of the interconnected elements of the system that cause its behaviour. Such understanding could be obtained by simulating or prototyping a model of the system (Goldsworthy, 2014). Prototyping is a common process in product design that allows to discover, generate and refine ideas (Lim *et al.*, 2008), yet there appears to be a lack of methods that enable a comparably accessible and iterative process for the design of systems. Instead, CE tools often seem ambiguous in their intended or possible influence on a shift to the CE (Konietzko *et al.*, 2020b). Therefore, the objective of this work is to develop a tool that provides both holistic and an in-depth understanding of the RFS and supports the FMCG industry in designing closed-loop systems.

The remainder of this chapter includes the following sections. Section 2 discusses the strengths and weaknesses of common tools that provide holistic or in-depth views of resource flows. Section 3 explains how Participatory Action Research was used to engage industrial users in the development and evaluation of a new tool, called the Flow Mapper. Section 4 introduces the philosophy of the Flow Mapper and demonstrates the tool. Section 5 evaluates the usability and usefulness of the tool. Finally, the implications of this work are discussed in Section 6, followed by limitations and future work in Section 7 and conclusions in Section 8.

7.2. Resource flows in systems thinking

Resource flows are a familiar component of systems thinking. Systems are often considered to have inputs and outputs of several types of resources (Chertow, 2000) where the term ‘flow’ is used in systems thinking to explain how stocks (e.g., resources) change (Forrester, 1968a; Meadows, 2008). The field of System Dynamics has put forward methodologies to study and model systems by taking resource flows and many other types of flows into account in relation to an overall function of the system (e.g., De Haan and De Heer, 2017; Meadows, 2008). Nevertheless, these methods typically focus on a system defined by a stakeholder’s objective, rather than on resource flow specifically. Methods that build on systems thinking theory and focus specifically on resource flow or parts of the flow do exist, however, they seem limited in their ability to provide both a holistic and in-depth understanding of the RFS. This section explores the strengths and weaknesses of common methods and discusses their limitations.

7.2.1. Obtaining a holistic view of the resource flow

Methods that aim to take a holistic perspective on resource flows are often based on Material Flow Analysis (MFA). MFA is a methodology used to map and visualise the flow of resources based on the law of conservation of matter. It entails quantitively analysing materials, selected based on their chemical composition, within a clearly defined system and at a set moment in time (Blomsma and Tennant, 2020; Brunner and Rechberger, 2004). The data is often visualised in a Sankey diagram (Allwood and Cullen, 2015) in which the width of the line correlates with the volume of material. MFA typically reviews the resource from extraction to disposal (Huang *et al.*, 2012) and adds nodes in the diagram as processes that partition resource volumes. MFA and its variants are used to consider the strategic use of materials in specific contexts (Voet, 2002), support sustainable decision-making (Huang *et al.*, 2012), and review the flows of material resources in relation to other flows such as energy (Brunner and Rechberger, 2004; Huang *et al.*, 2012; Moriguchi, 2007; OECD, 2008).

Indeed, MFA is a useful method to obtain a holistic view of the quantities of a single resource within a specifically defined system, therefore, providing a holistic understanding of a resource flow This system, however, is typically defined based on geography instead of the actual reach or spread of resources, thus limiting the ability to obtain an understanding of the entire resource flow. Resource flows are often compared to product life cycles. Product life cycles are used in Life Cycle Engineering to ensure design considers the engire journey. They are also used to understand and estimate the impacts of a product using LCA (e.g., Vogtländer, 2010). Different to MFA, the product life cycle revolves around the production and consumption system. When used for LCAs, the product life cycle is sectioned into phases (e.g., origin, production, use, and EOL) and the assessment involves estimating the environmental impacts in each phase (Finnveden, 2000). These outcomes are then used to identify the priority areas for reducing environmental impacts (Niero *et al.*, 2017). Although this provides an idea of the impacts of a resource flow, there is a lack of granularity of the flow and whether the resources will flow or not is merely an assumption.

Both MFA and product life cycles provide a holistic view of a system that entails resource flows and could support environmental improvement. MFA is at the basis of the practice of sustainable materials management, which integrates material flows and life cycles to achieve economic and environmental viability (Fiksel, 2006); and MFA has potential to be used to close material balances in economic systems (Fischer-Kowalski *et al.*, 2011). LCA is used to understand and anticipate the environmental consequences of design decisions. Nevertheless, both methods are simplified to include only certain processes or phases of the journey of the flowing resources. Considering materials and products to be part of a single circular flow implies that there are more subtle changes from one resource state to the next, which are not explicitly included. Rather, MFA focuses on the entire volume of a single material and captures processes that partition its volume but no other processes that impact the success of the entire flow. LCA studies heavily focus on the impacts of the flowing resource and allocates these to certain life cycle phase but they do not clarify the actual or intended physical journey of resources (Guinée *et al.*, 2011). Such simplification limits the potential of these methods to build holistic understanding of the entire resource flow, as important movements and transformations might be obscured. Further, both LCA and MFA are complex and time-consuming in use, making them unappealing to use. For example, LCA studies require capable users to employ the method (De los Rios and Charnley, 2017) as well as expertise to put the results into context (Finnveden, 2000).

A popular approach to facilitate the shift to a CE is to focus on business models for the CE. Resource flows appear to have a central role in business models for the CE. Nevertheless, support that focuses on the effects that business decisions have on resource flows is scarce. For example, the 'In the Loop' tool stands out because it educates users on the consequences of their business decisions on the resource flow over time (Whalen *et al.*, 2017). On a practical level, the elements of business models can be considered components that can be embedded specifically to establish flow (Zeeuw van der Laan and Aurisicchio, 2019c). More prominent is support that focuses on the value that can be generated from circular flows. For example, Consumer Intervention Mapping is a business-oriented tool, which can be used to identify opportunities to intervene at various moments in resource life cycles (Sinclair *et al.*, 2018). The Value Mapping Tool uses a collaborative method to conceptualise value and value propositions based on circular flows (Bocken *et al.*, 2013). Scholars have attempted to embed circularity within different phases of the business model development process (Bocken *et al.*, 2019). Although this may incentivise circular business models, these tools still only focus on parts of the flow, i.e., those that generate immediate value, such as increasing yield in the use phase. Beyond those parts of the flow, resources can still escape if they are no longer generating value in the business model, such as when it becomes too expensive to maintain them (Retamal, 2017). A focus on innovating in a business model alone may be insufficient to achieve fully circular solutions (Konietzko *et al.*, 2020b). Understanding environmental impacts or commercial implications of resource flows is valuable for CE design. Nevertheless, such understanding builds on the assumption that the resources will flow for the parts of the system investigated, instead of investigating if they will flow through the whole system. Therefore, it does not provide a holistic understanding of the system and thus limits the use of such methods for the purpose of CE design.

7.2.2. In-depth understanding of resource flow to evidence its success

For an in-depth understanding of the RFS, one can look at methods and tools that provide evidence for the success (or failure) of flowing resources. As resource flows entail a wide variety of processes that move and transform resources, it is logical that the methods to study them also vary and are process specific. For instance, a considerable number of tools is available for the processes controlled by manufacturers. Their focus often is on the physical implications on resources due to their movements and transformations. For example, Computer-Aided Design (CAD) software is used to understand the strains and stresses put on materials in production and on products in use contexts (Woldemichael and Hashim, 2011). Besides technical properties, elaborate studies can be conducted to on the sensorial properties of materials and products (Karana, 2009). Recently, the prediction of changing aesthetics in certain use conditions has been investigated (e.g., how resources resist certain processes) and proposed as a tool for manufacturers who wish to anticipate user attachment to aging resources (e.g., whether aged resources still succeed in processes) (Lilley *et al.*, 2019).

Another common approach is to focus on processes that are likely to disrupt the resource flow, such as through leakage or losses of resources. The Toyota Production System's methods to optimise production and achieve lean manufacturing practices with minimum losses (Womack *et al.*, 1992) has become popular with manufactures in different sectors. Lean manufacturing uses tools such as process flow diagrams to map processes and identify where losses occur. Manufacturers are not the only stakeholders benefiting from these methods, as stakeholders downstream in waste management are using variations to investigate material losses and inefficiencies in the handling of materials and waste (Kurdve *et al.*, 2015). There are also methods and tools focused on disrupted processes that revolve around human behaviour. For example, the Use2Use design toolkit allows designers to take a user perspective and design circular consumption behaviour that is convenient and preferable (Rexfelt and Selvefors, 2019). Other examples include triggers to encourage behaviours such as caring for products, which can lead to extended product lifetimes (Ackermann *et al.*, 2018). In general, a focus on disruptions provides an opportunity to optimise processes and design experiences to ensure that resources will continue their journey, such as the moment when resources become obsolete (Baxter, 2017; Choi *et al.*, 2018; Macleod, 2017; Zeeuw van der Laan and Aurisicchio, 2019a). A focus on losses and disruptions is valuable for a transition to the CE, however, a focus solely on these parts of flow is limited by a lack of holistic understanding of the RFS and risks to incorrectly identify the root causes.

Besides the support focused on the success and failure of resources in manufacturing and use processes, there are emerging and evolving methods and tools that focus on the ability of a resource to flow. This type of support can roughly be divided in two groups.

The first group includes guidelines for the physical design of products and selection of materials following the principles of a CE. Some suggestions include, for example, designing for disassembly and avoiding mixing materials (e.g., IDEO and EMF, 2016; Mestre and Cooper, 2017; Moreno *et al.*, 2016). Others relate to design and business modelling for the CE and focuses on extending the lifetime of resources through modular design or customisation for user attachment (Guldmann *et al.*, 2019a; Mugge, 2017). Further tools aim to assess the circularity of designs (European Commission, 2018c; Saidani *et al.*, 2017) although it is argued that the criteria behind such indicators are still poorly defined (Elia *et al.*, 2017). Such guidelines can indeed support designing products or business models for a CE. However, the outcome of the tool remains a prediction or a simulation of specific (sets of) processes which often must be simplified to be carried out. Although they help the uptake of circular principles, they are limited in their ability to provide evidence for why and how a process is likely to fail or succeed.

The second group includes information on materials and products that are part of resource flows. Designers typically rely on material databases that provide information on technical (Ashby and Johnson, 2002) and experiential material properties (Karana *et al.*, 2014). Nevertheless, the conventional data is not always sufficient to make sustainable design decisions (Sherwin and Evans, 1998). Newly proposed types of data on resources are supposedly more meaningful in relation to the flow. For example, more *topical information*, such as biographical information on materials, can be used to influence consumer experience (Bahrudin, 2019) or inform recovery processes (Chileshe *et al.*, 2019). Topical information on materials can be recorded in a material passport (Jensen and Remmen, 2017) or collective database (Rau and Oberhuber, 2016), although these systems are complex and require sector-wide adoption to be successful (Corbin *et al.*, 2018). Further, more *transparent information,* such as on the origins and compositions of resources, would allow one to assess the sourcing of materials and identify the flows of each substance (IDEO and EMF, 2016), for example, by organising materials on origin (Ayala-Garcia *et al.*, 2017) or presenting the recipes of materials that provide information on the availability of specific ingredients (Corbin and Garmulewicz, 2018). Finally, more *practical information*, such as establishing networks of stakeholders for recovered resources would allow to match materials vendors to buyers (Josefsson and Thuvander, 2020). Collecting and sharing these types of data on resources can support the design process and as a result influence the long-term ability of resources to flow. In addition, the data could potentially be used to evidence resource flows, at least once they are active. Nevertheless, besides the challenge of defining valuable types of data, accumulating and managing data over the entire resource flow is greatly complex and requires technological advancements. Unless they are used in quantitative simulations of resource flows, they do not provide sufficient depth in how and why.

7.3. Methods

This study involves the development and evaluation of a tool that enables users to obtain both holistic and in-depth understanding of an RFS. The main method is Participatory Action Research which entails cycles of action, i.e., prototypes of different iterations of the tool; and research evaluations, i.e., studies of individuals using prototypes (Blessing and Chakrabarti, 2009). This method allows to simultaneously constitute and elicit insights from users and researchers to inform the development throughout the project (Creswell, 2007; Spinuzzi, 2005). Participatory Action Research is a qualitative research inquiry in which participants engage in the research process to help find a suitable solution (Creswell *et al.*, 2007). Although the initial direction for the tool was set by the researchers based on earlier theoretical work (e.g., Chapter 6), user-participation markedly shaped the delivery and workflow of the tool, aligned and positioned it with current innovation processes in practice and helped translate future user needs and use scenarios to deliver meaningful outcomes of the tool. Close involvement of future users was made possible through the industrial collaboration with P&G – who granted access to facilities, training, and live projects – allowing a natural translation of company and stakeholder needs to tool requirements. Such deep industry-engagement in tool-development is important, as it can ensure a more successful uptake of the tool (Peters *et al.*, 2020). In this light, it is worth emphasising the use of the tool in consultancy work, allowing its application in a live and real-world project at P&G during the development process. This section describes the methods used to develop and evaluate the Flow Mapper in the period between December 2018 and May 2020.

7.3.1. Development

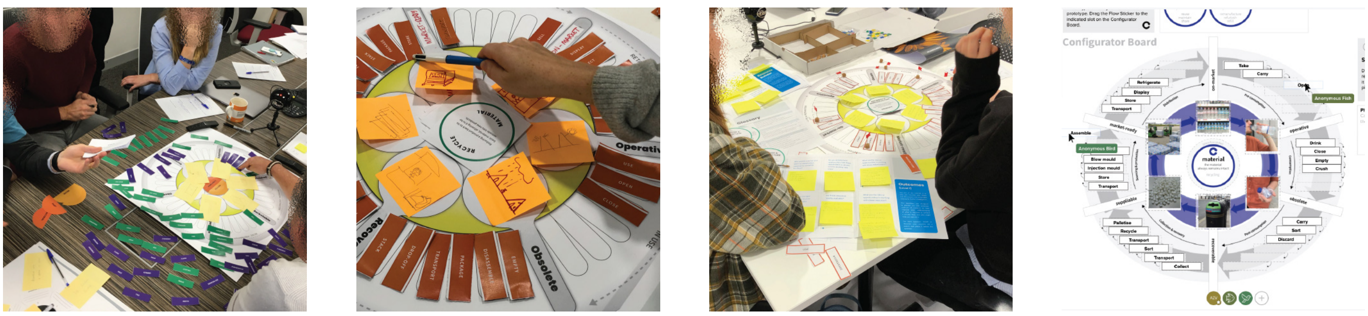
To deliver a tool that provides both a holistic and in-depth understanding required to focus on two main development areas, i.e., a method to model the RFS and a process to apply the modelling method and analyse it. Several iterations of the tool were prototyped, see Figure 7.1, which are structured in the following development stages: *pilot* – developing the initial modelling method and process to apply it (overlaps with the pilot focus group of Chapter 6); *stage 0.9* – developing the first applicable and tangible prototypes of the tool tested with end-users; and *stage 1.0* – developing the first digital prototypes tested in the consultancy project. An overview of development of the key components of the prototypes is available in Appendix C. In the remainder of this section, the approaches to the two main areas of development are detailed.

7.3.1.1. Modelling method

As this work was carried out partly in parallel with the previous chapter, the modelling method of the tool shares its fundamental principles with the method presented in Chapter 6. Nevertheless, the focus in the current chapter is to use the method in industrial contexts, which accentuates the importance of the feasibility of applying the method. Applying the method can be challenging as there is no single owner of the RFS, even though numerous stakeholders have an interest in its parts. Defining a system based on stakeholder objectives is likely to be the more intuitive approach to applying a tool (Buede, 2009; Charnley *et al.*, 2011) but the RFS is defined based on its overall function 'to flow resources' – a statement that describes what the system does, or is intended to do (Burge, 2006; Maier and Fadel, 2009; Ullman, 2016). A functional approach can lead to a broader and more inclusive set of boundaries (Halbe *et al.*, 2014) and, aligning with Chapter 6, can be used to define the RFS and identify its structure.

As they flow, resources physically *transform*, for example, from materials to components or products (Blomsma and Tennant, 2020), and physically *move*, for example, between locations or between stakeholders. Resources, thus, take the form of materials, components, or products, but remain in the same journey (a single loop (Stahel, 2019)). This research focuses on RFSs that produce a flow that is a *continuously closed loop*, i.e., the journey is immediately and continuously repeated after completion. A continuous closed-loop flow does not guarantee eternal life to resources, for example because materials will gradually degrade or components can wear. However, it aims to use resources at their highest utility for an extended period. The

Figure 7.1 Iterations of the tool in development.



version 0.9.2 *version 0.9.3* *version 0.9.4* *version 1.0.2*

method models one such journey to the level of one product, by overlaying two models of the RFS.

First, a State Model, which can be used to represent the states of interest (Gedell *et al.*, 2011). Rather than by their physical form, resources can be characterised by more subtle changes such as from an 'in-use' to an 'obsolete' state. Resources are, therefore, expected to be in a certain state at a certain time. This work defines a 'resource state' as the conditions and way of being of a resource at a particular moment in the flow. A resource state, thus, represents what a system produces, or in other words: what its effects are on flowing resources at specific moments in time. A State Model can be used to investigate the transition from one resource state to the next. Resource states are descriptively expressed textually or visually through 'snapshots' that describe the resource and characterising context, for example, an emptied resource that is crumpled up and left in a household recycling bin in a kitchen.

Second, a Functional Model, which can be used to break down the overall function of a system into smaller subfunctions required to deliver the overall function (Stone and Wood, 2000). This provides a comprehensive description of a system without reference to its elements (Kasser and Mackley, 2008). Different RFSs can move and transform resources in the same way and produce the same closed-loop continuous resource flow, even though their elements and enabling structures can be significantly different (see Chapter 6). Therefore, the Functional Model is used to describe what the system has to do to deliver the overall function. Functions are processes that require turn a certain input into a certain output (Burge, 2006; Maier and Fadel, 2009; Pahl *et al.*, 2007), which are interpreted here as the movements and transformations of resources as processes that are subfunctions deduced from the overall function (Burge, 2011), i.e., 'to flow resources'. The modelling method builds on the formalism of a function structure, which uses a flowchart in which subfunctions are connected by flows of matter, energy, or signals to capture a network of functional relationships (Aurisicchio *et al.*, 2012; Pahl *et al.*, 2007). Functions are expressed as verb-noun structures in which the verb represents a process and the noun represents the resource (Stone and Wood, 2000). For example, *transport* products or *sort* materials.

By overlaying the two models a high-level view of the flow produced by the RFS can easily be visualised through the State Model, which is detailed by adding the processes that explain the transitions between states describing exactly what the RFS does to cause the movements and transformations of resources in the Functional Model. As a result, the method delivers a visual and descriptive model of a single journey to the level of consumer use of the product.

7.3.1.2. Processes to apply the modelling method and analyse the model

The second development area involves the processes 1) to apply the modelling method, i.e., enabling users to model the RFS to obtain a holistic understanding; and 2) to analyse the model, i.e., obtaining deeper understanding of the RFS and translating this into meaningful outcomes. The processes were developed based on, insights into the needs of future users which were obtained through testing prototypes with future industrial users, young and experienced designers, as well as through interviews and discussions with P&G.

Applying the modelling method

To develop a comprehensive model of a complex system, such as the RFS, different stakeholder perspectives as well as expertise from multiple domains are needed (Charnley *et al.*, 2011; Miser and Quade, 1985). Sector-wide and multi-disciplinary stakeholders in the FMCG sector are expected to have relevant insights to the RFS. For example, a process engineer of a Material Recovery Facility MRF can provide technical insights into the EOL stage of the flow, whereas the brand manager of a multinational FMCG company brings insight into consumer demands. Therefore, the process to apply the modelling method must enable multi-disciplinary users to share their expertise and model the RFS collaboratively.

To facilitate such collaboration, first, the process of applying the method was turned into a pragmatic exercise using the analogy of a puzzle with a presumed ultimate solution to flow resources. Resource states and functions can be seen as 'pieces of the puzzle' that need to be put together to model the RFS. Templates and movable parts were developed to make the modelling method applicable and easy to use. First, the puzzle analogy was reinforced using a template resembling a game board as the base for the model. Second, entry barriers for using the tool were reduced by minimising preparation activities and training through self-guided step-by-step instructions. Reducing such entry barriers eliminates the need for specialist facilitators, making the tool more accessible. Third, language was adopted that is understandable to different stakeholders, acknowledging that different domains use different terminologies (Hughes, 1987). In addition, it cannot be expected that all users are CE experts, putting emphasis on the need to develop a language and instructions suitable for all levels. Finally, the collaborative interaction between stakeholders was developed to be effective and efficient by limiting the duration of multi-stakeholder collaboration to 60–90 minutes and minimising the need for a facilitator. Human-to-human interaction was prioritised to allow for immediate decision-making and avoid the need to chase team members for answers which could delay the modelling process.

Analysing the model

The model was developed to provide stakeholders with a means to analyse an RFS and develop insights that can support the design (or optimisation) of products and systems for the CE. These insights can be derived from the RFS' ability to flow resources. Such support can be useful in the early and later stages of the design process, namely, in the ideation phase (e.g., when exploring circular business models and new partnerships for novel or pre-existing products), in the prototyping phase (e.g., when redesigning a product to use pre-existing recycling infrastructure), and in the evaluation phase (e.g., when implementing new product-system solutions and measuring their effectiveness). The development was iterative and explorative, using user insights to identify and trial the usefulness of the tool to different design objectives.

Delivering outcomes that are relatable and actionable results for industrial users was set as a key aim. To achieve this, first, the process was designed to visualise the RFS' model. Visual models provide valuable means of communication, especially in collaborations (Eppler and Bresciani, 2013). Second, System Dynamics theory was integrated to develop an understanding of system causalities and deliver deeper insights into the RFSs. Where the State Model provides representations of the resources (e.g., in a cupboard), the Functional Model describes what the system does (e.g., save up resources). The two models together enable users to first comprehend how flowing resources are changing in the course of the flow; and then to reason why and how the system does what it does. In other words, what causes the system to operate in this way. For example, to save up resources, a location is needed with capacity for a certain volume of resources but also a motivation for consumers to save up the resources. Third, a means to translate insights into actions for change was proposed. The final steps of the analysis provide users with practical insights into the structure of the system that delivers the overall function. These insights can be used to set design targets, for example, to explore the incentives that motivate consumers to store resources. Finally, compatibility of the tool with pre-existing (industrial) design processes and conventional tools was considered. The FMCG sector is currently linear, and despite the emergence of circular solutions, industrial innovation processes have not evolved to embed circular design needs. Although this study did not aim to replace existing tools or established processes, it did aim to provide additional support to users to understand the entire RFS. The outcomes of the tool may be suitable to support and improve the use of established tools, for example, reducing the uncertainties in LCA studies.

7.3.2. Evaluation

During its development the iterations of the tool were evaluated based on the qualitative analysis of data collected during interactive sessions. The purpose of these evaluations was, first, to support the development of the tool (i.e., formative evaluation); and second, to assess whether the tool was able to support the delivery of solutions for the CE and satisfy our future users' strategic needs (i.e., summative evaluation). This section describes how data were collected and analysed to support the evaluation of the tool.

7.3.2.1. Data collection

To gather data to support the evaluations of the Flow Mapper the tool was used in simulations and workshops, see Table 7.1. Simulations are brief interactive demonstrations of the tool oriented at discussion to gather feedback. Workshops involve the completion of the entire Flow Mapper process by a group of users for a case study. The two differ in terms of time required to prepare and execute as well as the type of insights that can be obtained and their purpose.

Table 7.1 Development stages, versions of the Flow Mapper, and formal evaluations.

Development stage	Main features	Version	Evaluation	Company involvement
Pilot	• Method for collaborative modelling • State Model and Functional Model • Capture emerging elements	*(pilot)*	Workshop 1	
0.9 -	• Physical playboard (Configurator Board) as a template for the model, embedding slots for resource states (Snapshots) and functions (Process Cards) • Workflow to model the system through timed and written instructions	*0.9.1*	Simulation	yes
		0.9.2	Simulation	
			Workshop 2	yes
		0.9.3	Workshop 3	
		0.9.4	Workshop 4	
			Simulation	yes
			Simulation	yes
			Simulation	yes
1.0	• Workflow simplified in three phases • Refined process to analyse the model • Digital playboard using Mural as an online collaborative space	*1.0.1*	Simulation	
			Workshop 5	
		1.0.2	Workshop 6	yes

Simulations

Simulations involved demonstrations of the tool using prototypes and PowerPoint presentations (Figure 7.2). Simulations typically engaged 1–3 participants in a brief and interactive setting, encouraging interruption and discussion by the participants. Illustrative cases were used to (partly) populate the tool to accelerate the process of creating a model, demonstrating the effectiveness of the form of the tool, and explaining the process. Simulations were used, firstly, internally with colleagues to review the iterations and stress test (parts of) the process; and, secondly, to receive feedback from individuals employed by P&G working in R&D and commercial departments. The latter provided an opportunity for future users and decisionmakers to review and critique the tool and help prioritise avenues for development (Mackenzie *et al.*, 2012). The main advantage of simulations over workshops is that they were quick to organise and easy to participate in. Notes were kept during the sessions and this data was analysed. The discussions were particularly useful to guide the strategic development of the outcome of the tool and meet the needs and interests of future users (Baum *et al.*, 2006; Creswell *et al.*, 2007; Mackenzie *et al.*, 2012).

Figure 7.2 The tool version 0.9.4 used in a simulation for a company.

Workshops

Workshops are believed to be an effective method because they allow close collaboration with future users (Peters *et al.*, 2020). In the workshops, groups of users applied the tool to a case (Table 7.2) following the instructions to the Flow Mapper process. Besides the real-world case part of consultancy work, all other cases were illustrative and the brief was provided by the researcher. Cases focused on a single specific resource, for example, an aluminium drink can; and one specific RFS defined by its service (e.g., recycling or reuse) and a single use scenario, for example, household recycling in the United Kingdom. The RFSs in the cases were either pre-existing (e.g., household recycling of conventional items), partly pre-existing (e.g., household recycling of non-conventional items), or entirely novel (e.g., new collection services).

Each workshop engaged 2-6 participants. Participants were identified and recruited first based on a variety of knowledge domains (e.g., technical and commercial) related to the case, and second based on their industrial experience and CE expertise. In the case of company employees, the company proposed eligible and available participants, which were confirmed by the researcher. Workshops took 60–90 minutes, excluding preparation activities, either prior or during the session, which were kept to a minimum burden for participants. All workshops were prepared and organised by the researchers but active guiding and facilitation during sessions were kept to a minimum to evaluate the potential and value of self-guidance. In the consultancy work, the researchers took a more active and participating role and contributed to the case with CE expertise.

Data were collected during and after each workshop using a variety of qualitative methods (Table 7.2) depending on what was permitted, feasible, and suitable for each workshop (Creswell, 2007; Robson, 2011). Notes were kept by the researchers of their observations and the encouraged discussion during and after each workshop. Further, interviews provided insights into the experiences of users and project leads and provided opportunity to identify avenues for further development (Mackenzie *et al.*, 2012). In some of the workshops, quantitative data was collected through 5-point Likert scales in a survey, asking users to rate specific aspects of the Flow Mapper, see the example in Appendix D).

7.3.2.2. Data analysis and evaluation

All data was analysed to support two levels of evaluation: usability and usefulness, see Table 7.3. Usability is often evaluated in system development and human-computer interaction (Hartson *et al.*, 2003; Hornbæk, 2010; Lindgaard, 2014). Usability is also a common focus in product design; it is used to discuss how easy it is to use something (Mugge and Schoormans, 2012). Here, the term is used to evaluate how easy it is to use the tool. This level of evaluation concerned, first, the modelling method, i.e., *whether it was feasible to develop a model of the RFS with the tool* – for example, whether the tool could be used to develop a state and Functional Model of the RFS. Second, the process to apply the method, focusing on

Table 7.2 Overview of the workshops and the data collected in the workshop.

		Workshop 1	Workshop 2	Workshop 3	Workshop 4	Workshop 5	Workshop 6
Case	*Version*	**Pilot**	**0.0.2**	**0.0.3**	**0.0.4**	**1.0.1**	**1.0.2**
	Type	Illustrative	Illustrative	Illustrative	Illustrative	Illustrative	Real world
	Resource	Biodegradable bottles	Double-edge razor blade	Cardboard tent	PET water bottle	Aluminium soda can	(confidential)
	Service	Collection for biodegradation	Household recycling	Reusing cardboard	Private collection for recycling	Household recycling	(confidential)
	RFS novelty	Pre-existing	Partly pre-existing	Novel	Novel	Pre-existing	Pre-existing + Partly pre-existing
Participants	*Who*	DE researchers	Company employees	Research group	UG students	Department peers	Company employees*
	No of participants	3	5	3	2	5	6 (+2)
	CE expertise	High	Medium	High	Medium	High	Low
	Industrial experience	Medium	High	Medium	Low	Low	High
	Knowledge domains	Chemist Design	Design Engineering Manufacturing	Design Engineering	Design	Design Social Manufacturing	Design Engnieering Marketing Manufacturing Recycling
Data	*Observation*	X	X	X	X	X	X
	Recording	X	X		X	X	
	Workshop material	X	X	X	X	X	X
	Surveys		X			X	X
	Participant feedback	X	X	X	X	X	
	Company feedback		X				X

Table 7.3 Tool evaluation levels.

Development area	Evaluation level		
Modelling method		Usability	• Is it feasible to develop a model of the RFS?
Process	To apply the modelling method		• Does the tool enable collaboration between multi-disciplinary stakeholders?
			• Is the tool pragmatic?
			• Is the tool accessible to future users?
	To translate the model into meaningful outcomes	Usefulness	• What makes the outcome of the tool meaningful in practice?

three areas: *whether the tool enables collaboration*, such as if users engaged with each other and how they contributed; *whether the tool was pragmatic*, such as whether the process was logical and manageable, and *whether the form and instructions were effective*; and whether the tool was accessible to future users, such as whether there were barriers for preparation, training, or translation of outcomes. Usefulness can be interpreted as the effectiveness or value that the tool can deliver. This level of evaluation focused on the value of the outcome of the tool. The outcome entails both the model of the RFS as well as the insights that users develop during its analysis. Valuable outcomes support the designs of products and systems for the CE. The evaluation concerned with *what makes the outcome of the tool meaningful for CE projects*, such as whether the outcome provided a holistic view, depth, and new insights; and how the tool can best support CE development in the industry.

The two levels were used to organise the data to be analysed. The various types of data supported the evaluation in different ways. Simulation notes could be translated into action points and, in the case of company participants, provide insights into the usefulness of the tool. The different types of data collected in workshops (Table 7.2) were of great value to the evaluation. Observations are considered one of the most common methods to evaluate tools (Peters *et al.*, 2020), and they were the main source of data for the evaluations. All workshops were observed by at least two researchers, who took notes during and after the workshop and compared them afterwards. With the consent of participants, workshops were audio-recorded. The recordings were used to deepen the insights of observations (McKechnie, 2000; Modaff and Modaff, 2010), for example, by revisiting certain discussions and evaluating the modelling process. The recordings were also used to review when and whether the process produced outcomes through discussion. For example, the recording of Workshop 1 was replayed to investigate when the first system elements emerged. Workshop material involved photographs (version 0.9) which provided a means of evaluating interactions and different steps in the modelling process; and exports of digital templates, which provided a means to evaluate the model in terms of quality, depth, and coherence. Surveys were used to gauge the experiences of individual users and their experience as a group (Konietzko *et al.*, 2020b; Robson, 2011). The survey questions evolved between workshops and focused specific Flow Mapper aspects, providing insights for both usability and usefulness. Further participant feedback was gathered through discussions during and immediately after the workshop sessions. These discussions provided an opportunity for participants to leverage and challenge each other's experiences and evaluations (Robson, 2011; Sharken Simon, 1999) and to empower participants to influence the development of the tool (Baum *et al.*, 2006). Finally, company feedback was obtained through interviews with the project lead(s) after the workshops. Rather than insights into individual user experiences, this provided insights into the acceptance of the process, value of the analysis and overall usefulness of the tool.

The analysis of each workshop involved three step-process, with the analysis per workshop captured in a session report, see Appendix D for an example. First, the report was drafted to include an overview of its setup and the available data. Details of the setup included descriptions of the case, the workshop aim (i.e., specific focus points and expectations of participants), facilitation (i.e., who was present and what their role was), and planning (i.e., time allocated to each part of the tool process). Further, the report listed all the types of data collected as well as survey results and workshop material. Second, the workshop was reviewed chronologically, structuring and consolidating all data against the Flow Mapper process and the preparation activities for participants. All activities were broken down into steps and outlined in a table serving as a timeline, allowing to map the data against each step to get a complete and comprehensive analysis of each step. For example, participant experiences emerging in the post-session discussion were aligned with the observations of certain steps, allowing us to strengthen these insights. Insights that indicated a concern about usability or usefulness were highlighted (e.g., an insight into participants' struggles or confusion); and insights that suggested an improvement to the tool, (e.g., suggestions to change the language and workflow). Third, to finalise the analysis of each workshop the insights were clustered into themes that concerned specific aspects of the tool. The themes emerged based on the reoccurrence of topics in our insights (Saldaña, 2013) and could be related to usability and usefulness. As the development of the tool was iterative, the themes evolved along the overall process.

Table 7.4 Summary of the themes and how they were related to the levels of evaluation.

Tool aspect	**Theme**	**Usability**				**Usefulness**
		Feasibility	*Collaboration*	*Pragmatic*	*Accessibility*	
Form (i.e., design and delivery of the tool)	*Templates*	•		•		•
	Language				•	•
	Instructions & facilitation	•	•		•	•
	Mural			•	•	
	Time	•			•	
	Interaction		•	•		•
	Skills and expertise	•	•	•		•
Process (i.e., overall workflow)	*Getting started*	•	•		•	•
	Case specification	•	•	•		
	State Model			•		•
	Functional Model	•				•
	System elements	•	•	•		
Outcome (i.e., result of using the tool).	*Analysis*	•	•	•	•	•
	Model		•	•		•
	Skill development					•

Table 7.5 Examples of formative evaluations used to develop the State Model.

	Tool	Formative evaluation	Suggested aspects to change
Workshop 1 (pilot)	• Users were given abstract descriptions of six resource states and tasked with finding snapshots individually prior to the session	• The definitions and exercise were very abstract, which made the exercise confusing • After comparing and discussing the states together, they became clearer to participants	• Integrate the identification and development of states into the process • Encourage the description of context in resource states
Workshop 2 (0.9.2)	• Resource states were introduced as snapshots positioned chronologically on a template • Labelled sections between snapshots. • Included definitions of snapshots. • Integrated taking snapshots into the overall process	• The snapshots gave users a clear sense of the chronology and narrative • The definitions of the snapshots could be interpreted in different ways • It was not always possible to include context if snapshots were sketched	• Clarify the definitions of snapshots and labels
Workshop 5 (1.0.1)	• Introduced image search bank in Mural • Clarified definitions	• Users who had used snapshots before could explain to the other users how this works • The online version allowed the use of images rather than sketches, which enriched the State Model	• Include an example of each snapshot in the template

Lastly, the evaluation of the Flow Mapper entailed a comparison of the workshop analyses. Organised per theme, the comparison allowed to evaluate the effect of the iterations in development on the Flow Mapper and its outcomes. The themes were used to evaluate the tool on the different two evaluation levels, as presented in Table 7.4, using two types of evaluations. First, formative evaluations were used to produce empirically based interpretations of the data, which were then used to identify actions to improve the tool (Venable *et al.*, 2016). Examples of the use of formative evaluations are presented in Table 7.5. Formative evaluation is important to develop an understanding of the effectiveness of the tool in practice (Stetler *et al.*, 2006). The formative evaluation focused predominantly on aspects of usability that were addressed in the different iterations during development (Hartson *et al.*, 2003) and to measure improvement as development progressed (Venable *et al.*, 2016). Second, summative evaluations were used to produce empirically based interpretations to understand the value of the tool and its outcome (Venable *et al.*, 2016), specifically in the context of use in the FMCG sector. This method of evaluation focuses on the efficacy of the tool in terms of its usability and compared to initial use scenarios (Hartson *et al.*, 2003). Summative evaluations were more exploratory and open-ended (Robson, 2011) and provided deeper insights into the usefulness of the tool. Exploratory evaluations can help identify focus areas and review the effectiveness of programmes or processes (Wholey, 2010). This supports the use of summative evaluation to assess the positioning of the tool in relation to the needs of future users (Wholey, 1996). As such, the summative evaluations were used to understand how and in which context the tool is best able to support the FMCG sector in designing for the CE.

7.4. Introducing the Flow Mapper 1.0

The Flow Mapper 1.0 involves a method to model the RFS as well as the process to apply the method and analyse the model. The process is collaborative and aims to provide users with both a holistic view and in-depth understanding of the RFS. This section describes the philosophy of the tool, and provides a demonstration through a case study.

7.4.1. The Flow Mapper philosophy

During its development and evaluation, the philosophy for the Flow Mapper evolved. The philosophy outlined here describes the main principles incorporated in this version of the tool and how it aims to achieve them. The Flow Mapper:

1) models an RFS, which is a system defined by the closed-loop resource flow of a single resource (i.e., one product) rather than by the objectives of individual users.

2) interprets the flow of resources as the overall function of the system, which can be broken down into subfunctions that describe the physical movements and transformations of resources.

3) captures knowledge about the system across domains, which is obtained through multi-disciplinary collaboration with sector-wide users, such as design, marketing, manufacturing, logistics, waste management and legislators.

4) produces a visual and easy-to-interpret model, which characterises the states of resources at key moments; uses simple descriptions of movements and transformations of resources that flow entails.

5) self-guides teams of users through a manageable process of modelling and analysis, which uses instructions to first develop a high-level model by specifying the system boundaries and type of flow. Next, the team develops a detailed model, which visualises the resource states and describes the flow. Finally, the model is used to provide deeper insights on key system elements. Any language used in the tool can be understood by all knowledge domains and levels of CE expertise

6) is accessible to industrial users, which is achieved by minimal preparation activities, a self-guided process, a brief interactive use session (maximum ninety minutes), no training activities, no CE knowledge requirements and outcomes that can be actioned directly.

7) supports the design of products and systems for the CE, which is delivered through the translation of CE theory into practical support that enables users to develop a holistic view of the RFS.

7.4.2. Demonstration of the Flow Mapper

The Flow Mapper process involves six steps in three phases, see Table 7.6. During the process, the user interacts with templates that serve as a canvas for the modelling and analysis of the RFS; and moveable parts that are used to develop the model, see Table 7.6. The Flow Mapper 1.0 is used in Mural, which is a digital workspace for visual and interactive collaboration that allows users to work both remotely and simultaneously. The remainder of this section describes and demonstrates the steps through a case study. The case study involves an aluminium drink can recycled through household recycling in the United Kingdom (UK). A version of the case study in the Flow Mapper is available in Appendix E.

Table 7.6 Six key steps of the Flow Mapper, supported by templates and moveable parts.

Phase		Step	Movable parts	Templates
Preparatory	1	*Specify the resource*		Resource Specification Sheet
	2	*Pick a flow*	Flow Stickers	Configurator Board
Modelling	3	*Take Snapshots*	Snapshots	
	4	*Map that flow*	Process Cards	
Action	5	*Pivotal processes*	Pivotal Markers	
	6	*Risks and opportunities*		Analysis Matrix

7.4.2.1. Phase I: Preparatory

In the first phase, the aim is to align the users on a (partly) pre-existing or novel RFS based on a single resource. Aligning users is important because the users may have different perspectives and understandings of an RFS. Users in the workshops sometimes assumed that certain parts of the system were self-evident. For example, this occurred if users were invited to participate based on their expertise related to aspects of the case but were not engaged in the overall project or aware of the overall aims of the project. Therefore, the purpose of the preparatory phase is to bring the team's focus to one system.

Step 1 – Specify the resource

In the first step, the users specify the case based on what they already know, decide or assume about the system. The objective of this step is to align on the case to model and analyse. Such alignment ensures focus on collaborative thinking on the same RFS, rather than variations of existing systems (e.g., a system of on-the-go or household recycling, communal bins or kerbside collection) or uncertainties on novel systems (e.g., collecting a new recyclable product through conventional recycling programmes).

To execute this step, the template ***Resource Specification Sheet*** is used. The template, see Figure 7.3, consists of a set of questions on the resource, the consumer and the context of consumption. In early versions, the questions revolved around the resource only but it was found that this limited users when developing a shared understanding of an RFS. Further, the questions evolved for multiple reasons. First, to encourage users to define the resource as tangible matter and consider that it can take the shape of a product (e.g., Can of Coca Cola), component (e.g., can) and material (e.g., aluminium) at different moments in the flow. Second, to enable users to further scope the RFS by specifying the user and use context. The questions are directive to elicit useful system specifics while allowing for open and descriptive answers to facilitate different levels of uncertainty, which is needed to enable users to specify both pre-existing and novel systems. The case study, for example, specified that the consumer buys large quantities of the drink and consumes the resource at home. Although there is no explicit mention of household recycling, the notion of consumption at home reduces the options, as it reduces the ambiguity of how and where the drink is consumed.

Step 2 – Pick a flow

In the second step, the users select the type of resource flow. The objective of this step is to further align users on the resource flow, which is essential because it defines the RFS. At this stage there could be uncertainties around the exact details of the flow and the system, therefore, this step entails a high-level decision based on the lowest utility that the resource obtains in the flow i.e., a flow that preserves materials, components or products. As such, it is the first step in which users position the function 'to flow resources' as the function of the

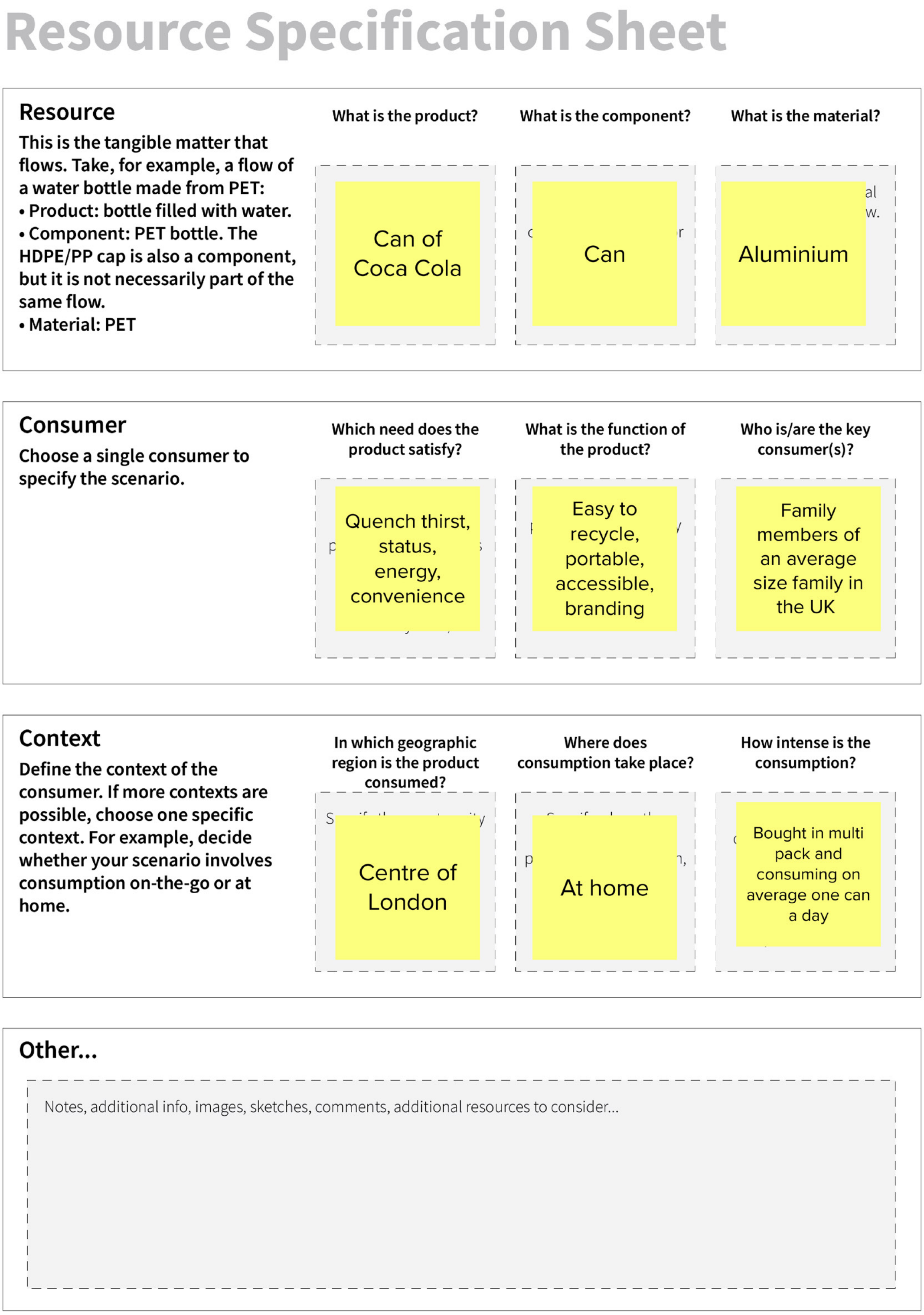


Figure 7.3 The Resource Specification Sheet completed for the case study.

system, encouraging them to prioritise the movements and transformations of resources over other objectives of the system or subsystems.

To execute Step 2, users are provided with ***Flow Stickers***, see Figure 7.4. Initially, circular strategies were used to imply different type of flows, i.e., 'maintain/prolong', 'reuse/redistribute', 'refurbish/remanufacture' and 'recycle' (EMF, 2015). Nevertheless, it appeared these led to confusion as users interpreted them in different ways. This commonly led to discussion on the meaning of circular strategies, rather than their implications. In particular for users with less CE

Figure 7.4 Flow Stickers.

knowledge, it seemed difficult to distinguish between strategies, such as remanufacture versus refurbish. Flow Stickers, therefore, present a simplified typology of resource flows based on their utility, i.e., materials, components and products. This liberates users from ambiguity of strategies and emphasises their focus on the actual physical resource flow. Common circular strategies for each utility level were prompted on the stickers for reference only.

7.4.3. Phase II: Modelling

The aim of Phase II is to model the RFS. System thinking and modelling, especially collaboratively and with multi-disciplinary teams, is complex (De Haan and De Heer, 2017; Miser and Quade, 1985). To ease and simplify the process it is broken down in two steps gradually taking users into depth. Users start with modelling a visual representation of the RFS i.e., the State Model, which is followed by a detailed description of the RFS in the form of a Functional Model. Together, the two models provide both high-level and in-depth understanding of the system. The basis for the model is the Flow Mapper's ***Configurator Board*** (see Figure 7.5.), which serves as the canvas for the model of the RFS. Using a circular shape for the flow, the

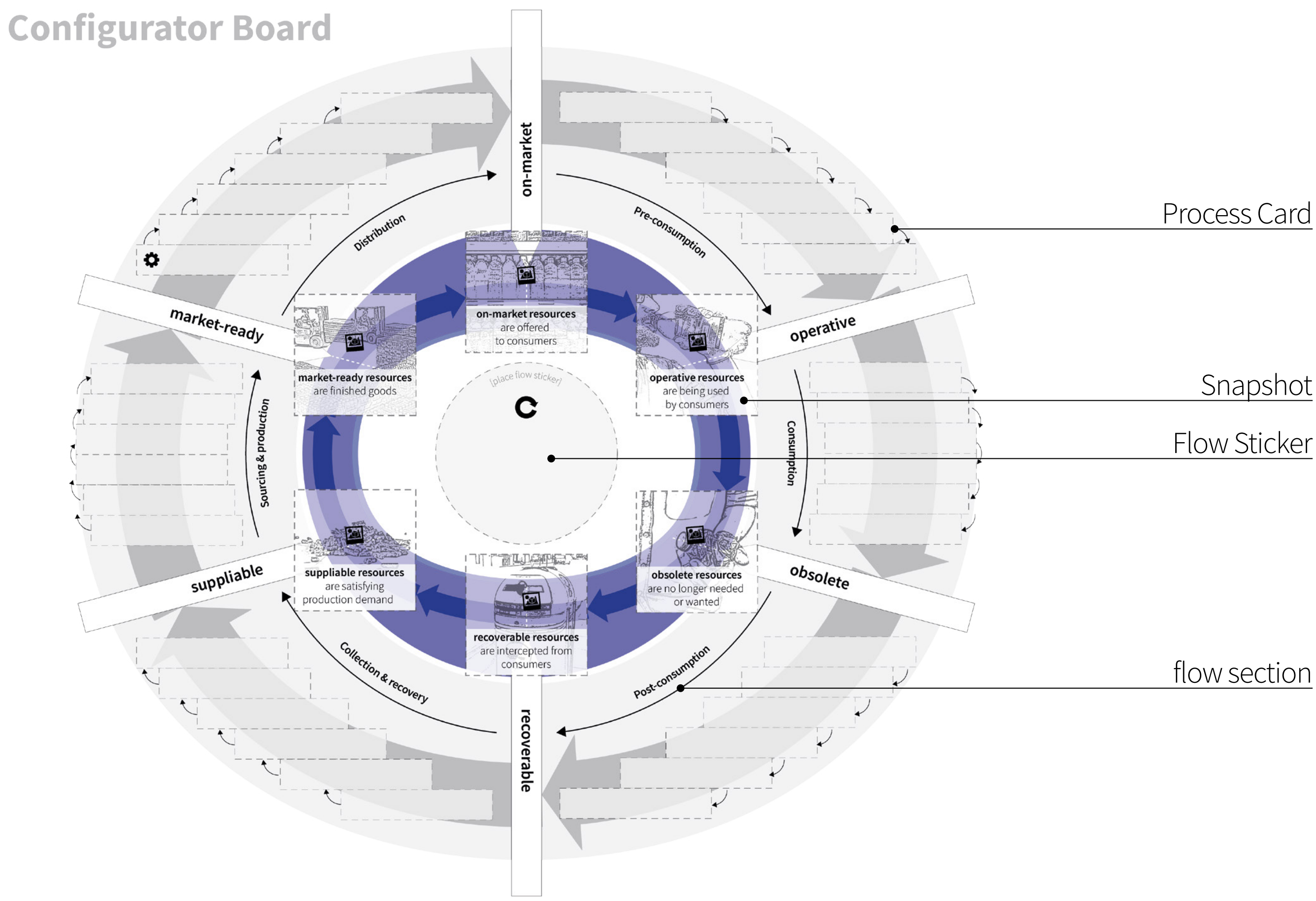


Figure 7.5 The Configurator Board, with indication of the key components.

template emphasises the objective to continuously flow resources in identical closed loops. Users start modelling in the centre Configurator Board and work outwards to add detail. The first ring's slot is reserved for the Flow Sticker; the second ring has six slots for the State Model; and the third ring is used for the Functional Model. The slots in the State Model are labelled with definitions and examples to chronologically place Snapshots. There are six slots for the Functional Model between two Snapshots, which are labelled with common supply chain terminology for reference. These cues with recognisable terminology and highly simplified modelling steps enabled users to model the RFS quickly.

Step 3 – Take Snapshots

The visual representation, i.e., the State Model, represents the RFS based on a visualisation of the resources in the flow at key moments of interest. By modelling the states of the resource, users produce an initial high-resolution model of the resource flow, broken down into manageable and meaningful sections. The resource states presented on the Configurator Board in the tool emerged in previous work, see Chapter 5 and Chapter 6. At first, users were confused by the meaning of individual ***Snapshots***, therefore, labels, definitions, illustrative examples and supply chain sections between Snapshots were introduced. The final definitions of each Snapshot in the Configurator Board (see Figure 7.5) aim to be applicable to a resource as a material, component and product. The states consider an equal balance between the conventional back-end supply chain (i.e., recoverable, suppliable and market-ready resources) and the consumer-facing front-end of the flow (i.e., on-market, operative and obsolete resources). In addition, they are defined as.

To execute this step, users turn to the Configurator Board to place Snapshots, see Figure 7.6. The term Snapshots is used to define visual characterisations of the same resource at different moments in the flow. Snapshots are movable parts created by users, such as using a sketch, description or image of the resource in its context at a specific moment in time. Mural has an integrated image search bank, which simplified the process of finding and adding images to the Configurator Board. This proved to be helpful, as using images as Snapshots seemed more effective method to characterise resources compared to verbal descriptions or sketches.

Step 4 – Map that flow

Next, the Functional Model describes resource movements and transformations of the. In this step, the aim is to express these movements and transformations as functions and organise them in a Function Structure-like representation, specifying what the system does to resources. A Functional Model can combine multiple knowledge domains and envision different solutions to satisfy the function (Pahl *et al.*, 2007; Stone and Wood, 2000). The formalism of the Function Structure is to use boxes for functions and arrows to indicate materials, energy and information inputs and outputs to the function. In line with the method in Chapter 6, this formalism was used to develop an informal modelling method, devising a representation where the inputs and outputs of all functions are (material) 'resources'. All functions, i.e., the processes that move and transform resources, are expressed as verbs only and the resource is always the recipient of functions.

To execute this step, users turn to the Configurator Board to place ***Process Cards***. Each Process Card contains a verb, which defines a process that describes the physical movement

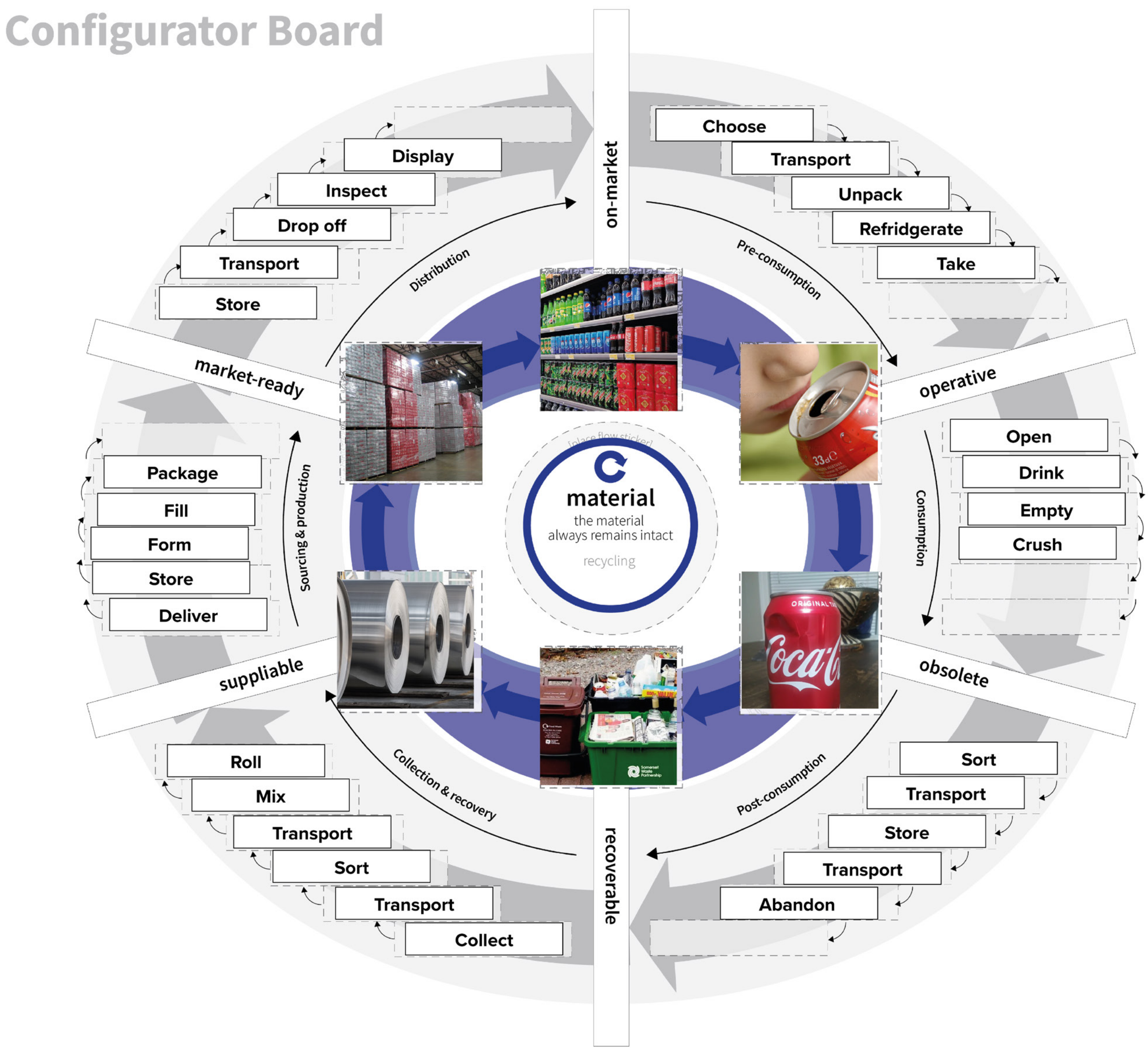


Figure 7.6 Configurator Board completed for the case study.

of resources, such as 'transport' or 'drop-off', and/or the transformation of resources, such as 'assemble' or 'save up'. Users must position cards in chronological order on the Configurator Board, see Figure 7.6. Initially, Function Definitions from Hirtz *et al.* (2002) were adopted to develop an extensive (130) set of example functions to describe the flow. However, the high number of examples seemed to confuse users, as they were inclined to look for 'the right one' or wanted to use all the cards provided. The extensive set also led to a discussion on the meaning of similar functions, rather than a discussion on which functions applied to their case. Therefore, the number of pre-filled cards was reduced, eventually using only a selection (15) that most commonly occurred in workshops, accompanied by blank cards to encourage the use of custom processes.

7.4.4. Phase III: Action

The final phase involves a qualitative analysis of the model and translating this into a meaningful outcome. Understanding generated during the modelling as well as the model itself are the input for this analysis. As the Flow Mapper aims to support the design for the CE, the outcome aims to inform design decisions.

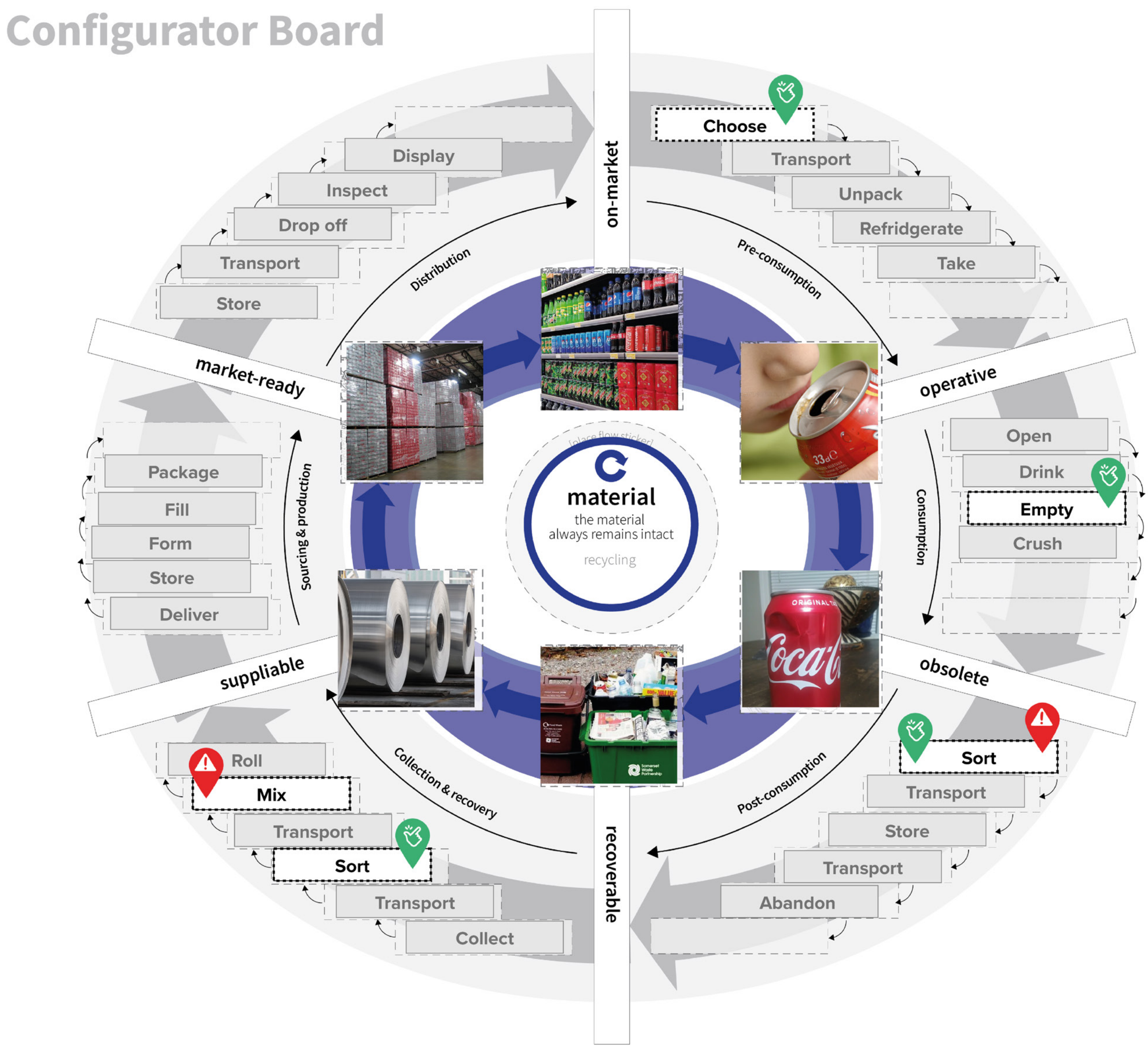


Figure 7.7 Configurator Board completed with Pivotal processes for the case study.

Step 5 – Pivotal processes

First, users are encouraged to prioritise specific parts of the RFS for a deeper analysis by selecting Pivotal Processes. Pivotal processes are those that stand out either because they are not satisfied or they are satisfied exceptionally well. Knowing where resources fail or succeed enables users to identify the most critical parts of the system. Whether to focus on success or failure depends on the overall project aims of the users.

Pivotal Markers are used to indicate pivotal processes, i.e., red markers to indicate a failing process and green markers to indicate a successful process. Since all processes represent physical movements and the transformation of resources, they can be interpreted as effects on resources that are caused by the dynamics of the RFS. Such effects of processes on resources can be identified visually the State Model. Users refer to these effects to assess and discuss the model and identify the pivotal processes. For the Coke can in Figure 7.7, for example, the process to 'empty' the resource is deemed pivotal, as emptying a can will undoubtedly be successful and serves as a cue for users to discard the can. In contrast, the process to 'sort' the resource post-consumption may fail, for example, if consumers decide not to recycle or do not have access to a recycling bin.

Step 6 – Risks and opportunities

Finally, users focus on pivotal processes for a deeper analysis, eventually identifying risks and opportunities for the RFS. Users are invited to consider that each process has certain effects on the resources, which encourages them to reason the structure of the system that is (or needs to be) in place to satisfy processes. Therefore, the structure of the system, i.e., its elements and their interconnections, should be interpreted as causalities (Forrester, 1968a; Meadows, 2008). Specifically, the causalities to pivotal processes provide insights on the failure or success of a resource flow. By discussing the causalities of failure and success in the RFS, critical system elements will emerge and become evident. Users main task is to objective these elements, highlighting the key elements that inform their design choices.

The basis of this step is the ***Analysis Matrix***. The pivotal processes are copied into the matrix. First, users copy the pivotal processes into the matrix and refine each of their scopes, see Figure 7.8. Focusing on a single process can be seen as scoping a subsystem of the RFS, and refining its scope helps to align the team. Second, users discuss what makes the processes fail or succeed, identifying casualties, and capturing system elements in the matrix, see Figure 7.8. Users benefited when examples this process were given, especially when demonstrating that elements from the social and technical domains are integrated which seemed to encouraged users to think more broadly. For example, the case study includes elements that involve the behaviour of consumers, such as brand loyalty, infrastructural elements as well as elements on the exposure of resources on supermarket shelves.

Figure 7.8 Analysis Matrix completed for the case study of an aluminium drink can.

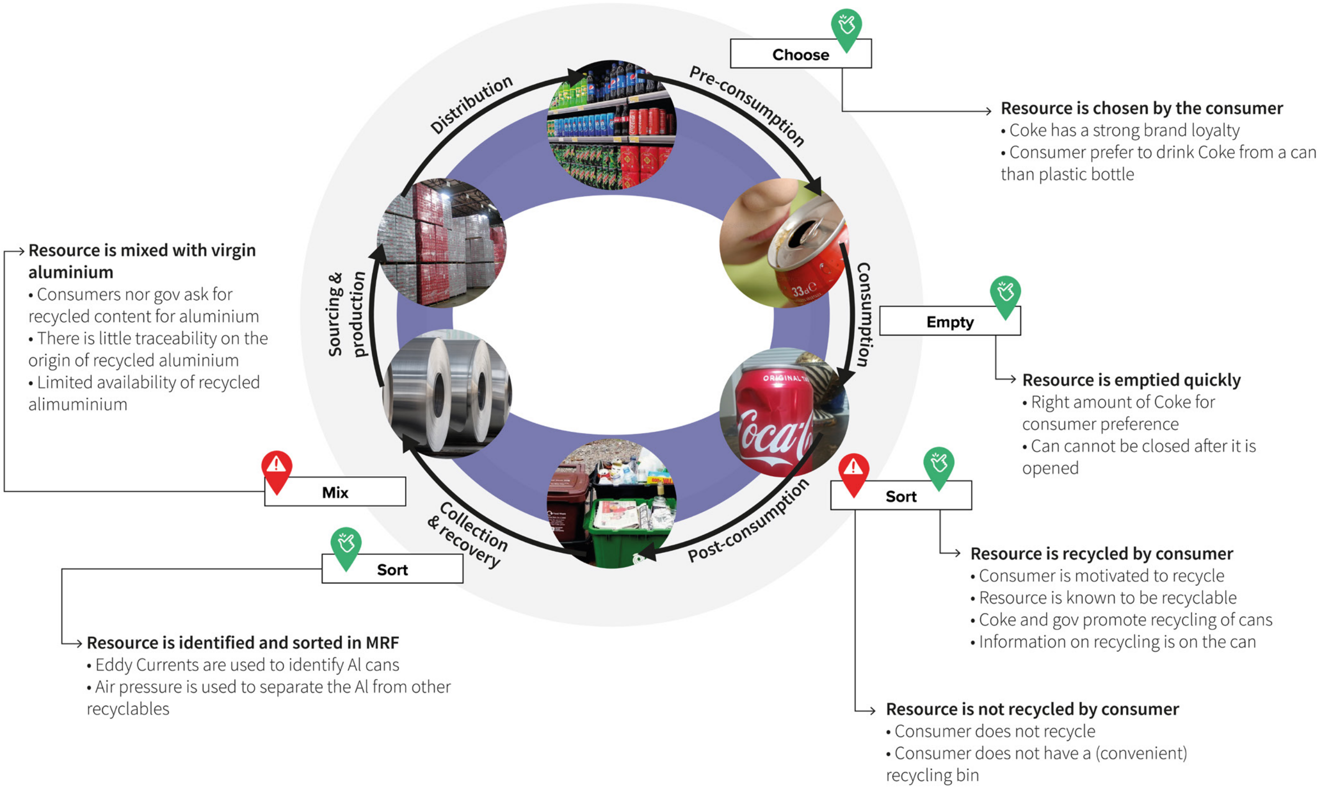


Figure 7.9 Synthesised results of the case study of the aluminium drink can.

Using the Analysis Matrix as the main output, users can synthesise their analysis in line with their core project aims. For the case study, see Figure 7.9, the analysis concluded that the combination of recycled aluminium and virgin aluminium is caused by a demand that is maintained by the suppliers. Further, there is a lack of incentives, such as consumer demand or legislation, to reduce the amount of virgin aluminium. Such takeaways can inform the (re) design of a product. For example, identifying the system elements that need to be considered or can be impacted when designing a can made from 100% recycled aluminium, e.g., product requirements, material availability and manufacturing processes, or which system elements constrain or favour the design of a new product that intends to use a (partly) pre-existing aluminium flow, e.g., recycling bins, sorting technology and dimensions of the product. The takeaways can also inform the (re)design of a system, such as which system elements could be improved, e.g., instructions on the packaging, location of bins or which system elements could be used when designing a new system, e.g., consumer education, sorting infrastructure and monitoring technology.

7.5. Evaluation of the Flow Mapper

All workshops and simulations provided valuable insights to the analyses and evaluation, however, it is worth stressing the importance of the insights of using the Flow Mapper with industrial users in a real-world live project (Workshop 6). This section describes the main findings of the formative and summative evaluations, structured against the levels of usability and usefulness.

7.5.1. Usability

The evaluation of the usability focused on the method and process to model the RFS.

The section is structured based on the four focus points for this level of the evaluation.

7.5.1.1. Feasibility of modelling with the Flow Mapper

Modelling the RFS subsequently as a State Model and a Functional Model, provided as semi-formal modelling methods, was generally a feasible exercise. Nevertheless, three mains challenges emerged that could jeopardise this.

Creating mutual mental models

The first challenge is a lack of or a poor shared mental model. As the Flow Mapper models one specific RFS, it is essential to start with an agreement on which RFS this is, develop a mental model of it and align on the mental model between the users. Observations indicated that good alignment on the case smoothened the modelling phase. However, if users had different models in mind, they struggled to define the boundaries of the RFS, got distracted by discussing possible inputs for unrelated systems, were unsure whether the input was pre-existing or novel and were inclined to map variations of the flow. When these circumstances arose, the modelling phase was time-consuming and lacked progress.

Interestingly, a misalignment between users happened with both (partly) pre-existing systems and novel ones. For example, a pre-existing flow, such as household recycling, may have a well-understood ‘recovery & collection’ with known processes in a MRF. However, the ‘post-consumption’ section of the flow varies between nations, regions, boroughs and individual households. Users seemed biased to describe flows and systems familiar to them personally. For example, in Workshop 6, a German participant focused on a yellow bin system, whereas a British participant discussed kerbside collection. Instead, in Workshop 4, users were asked to conceptualise a flow, and they appeared to make decisions more confidently. Whether the Flow Mapper was applied to novel or pre-existing flows did not seem to affect the feasibility of modelling. These struggles existed, despite the steps in the preparatory phase to align users on the RFS. It seemed that users often preferred to avoid converging on a single case and mere more comfortable to stay on a higher-level and keep their options open. For example, users in Workshop 5 decided that consumption takes place (Step 1) in ‘public – school - on the go - pub - restaurant - dining locations – home’, even though the template asked to specify a single-use context. This implies that despite having to make decisions, users often preferred not to.

A reason for this might be that the users were simply insufficiently made aware of the need to specify parts of the case based on their knowledge and assumptions. The Flow Mapper was tested in workshops using predominantly illustrative cases that were verbally explained. Possibly, it was insufficiently stated that users had to further specify the case. However, even when a written brief for the case was provided, such as in Workshop 5, users tended to avoid decisions related to system boundaries. Another plausible reason for the lack of decision-making, is that users may have felt unequipped to make the converging decisions required to model the RFS. It seemed that it was not always obvious to users what the consequences or trade-offs of their decisions were. This may imply that users do not have the skills and knowledge to make these decisions, and the Flow Mapper does not provide suitable support. Finally, the reason could be that the users expected or were interested in exploring or designing solutions rather than modelling an RFS. Users may have become aware for the first time of different design choices, which is plausible because it is unlikely that the users explored how a resource flows before. Therefore, they could have struggled to make decisions, even when it was emphasised that these were not final. In addition to this, users could feel trapped by not having the opportunity to compare and weigh-up options before making decisions.

Specifying the case clearly and collaboratively is necessary for the feasibility of the modelling. In addition to the preparatory phase, some steps in the modelling phase guided users to be more specific in their case. For example, the Snapshots encouraged users to be explicit and align on the case. Although the Flow Mapper helps to develop a shared model visually, a mutual mental development is essential to the usability of the Flow Mapper. In its development, activities were added to the preparatory phase to help to align the users on the RFS, the aim of the project in which the Flow Mapper was used and the expertise that the different users brought to the table. In future work, these insights could be used to improve the preparatory phase to make developing an effective mutual mental model.

Obtaining a functional view

The second challenge is to enable users to obtain a functional view of the resource flow. Thinking about the resource flow as abstractly as the movement and transformation of resources was not always intuitive and easy. Adding cues to the Configurator Board seemed to provide support in imagining the journey. Nevertheless, it was not always easy for users to only use processes to describe physical movements and transformations of resources.

Although the pre-defined Process Cards were provided to encourage functional thinking, the high number of cards initially included in the Flow Mapper confused users. Instead, the smaller number and blank Process Cards seemed more encouraging. During earlier workshops, users included processes that the resource was not the recipient of, e.g., the process 'to regulate' implies control over activities that involve using the resource, rather than regulating the resource itself. These discrepancies were minimised when the instructions were more explicit. Despite this, certain processes continued to slip into the Functional Model that did not describe physical movements and transformations. In particular, the process 'to purchase resources' was often included. Although transactions of both resources and money are important and indispensable activities in the RFS, they do not directly represent physical movement and transformation of resources. Such non-physical functions can be compared to as 'pseudo functions' that are expressed as verb-noun combinations but do not define the action on the physical object (Burge, 2006). Since these elements represent important aspects of the RFS and appear to emerge naturally for users during Step 4, future work on the tool could focus on the appropriate methods to capture these elements.

Organising and capturing system elements

The third challenge is related to the feasibility of modelling, which is to organise and capture system elements during the modelling method. Users were only explicitly asked about system elements in Step 6 when discussing risks and opportunities. Although users were aware and capable of discussing elements, only tasking users to capture system elements at the end of the Flow Mapper was a detached exercise, as the observed users struggled to identify and articulate the elements. Capturing the system elements is further complicated as users discussed elements that already exist in the system and conceptual or missing system elements. People are naturally inclined to think about solutions; for example, rather than identify the problems, a participant said, 'we would really need a bin'. This can contaminate the clarity of the Functional Model. The Flow Mapper did not provide explicit guidance to distinguish between the existence of elements.

However, based on the observations, it appeared that system elements emerged throughout the entire process. They appeared in the preparatory phase when users discussed the mental model of the case; in the modelling phase, when users mapped the flow of resources and discussed and identified barriers; and in the action phase when users discussed which processes were pivotal and why. Users rarely only talked about the resource flow. In fact, to describe the functions that enable the movement and transformation of the resources, users often mentioned several important system elements. For example, one may explain that resources are transported in a truck from location A to B. In this example, the truck and both locations emerge as system elements that users may want to capture. This suggests that functional and structural models evolve simultaneously rather than sequentially. Although positioning the Functional Model as an independent entity, such as in the Flow Mapper, may encourage users to prioritise flow as an objective, it risks complicating its use in practice.

7.5.1.2. Multi-stakeholder collaboration

To achieve knowledge-sharing across domains, users were recruited based on their knowledge. Users indicated in surveys and post-workshop interviews that they felt that they had contributed and that others had picked up on their contributions. Users were also observed to be prompted ask questions whilst using the Flow Mapper. For example, users asked each other about technical issues, historical company strategies and consumer needs. As a result, system elements in different domains did indeed emerge as causalities of the resource flow, indicating that collaboration was successful and that combined knowledge and expertise was useful. However, the expertise that contributed to the process and the outcome of the Flow Mapper was not solely commercial and technical, rather different types of expertise were valuable and influenced the outcome of the tool.

Technical and commercial expertise

First, identifying and closing knowledge gaps requires technical and commercial expertise related to the RFS. Users with extensive industrial experience have this expertise. The six resource states were used to assess the knowledge distribution and inform the recruitment process. Nevertheless, it can be challenging to find eligible and available individuals to participate. Recruiting experts outside the company may be restricted by project sensitivity. Therefore, there is a risk that the technical and commercial expertise is suboptimal during the modelling. As a result, models leaned towards specific domains. In Workshop 6, for example, although the users had plenty of technical knowledge, they had less commercial expertise. These participants indicated in the survey that they had gained a few new insights on the case. Nevertheless, the identification and articulation of knowledge gaps in the RFS in this workshop were considered a valuable overall outcome of this workshop.

Circular Economy knowledge

Second, CE expertise ensured a smoother Flow Mapper process and in-depth results. In developing the Flow Mapper, the aim was to simplify and rationalise CE language to remain accessible for users with all levels of CE knowledge. However, for the illustrative workshops, participants with CE expertise were recruited. It seemed that these users were more understanding of the purpose of using the tool. Users with greater CE expertise seemed to better understand the decisions that had to be made in the process, perhaps because they were more skilled at assessing circular trade-offs. Knowledge about the CE was also exchanged between users, particularly when users were faced with those decisions. Nevertheless, although CE knowledge did not always provide sufficient confidence to make decisions, the process was generally smoother if there were one or more members with CE know-how. Participants with less CE expertise indicated that they obtained new skills, which suggests that the tool has educative capabilities. Instead, in sessions with greater CE expertise, users indicated that they obtained new insights on the case. This implies that CE expertise could lead to more detailed outcomes.

Level of project engagement

Third, a lack of understanding of the overall project limits the effectiveness of collaboration. This was apparent in Workshop 6 where P&G had to consider who to bring together on an RFS modelling exercise. Not all the individuals had yet worked side by side on this project, which complicated their alignment on the purpose of the exercise. Since the Flow Mapper supports the design of products and systems for the CE, it was developed assuming users would have such design objectives ready at the start. However, their objectives were not always explicit prior to using the tool. A lack of clarity on the purpose of using the Flow Mapper in relation to a design objective also confused users in the illustrative cases and challenged decision-making in the process. The importance of introductions between users, as well as an understanding of the project aim, should not be underestimated in terms of how they contribute to meaningful and constructive interactions between users. Therefore, the level of project engagement is essential for the usability of the Flow Mapper.

7.5.1.3. Pragmatic process

Compared to formal methods, which are quantitative and mathematically rigorous methods to model systems (e.g., Attri *et al.*, 2013), the Flow Mapper modelling method is much more flexible. The advantage of this qualitative method is that it does not require the collection of data and the formulation of complex relations, allowing it to model systems more quickly. The method can be seen as semi-formal, as it uses consistent language and formalisms, but the outcome is the result of users' interpretations of the instructions. Workshops were facilitated, bu involvement by the researchers was minimised in all workshops. Nevertheless, a self-guided tool did present a number of impracticalities and challenges that imply a consultancy facilitation could be preferred.

Management of the process

The manageability of the process was subject to several aspects of the tool. First, instructions appeared to be sufficient to enable users to work through the entire process, although first-time users naturally required more time to read and digest the instructions than second-time users. As early workshops suggested that it was tempting to go in-depth and spend much time on individual steps, time indicators were introduced for each instruction to fit the process into a 90-minute slot. It seemed feasible to complete the steps within the indicated time slots, but users were still inclined to take more time than indicated for each of the steps. Time pressure did seem to push users to reach conclusions quicker, however, some noted that the process felt like a test. Interestingly, the time required to complete steps seemed to strongly depend on how well the case had already been specified and aligned. For example, in step 2, users may have required time to discuss the differences between the flows and/or to decide which one to choose. Similarly, in step 3, users seemed to find Snapshots more quickly if they had a more comprehensive mutual mental model.

The aim to limit the use of the Flow Mapper to a one-and-a-half-hour slot aligns well with business-as-usual meeting times. Although this interaction is efficient and decreases entry barriers, it risks compromising the quality of the outcome if the session and its expectations are not clear. For example, if there is no time for users to introduce each other and the project aims, they may not be aware of how they can best contribute. In addition, if the project objectives are not known, the intent of using the tool could be unclear. Furthermore, some teams may require more time than others, for example, if there is no shared mental model, if the team has limited CE expertise, or if they are using the Flow Mapper for the first time. To address some of these issues, pre- and post-session activities were included, see Table 7.7. Despite this, the synthesis of the outcome of the tool for Workshop 6 required significant time, mostly invested by the researchers, to provide support in the continuation of the project. To address this, the action phase could include steps to support the synthesis and deepen the analysis.

Logic of the process

The Flow Mapper uses guided steps to develop a high-level model, and it gradually proceeds into becoming a detailed RFS. This approach made sense to users, but possible limitations of a strictly sequential approach did emerge. For example, users rarely referred to the decisions in the preparatory phase, which limited its usefulness in developing a mental model. In some instances, decisions made in the preparatory phase were forgotten or were completely ignored during the modelling phase. This situation presented the need to better integrate this step; this could be done by linking the first steps to the modelling steps and, perhaps, even continuing to detail the Resource Specification Sheet as the mental model is refined.

In the later steps, system elements emerged naturally during discussions, but users did not have an opportunity to capture them. Unlike in the Flow-Causality Diagram in Chapter 6, this version of the Flow Mapper did not include a step to explicitly model the structure of the system that contains elements. When users were asked to discuss system elements in relation to risks and opportunities in the final Flow Mapper step, they struggled to recall and capture system elements. To address this, instructions and exercises evolved, guiding users to think about a variety of system elements. Nevertheless, it seemed that the transition from a functional

Table 7.7 Inclusion of steps in the Flow Mapper process and the pre- and post-workshop activities.

	Phase	Step	Activity	Pilot	Flow Mapper 0.9	Flow Mapper 1.0
			Pre-brief	•		•
			Team building			•
			Case discussion	•	•	•
Flow Mapper session	Preparatory	Step 1	*Specify resource*		•	•
		Step 2	*Pick a flow*		•	•
	Modelling	Step 3	*Take Snapshots*	•	•	•
		Step 4	*Map that flow*	•	•	•
	Action	Step 5	*Pivotal processes*			•
		Step 6	*Risks & opportunities*	•		•
			Reflection	•		
			Analysis		•	•
			Synthesis			•

to a structural model would require more consideration in the overall modelling process. An explicit step to model the structure of the system could have prevented system elements from contaminating the Functional Model and could have ensured that users captured elements that arose in the discussion of flow functions. As users struggled to discuss movement and transformation without discussing elements, it would be worth considering developing these as parallel and iterative steps. This may also better support the identification of the relations between system elements and processes in the final step of the tool.

The Flow Mapper enables users to model an RFS for a resource in a single flow. This seemed to have limitations and affected the logic of the process. For example, users were inclined to model more than one route for the same resource, or they identified multiple materials or components and wanted to model the journey of all these materials, possibly due to undecided aspects of the case and the lack of a mutual mental model. If users expect to be guided in making decisions on their design and to develop work that the Flow Mapper does not support, this could negatively affect the process.

Visual support

Initially, the Configurator Board as a physical playboard enabled an interactive face-to-face setting for collaboration. Mural allowed us to retain the presence of users around the board because the platform visualises active users' cursors, see Figure 7.10. One of the participants even described the users as 'pawns' on a playboard. This interactive setting and the presence of participants seemed to strengthen user engagement and the sense of a shared objective.

The visualisation of the model seemed to make the process pragmatic. In particular, the circular shape of the Configurator Board encouraged participants to think about the continuous nature of the flow. One participant mentioned that it 'forced us to think about how we can get [the resource] back to this point'. Including the State Model and the Functional Model together the Configurator Board was very helpful for users. The State Model provided them with the narrative and provided the structure for the resource flow. The State Model also helped users to set system boundaries, refine the mental model and section it into relevant sections. The order in which users provided and discussed Snapshots and developed the Functional Model did not appear to matter, but the process was smoother if the instructions specified where to begin. The State Model provided reference points that improved users' discussion, e.g., 'I'm working from [resource] in the bin', and enabled them to develop a holistic and integrated understanding of the system. The use of Snapshots with Mural's image search function allowed users to quickly and easily find and add photographs from the internet; these provided richer and more detailed characterisations than sketches and descriptions would offer. Snapshots that were rich in context seemed to be more meaningful, as they provoked discussion about the order of the resource flow and key processes and system elements.

7.5.1.4. Accessibility of the Flow Mapper

The Flow Mapper was designed and developed in collaboration with P&G. Consequently, the understanding of, and insights on, the needs of users are predominantly based on the perspective of a multinational manufacturer of FMCGs. It is indeed probable that the manufacturers of FMCGs initiate CE projects, but it is also conceivable that other stakeholders initiate and drive these projects and would be interested in using the Flow Mapper. The accessibility of the Flow Mapper appears to depend on several barriers to adopting the tool in

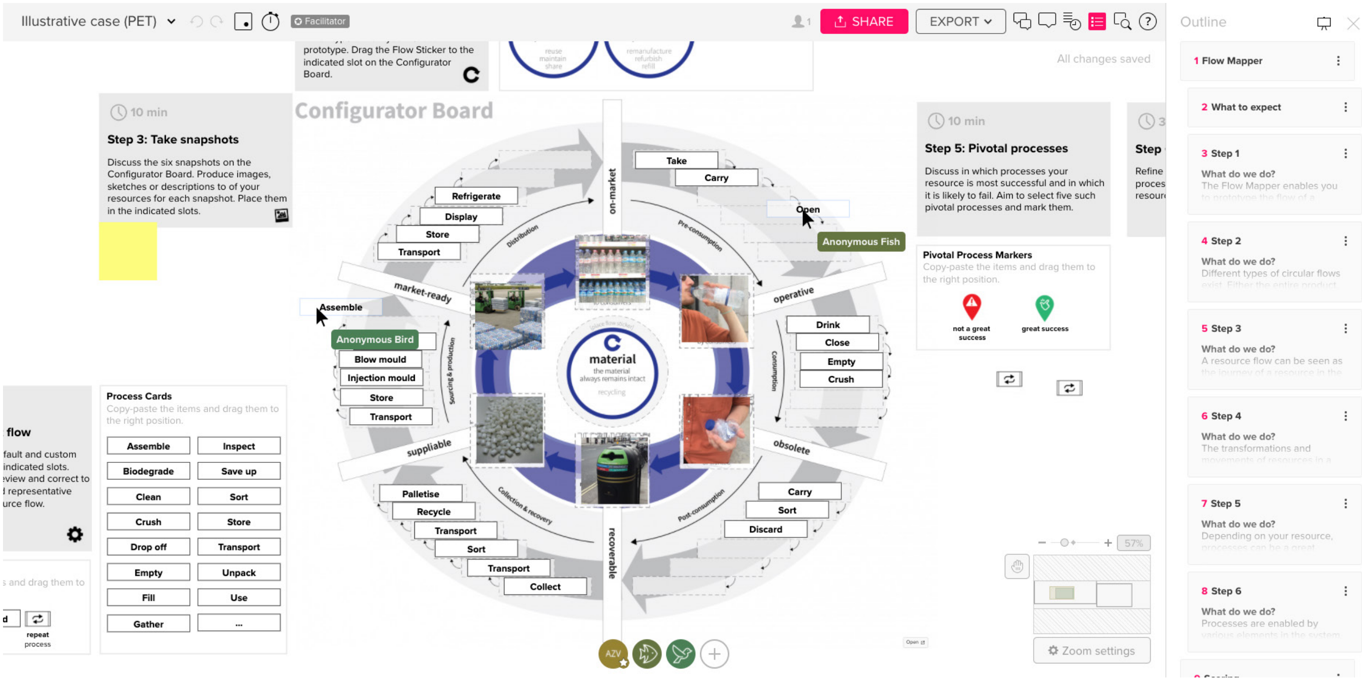


Figure 7.10 Screenshot of the Flow Mapper in Mural.

projects, as well as on barriers to participating in a session.

Adoption barriers

The decision to use the tool is likely made by a single stakeholder, such as a project manager, who sees the advantage of obtaining a holistic and in-depth view of an RFS. Despite being self-guided, pre- and post-session strategic thinking proved to be a necessity for a meaningful outcome of the Flow Mapper. These activities involved scoping the initial RFS, recruiting participants, introducing participants to each other, familiarising participants with the Flow Mapper and with the project objectives, facilitating the session, synthesising the outcome, and identifying takeaways. Specifically, Workshop 6 was part of a live project and required significant synthesis after the workshop. It is worth considering whether future industrial users may be discouraged by this and would prefer an expert facilitation.

Participation barriers

As interest in the CE within the FMCG sector is relatively novel, developing a tool that is accessible to anyone in the sector regardless of their CE knowledge was an important aim. Significant participation barriers were not identified. In fact, several users shared that they enjoyed the workshop and that they learned new CE skills. This can be ascribed, first, to the fact that there was little preparation work for participants in any of the workshops. Second, a language developed based on user feedback to effectively communicate CE and systems theory in a way that was easy to understand. Third, the form of the tool appeared to users to resemble a game or a puzzle, to the extent that some users asked what 'winning looks like'. This was strengthened by using the term digitally in Mural. Fourth, the digital format reduced logistical and planning barriers for both decision-makers and participants. However, despite the benefits of using Mural or other online platforms, it must be taken into consideration that using digital visualisation tools rather than analogue tools can be challenging for some users.

7.5.2. Usefulness

The evaluation of the usefulness of the tool focused on the value of its outcome. In particular, evaluating how users used, or intended to use, the outcome of the Flow Mapper to support their design projects. The exploratory nature of this part of the evaluation allows to identify and leverage the potential of the tool.

Enabling users to visually model the RFS

Visual models of systems are typically a difficult and time-consuming task due to the complex and integrated nature of systems (Charnley *et al.*, 2011; De Haan and De Heer, 2017). The Flow Mapper provides users with a simple and intuitive method to visualise the RFS. Participants, particularly users from an industrial background, indicated that they saw value in how the Flow Mapper allowed users to produce such a model with ease. The visual approach seemed useful for different reasons. First, the State Model, represented by the Snapshots, provided a narrative of the RFS, which was useful to users for developing a more tangible and mutual mental model. Second, the Functional Model provided detailed, high-level requirements of the system. This model was a non-physical description of the RFS, which was visualised in the Flow Mapper through Process Cards on the Configurator Board. This enabled users to reflect on all the sections of the flow and whether they were underdeveloped. Users indicated that the visual model was also useful in explaining a system to peers and in overall communication on the project. Third, the pivotal markers provided easily interpretable focal points of the system, which was useful in explaining priorities in CE design projects. For example, the industrial users discussed 'how [to] turn the reds into green', indicating that the visual model is useful to identify problems and set actionable objectives. This was useful because it provided a means to prioritise actions and progress the project.

Positioning the flow of resources as the primary design objective

The Flow Mapper positions the flow of resources a primary design objective. This was useful, first, because it made stakeholders aware of how their interests relate to and depend on each other. Users were able to identify system elements outside their own familiar subsystem, and they could use them to influence their design decisions. For example, the availability of 100% recycled aluminium could influence the design of a drink can. Second, it provided users with a shared objective. Although several stakeholders benefit from an established resource flow, the RFS does not typically have a single owner. The Functional Model is a description of the collective objectives of stakeholders. Third, the Functional Model enabled users to think about what the system does before thinking about the structures that enable it. By separating the processes that involve physical movement and transformation from other processes in the system, users were able to comprehend multiple solutions without thinking about specific elements of the system. This enabled a performance-centric analysis of the system, as users were encouraged to identify causes for the success and failure of flow.

Obtaining a holistic view and deep understanding of the entire RFS

The Flow Mapper provides users with a view of the entire resource flow. This provides practical evidence for the success of systems, which believed to be a key need for industrial users when adopting new strategies. Users' holistic view provided valuable perspective on the design problem. The industrial users confirmed that using the Flow Mapper gave them the confidence to take the next steps and progress in their project. Their model brought together system elements that overlap with familiar subsystems e.g., manufacturing processes, purchasing behaviour; and with subsystems that are less familiar, e.g., technological limitations of recycling, commercial dynamics on the market of recovered materials, recycling behaviour. Further, they were able to relate and integrate several elements with the resource flow, including characteristics of the resource itself, e.g., dimensions and aesthetics. Users confirmed that they felt they obtained a holistic view of the RFS and emphasised that gaining a deeper understanding of the problems they faced. This enabled them to compare systems on a high level, identify knowledge gaps, and prioritise issues in the system for development. Users also identified opportunities for improvements to the relation between systems and products. For example, suggesting improvements to a product's geometry to reduce the inconvenience of carrying it to a bin. Although the scope of our evaluations did not include later design stages, these insights indicate leading to a more integrated design approach to products and systems.

Identifying actionable next steps

Throughout the development of the Flow Mapper, different approaches were tested to deliver concrete outcomes based on the aims of the workshops. Feedback from the users in workshops and future users in simulations provided the following insights on how outcomes could be and were actioned.

The outcome enabled users to prioritise their next steps. In particular, the final phase helped users to identify challenges in the RFS. In line with the design intent, the red pivotal markers were seen as action points, i.e., tasks taken on by users to turn them into green markers. In some of the workshops, the outcome was used as a benchmark to conduct a qualitative risk assessment, as shown in the case study in Figure 7.11. This provided users with a deeper understanding of the significance of risks in the RFS. Users explained that this helped them to see where to intervene to have the greatest impact on sustainability. They identified different types of actions: for example, when they found knowledge gaps, their first actions involved gathering further information. In this case, the outcome was used to scope and articulate the knowledge gaps, which helped users to determine which specialists to reach out to and what questions to ask. Users also found that the outcome served as a design roadmap for the next design and development stages.

Although these are reasonable next steps that lead to systems action, our industrial users indicated that they would appreciate outcomes that were even more immediately applicable

Flow section	*Pivotal process*	*Scope of process*	*Failure*
pre-consumption	**Choose resource**	resource is chosen and purchased in the supermarket	resource is not chosen by consumers
consumption	**Empty resource**	resource is no longer used by the consumer	resource is used beyond functional life
post-consumption	**Sort resource**	resource is placed in the recycling bin by the consumer	resource recyclability is unknown to consumer
		resource is not placed in the recycling bin by the consumer	resource is not placed in a recycling bin
collection & recovery	**Sort resource**	resource is automatically identified and separated	resource is not identifed
sourcing & production	**Mix resource**	resource is mixed with virgin to bec omecommercially available	resource is mixed with virgin

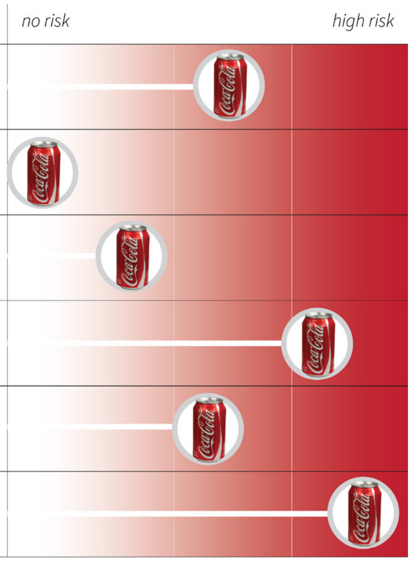


Figure 7.11 Example of risk assessment based on the outcome of the Coke can case.

or implementable. The outcome of the tool still required significant synthesis to support the live project in Workshop 6. Moreover, suggestions from industry were made to develop scoring mechanisms to make the assessment more measurable and to align it with existing processes in companies. This would resonate well with competitive corporate settings, achieving an outcome that could encourage users to achieve the best possible result.

Facilitating, enabling and encouraging collaboration

The workshops have demonstrated that the Flow Mapper encourages and enables collaboration between multi-disciplinary stakeholders. A short and structured interaction, with minimal preparation time, was found to enable an effective and efficient knowledge exchange and that facilitated constructive outcomes. Users from different disciplines appeared to connect over the shared objective to establish flow rather than trying to find common ground among only their own disciplines. Nevertheless, none of the workshops included users employed by different companies who might be more heavily pressured by differing agendas. The playboard form and the self-guided structure of the tool brought stakeholders together in a fun way, as aspects of the Flow Mapper could easily be likened to those of a game. Methods, such as serious gaming (Whalen, 2017), that encourage constructive collaboration could be investigated for future development of the tool. Nevertheless, the significance of the pre- and post-session work is concerning as it places responsibility on project leads to ensure successful outcomes. It is worth investigating further whether the needs of future users are better satisfied if the pre- and post-workshop activities would be facilitated by (external) consultants.

Upskilling users on the CE

In interviews and surveys, users shared that they learned about the CE and that they gained new skills that they could apply to other projects. The Flow Mapper was not primarily developed as an educational tool. The topic, however, is relatively new in the FMCG sector. It is not surprising, therefore, that users expanded their knowledge. It is possible that users learned from co-users or that the Flow Mapper embedded CE theory. A theoretical context was observed to be helpful because it sparked discussion on the theory and encourages knowledge sharing. However, too much context led to confusion and diverted users into discussing the theory instead of their project. This leads to the conclusion that CE theory that is included and how it is explained will influence both the usability and the usefulness of the tool.

7.6. Discussion

This work aimed to address a gap in tools that provide both a holistic view and in-depth understanding of an RFS, aiming to support industrial users in designing for the CE. Emerging support for the CE predominantly focuses on (re-)educating industry and (re-)developing business strategies, yet business seek for evidence for solutions. The Flow Mapper presents a novel tool which uses systems thinking theory to investigate systems as a whole and identify why and how they fail and succeed.

7.6.1. Enabling design for the CE

Sustainable innovation is usually linked to cost optimisations (Ashby and Johnson, 2002; Hunt and Franklin, 1996; Taylor, 2017). This typically translates to reducing the amounts of resources consumed, essentially narrowing the flow of resources (Bocken *et al.*, 2016). It appears that most methods and tools that are used in practice are based on conventional methods such as LCA, while attempts to formulate new theories are often unsuccessful (Yuan *et al.*, 2006). Perhaps because life-cycle methods focus predominantly on environmental impacts, they often lead to solutions that reduce or minimise environmental impacts (Braungart and McDonough, 2008). Nevertheless, the limitations of reduction strategies stress the need for more systemic change, especially in the FMCG sector (Kuzmina *et al.*, 2019). The Flow Mapper moves away from conventional life-cycle methods and instead builds on theories of System Dynamics (Meadows, 2008) and Function Structures (Aurisicchio *et al.*, 2012; Pahl *et al.*, 2007). Systems Dynamics can provide both a holistic understanding and an in-depth understanding of system elements and their interdependencies (Meadows, 2007; Senge, 2006). As this theory arose from a need to understand matters as a whole rand not only their individual parts (Flood, 2010) it can be appropriately used by designers to ynderstand social systems (Pourdehnad *et al.*, 2011). Function Structure allow one to ideate several solutions to a problem (Pahl *et al.*, 2007). This theory is embedded in engineering design processes, but it is very rarely used explicitly to integrate non-technical systems (e.g., Halbe *et al.*, 2014; Van Ostaeyen *et al.*, 2013). The Flow Mapper builds on both these theories, emphasising the consideration of resource flows more explicitly in design. The implications of this work involve the complete industrial innovation process.

Innovation in industry, particularly in the FMCG sector, often starts with a market opportunity driven by consumer needs. Companies have processes to formalise these opportunities into product concepts and business models that define and prioritise further research and development (Buijs, 2003). This work demonstrated that innovation can depart from resource flows. The opportunities that emerge from this entail several types of system elements, stretching beyond the product. The formalisation of systems solutions requires a mental model, which, as also highlighted in this study, is a challenging exercise (Bijl-Brouwer and Malcolm, 2020), especially when working in teams (Senge, 2006). The ability to develop explicit mental models is significant in facilitating discussion and change (Forrester, 1968a; De Haan and De Heer, 2017). However, visualisations of systems are uncommon (Charnley *et al.*, 2011), and mental modelling for design is poorly understood (Bijl-Brouwer and Malcolm, 2020). This work demonstrated that the Flow Mapper can be used to develop a shared mental model that can be used to formalise system solutions, leveraging the ideation phase of innovation processes.

Despite the availability of several methods and tools to conceptualise integrated products and systems such as PSSs (e.g., Pieroni *et al.*, 2019b), the final outcome of the innovation process of manufacturing-oriented companies is still, most commonly, a pure product. A reason for this might be the fact that, unlike products, systems are not typically prototyped. Prototyping allows designers to discover, generate and refine ideas (Lim *et al.*, 2008), allowing them to build and develop concepts into feasible solutions supported by evidence (Goldsworthy, 2014). Thus, not prototyping systems could limit the development and interpretation of the system as a solution. Modelling a system with the Flow Mapper deepened users' understanding of that system, and it enabled them to articulate and scope the development needs and to seek new opportunities. Further, it enabled users to include and relate elements that span across social and technical domains. Therefore, the tool offers an approach to prototype a system. Similar to product prototypes, a concept for systems could then be subject to iterations throughout the design process to assess its feasibility, leveraging the concept development phase of innovation processes.

Product designs are often evaluated based on prototypes and product specifications; for example, common evaluations of packaging development include drop impact, market response and shelf-life testing (Coles *et al.*, 2003). The evaluation of systems requires the clarification of performance indicators such as circularity indicators (e.g., EMF, 2015; Saidani *et al.*, 2017). Compared to product evaluations, however, methods to evaluate systems require very complex and detailed specifications. One of the main barriers for companies to undertake life-cycle assessments is the need for expertise and data, which are both expensive and time-consuming (Finnveden, 2000). The Flow Mapper develops a qualitative model of a system; this drastically simplifies the specification process and also allows the specification of conceptual systems. The tool enabled users to articulate the strategy of a system and to achieve a shared discourse on its planned performance; this is thought to be fundamental for implementable system solutions (Pieroni *et al.*, 2020b). Furthermore, the outcome of the tool enabled industrial users to perform qualitative benchmarking studies. Thus, this work demonstrated the Flow Mapper's ability to specify systems on a level of detail sufficient for assessment, making it applicable for the evaluation phase of innovation processes.

7.6.2. Aligning with industrial needs

Industrial innovation processes have evolved over years of business success in the linear economy (Buijs, 2003). It is suggested that methods that are complementary to this existing process can overcome gaps and shortcomings in innovation processes (Andrews, 2015; Bakker *et al.*, 2010). Complementary tools to design products and business models for a CE (e.g., IDEO and EMF, 2016; Konietzko *et al.*, 2020) make important contributions by providing guidance. However, there is a general shortage in the uptake of tools in industry (Bocken *et al.*, 2019; Vallet *et al.*, 2013), which might be due to the lack of evidence for the effectiveness of many design tools (Peters *et al.*, 2020). Companies appear to source new knowledge and skills externally, possibly to ensure confidence in their success (Peters *et al.*, 2020; Vallet *et al.*, 2013) before investing in them and internally adopting new thinking (Tukker, 2015b). Another reason could be that methods are simply not yet available to industrial users (Peters *et al.*, 2020) or are too complex to use without facilitation (De Haan and De Heer, 2017; Konietzko *et al.*, 2020b).

Industrial users have been engaged throughout the development of the Flow Mapper, benefitting from a strong industrial collaboration. Future users have been engaged throughout the process of development and evaluation through using participatory action research. This method allows participants to actively and critically engage (Mackenzie *et al.*, 2012). The engagement of users in tool development can overcome adoption barriers by the future audience (Peters *et al.*, 2020). Using the tool in a live industrial project provided unique insights into user needs and the tool's potential value. The strong level of engagement with P&G suggests that there was significant trust, indicating that the company was able to accept vulnerability, possibly due to the positive expectations of the intentions of our work, which may otherwise be perceived as risky (Hemmert *et al.*, 2014). Trust reduces barriers between universities and companies, smoothing the way for industry's adoption of novel academic knowledge (Bruneel *et al.*, 2010); this was also demonstrated in our work. P&G has expressed an interest in supporting its advancements, and it is engaged in positioning the tool alongside other methods and tools used in the company.

This work has implications for the research and development of tools that intend to support industry in a transition to the CE. We stress that methods and tools to strategize and conceptualise business and design for the CE are indispensable. However, industry is typically encouraged by the success of others to adopt strategies for business (Murray *et al.*, 2017; Yuan *et al.*, 2006). Although case studies are available for some sectors, in particular through the EMF (e.g., 2013; 2016) there seems little evidence on the exact and immediate value that can be perceived from such solutions. Systems engineering can be used to develop such understanding (Rittel and Webber, 1973) but convenitonal methods are complex, time-consuming and typically requires experts to lead data collection and analysis (De Haan and De Heer, 2017). The Flow Mapper makes it feasible and manageable for industrial users to develop comprehensive system models by applying proven theories and produce evidence for the success and failure of systems. Although further synthesis of the model is to be incorporated in the Flow Mapper, the process has reduced complexity of modelling and provides users with both a holistic understanding of the system, as well as in-depth insights on the relations between system elements and processes.

7.7. Limitations and future work

The Flow Mapper is still young and there are several limitations to the current version which can be considered in future iterations, as has been discussed in the evaluation. Further aspects to consider in future iterations include: focusing on a flow based on a product often requires to simplify or reduce to single materials which limits the complexity that can be captured; the inability to model multiple scenarios for the same resource; a strict split between functions and elements. The development has focused heavily on System Dynamics and Function Structure theories, and translates CE theory into an applicable and practical tool. Further theories can be incorporated in the field of multi-disciplinary collaboration which is essential for the successful use of the tool (Bocken *et al.*, 2019). The tool was developed in collaboration with P&G but aims to appeal to the overall FMCG sector and has potential to support other sectors. Future developments would benefit collaboration with other stakeholders to incorporate their user needs (Peters *et al.*, 2020). Further, the tool focuses on needs for the FMCG sector, but other sectors may benefit from using the Flow Mapper.

The evaluation of the tool is based on several simulations and six workshops which allowed to perform formative and summative evaluations. There are always limitations to qualitative observations (Hertzum and Jacobsen, 2003) in particular if the evaluation involves tools developed by the researchers themselves (Peters *et al.*, 2020). To address bias and tunnel-vision, we used mixed methods to cross-reference and validate insights as much as possible and limited our involvement during the application of the tool. Further evaluation of the process as well as the outcome would be beneficial, especially with industrial users and in live projects.

7.8. Conclusions

Resource flows are used in methods and tools to understand systems, but they do not provide a holistic view and in-depth understanding of a system. This limits industry in obtaining a holistic view of the RFS and develop evidence for the success of existing and novel systems solutions for the CE. This chapter presented a tool called the Flow Mapper, which was developed and evaluated through Participatory Action Research with industrial users in the FMCG sector. The tool involves a modelling method and the process to apply the method and analyse the outcome. The Flow Mapper offers support to industrial users and their circular design projects.

The usability of the tool was evaluated on four sublevels:

- feasibility of modelling the system, which was influenced by the ability to create a mental model, obtain a functional view and capture system elements;
- enabling multi-stakeholder collaboration, which found to benefit from users with technical and commercial expertise, CE knowledge as well as a certain level of project engagements;
- pragmatic use of the tool, which depended on the management and logic of the process and benefited from visualisation; and
- accessibility of the tool for future users, which is subject to several adoption barriers, but relatively few participation barriers.

The usefulness was evaluated exploratorily to identify meaningful outcomes of the tool. The usefulness related to the ability to visually model RFSs; position flow as the primary design objective; obtain a holistic view of the system; identify actionable next steps; collaborate; and upskill CE knowledge.

This work makes important contributions to the design of systems for the CE. First, the Flow Mapper makes systems engineering accessible and more feasible for industrial use. The tool is based on System Dynamics and Function Structure theory. Second, this makes the Flow Mapper significantly different from conventional methods and tools which are typically based on conventional life cycle thinking. Third, it provides several opportunities to reform the innovation process by integrating methods that allow to position systems as a design deliverable. Finally, it provides new focus on the purpose of tools developed for industry. Rather than conceptualising tools, industry would benefit from tools that enable them to gather evidence for the success of systems. One of the workshops used to evaluate the tool involved a live industrial project which has been of significant value to the development and evaluation. Evaluation of the tool through live projects, both in the FMCG sector and other sectors, are recommended to further improve the usability and usefulness of the Flow Mapper.

8. Summary, Discussion and Conclusions

This chapter summarises the research findings, discusses the implications and contributions of the thesis and draws the main conclusions.

8.1. Summary of the research

The findings of this research provide both novel understanding of circular systems and methods that can be used to analyse and design systems. This section summarises the findings against the research objectives.

Objective A: *Understand why the FMCG sector lacks circularity*

This objective was achieved through a literature review and observation of industrial practices, as presented in Chapter 2. As products, FMCGs address consumers' steady needs by delivering temporary satisfaction through convenient offerings. Combined with an industry that is volume-driven, has a materialistic throughput and takes minimal responsibility, FMCGs come with severe negative environmental impacts. While the FMCG sector seems to respond to its impacts, its efforts appear to be mostly driven by sustaining the current linear business model. This poses three main concerns for FMCG manufacturers. First, continuing business as usual is risky because it depends on finite resources, thereby jeopardising the availability of resources, which have increasingly volatile prices. Second, the loss of resources implies a loss of business due to reputational losses and significant untapped value of unrecovered material resources. Third, the supply of recovered materials does not satisfy the demand for virgin materials because FMCGs are not designed for optimum recycling, and the sector insufficiently pulls the demand for recovered materials. The review indicates that the main challenge for the sector is to make systemic changes that allow the establishment of closed-loop resource flow, either of recyclable materials or reusable components.

Objective B*: Understand implications of using the design of systems to close loops*

This objective was achieved through a literature review on design and the CE, as presented in Chapter 3. The CE concept suggests that resources can be used efficiently to satisfy both environmental and economic strategies. Despite concerns about whether a CE is environmentally sustainable and economically prosperous, governments are increasingly promoting its uptake, and industrial sectors are gradually adopting the concept. Design is suggested to serve as a catalyst for the transition to a CE. Emerging design objectives for the CE usually describe resource describe resources flows as circular strategies (e.g., reuse, refurbish, recycle) and interpret them as lifecycles. Although this supports life-extension strategies, which result in slow resource flows, it provides insufficient granularity on and acknowledgement for the physicality of resource flows. For example, a resource becoming obsolete poses a significant risk to disrupt resource flows, but this is not typically considered in design. Following the changing objectives, new design deliverables imply products specifically designed for biological or technical loops and behaviours, services and larger systems that broaden their scope. Three overlooked areas in the literature emerged, which are important to design for the CE: *I) resources are products, components and materials*, which exist in a single flow of resources (Blomsma, 2020; Stahel, 2019); *II) flow involves the physical movements and transformations of resources*, which are all indispensable to establish flow; and *III) systems produce flow*, which implies that establishing flow is the behaviour of a system and requires a holistic intervention (Dewberry and Monteiro de Barros, 2009; Meadows, 2008). To address these gaps, the investigation focuses on the disruption of the resource flows in relation to obsolescence, allowing the understanding of factors that enable or disable resource flows.

***Objective C**: Understand and define the role of consumers in closing loops*

This objective was achieved through an empirical investigation of the instructions provided to consumers for eighteen reuse and recycling Product-Service Systems (PSSs) and household recycling in London Boroughs, as presented in Chapter 4. Positioning obsolescence as a moment in the flow allows to investigate the consumer's role in relation to behaviour and other systemic elements. The data was used to systematically construct and compare Customer Journey Maps for the various revalorisation services. In both reuse and recycling services, the role of consumers always has the same outcome for resources i.e., they are placed in designated locations where they can be accessed for revalorisation. Four dimensions of PSSs emerged that characterise the roles of consumers: the form of obsolescence, the changed state of resources from obsolete to operative or recoverable, the prerequisite activities required of consumers for revalorisation and the facilitators of the activities (i.e., investments and incentives). The dimensions were used to model four archetypical roles of consumers named after the interaction between consumers and the resource in the obsolete state, namely keep, bring, consign or abandon obsolete components. Then, gateways were defined as entry points to revalorisation for resources. Two factors of gateways emerged that implied different levels of effort to consumers: the accessibility of gateways and the resource entry criteria. These findings imply that such dimensions and factors could be designed to reduce the costs of consumers' roles in revalorisation to avoid disruption of resource flows. These findings can support the design of PSSs for a CE.

***Objective D**: Explore the potential of PSSs to enable closed-loop resource flows*

This objective was achieved through a systematic literature review, as presented in Chapter 5. Although PSSs have been advocated in a CE context, there is scarce evidence showing that PSSs use can overcome obsolescence and close resource loops. Publications on PSSs across sectors were reviewed systematically to identify elements that could enable closed loops. A total of twenty-one elements of PSSs emerged that were structured in an architecture with six categories: services, resources, stakeholders, contract, value delivery, and systems and tools. These were mapped in a framework against four subfunctions to close loops: state resource lifetime (acknowledging the impermanence of resources), govern resource lifetime (making accurate predictions on obsolescence), intercept obsolete resources (obtaining physical access to resources), and transition obsolete resources (ensuring that resources become a supply for new demand). Based on these results, a set of Circular Design Guidelines was developed to provide guidance on embedding PSS elements to satisfy the four functions. This study implies that 'intercepting and transitioning obsolete resources' could be considered demanded requirements for a closed-loop PSS since they concern the physical flow of resources, whereas 'stating and monitoring resource lifetime' could be considered wanted requirements because they can improve the success of interception and transitioning.

The framework demonstrates that there is a broad set of PSS elements that can be embedded in future PSS design for the CE.

***Objective E**: Develop a method to explain how systems produce resource flows*

This objective was achieved by developing a modelling method based on case study research on nine closed-loop FMCG systems, as presented in Chapter 6. Systems thinking, i.e., looking at the whole as well as the interrelated elements of a system to understand its behaviour, has proven to be a useful tool to understand how systems work. The existence of resource flows can be interpreted as the behaviour of a system, which allows the interpretation of its structure as the mechanism that produce this behaviour. The resource flow-system (RFS) is defined as the system that encompasses the structure in place to satisfy its overall function to produce resource flow. As the structure involves behaviours, services and infrastructure, the RFS is a sociotechnical system. The method to model it is based on the theories of Systems Dynamics and Function Structure. First, ten Flow Functions emerged from the data analysis, which decompose the overall function into a set of subfunctions that describe processes to physically move and transform resources. The Flow Functions are used both as a functional model; and as a function tree, breaking down the functions in more specific and concrete processes that describe the exact physical movements and transformations. Second, a method to model flow-causality, termed Flow-Causality Diagram, was developed. The Flow-Causality Diagram is a visual representation of the RFS, which uses nodes and arcs to express causalities between system elements and between system elements and processes. The nodes in the Flow-Causality Diagram represent the Flow Functions serving as a blueprint of the functional model of the closed-loop RFS; processes specific to the case; and system elements that represent physical and non-physical features of the system. The system elements, organised in a library, emerged from the data analysis and were visualised through icons representative of six classes: principles, value, actors, infrastructure, data and resource. This enables easy and intuitive interpretation of the elements, as well as their context and meaning. Furthermore, all the processes and elements were annotated with stakeholders to indicate responsibility and ownership. The arcs in the Flow-Causality Diagram represent three types of causality: neutral, i.e., the node does not change; positive, i.e., the nodes change in the same direction (an increase or decrease of a node causes the same effect on another node); or negative, i.e., nodes change in the opposite direction. The Flow-Causality Diagram provides a holistic view of the RFS and can be used to explain how and why the elements enable or disrupt closed-loop resource flows.

***Objective F**: Develop a tool that enables the FMCG industry to use design for closed-loop systems*

This objective was achieved by developing and evaluating a tool through Participatory Action Research, as presented in Chapter 7. Existing methods and tools to invest resource flows do not provide a holistic view nor in-depth understanding of the entire RFS. This limits their potential to provide support for the CE. The Flow Mapper was developed to model the RFS by interpreting flow as the overall function of the system. The tool includes a modelling method and a process to apply the method and analyse the model. This process entails preparatory, modelling and action phases provided with instructions that enable a multi-disciplinary team to self-guide. Templates and moveable parts are introduced in the Flow Mapper to build the model. The Flow Mapper combines a state model, i.e., providing a high-level understanding of the system through visual representation of resources at different moments in the flow using Snapshots; with a functional model, i.e., providing a non-physical description of the system through the chain of processes that describe resource movement and transformation. The tool was evaluated through in-house and live industrial case studies, based on usability and usefulness, using both formative evaluations. The Flow Mapper enabled users to develop a holistic view of the RFS, which permits users to gather evidence on the success of existing and novel system solutions for the CE.

8.2. Discussion

Ever since sustainability became a societal and industrial concern, designers have been increasingly held responsible for unsustainable outcomes (Bhamra and Lofthouse, 2007). As a result, design has evolved to include social and environmental factors (Ceschin and Gaziulusoy, 2016). The suggestion that design can be a catalyst for the transition to a CE (EMF, 2017; Moreno *et al.*, 2016) challenges designers with even broader, more complex and increasingly multi-disciplinary problems to solve. To prepare designers for their role in the CE, it is suggested that they could be equipped with new skills, such as knowledge of CE principles and know-how to apply them (Andrews, 2015), as well as a variety of specialist skills, including knowledge of material science, engineering techniques, service design and human behaviour (De los Rios and Charnley, 2017). Some have argued that design is too pragmatic and lacks systematic checks and balances that are needed for system solutions (Dorst, 2019). It seems unlikely that a single designer can obtain and maintain such broad knowledge required to provide solutions for complex problems (Meyer and Norman, 2020). There is also concern that a more holistic role for designers in the CE could overlook traditional focus areas, such as human behaviour (Lofthouse and Prendeville, 2018). Furthermore, despite the suggested potential value gains of designing services and systems, design in business is still most applied to product-oriented problems, and there are few successful examples of solutions to other problems (Pourdehnad *et al.*, 2011).

The actual contribution that design can make to a CE is ambiguous, but there is a strong belief that design has a role in addressing complex systems' problems that threaten the environment. This thesis developed new knowledge and methods that support industrial stakeholders in the FMCG sector to use design to enable a transition to the CE. The knowledge and methods that resulted from this research shed new light on the use of design to invent and implement circular FMCGs. These findings provide novel insights on the use of design in the CE, the role of designers in the CE, design deliverables for the CE and skills to integrate into innovation processes for the CE. This section discusses these topics and serves as the general discussion of the thesis.

8.2.1. Towards resource flow-centred design

Integrating the design of products with services in PSSs is advocated for its potential to deliver outcomes that dematerialise consumption and preserve resources longer (Goedkoop *et al.*, 1999; Mont, 2002; Tukker and Tischner, 2006). This opportunity appears to have accelerated the research on integrating business modelling and design, typically based on conventional sustainable design philosophies such as life cycle thinking (Blomsma *et al.*, 2018; Bocken, 2016). The notion of circular resource flows, for example, aiming to optimise the yield of resources, by keeping flows pure and resources at their highest utility (EMF, 2015; Stahel and Clift, 2016), is embedded in these new methods (Moreno *et al.*, 2016). However, they poorly define and incorporate the physical and actual resource flow, i.e., the volume of matter existing per time unit within a system's boundaries (Brunner and Rechberger, 2004). This is concerning because the CE is a new economic model in which growth, value and development suggest changes to today's relationships with resources (Stahel, 2010; Raworth, 2017). Circular strategies and life cycle thinking do not explain what really happens to resources, thus providing insufficient granularity on and acknowledgement for the physicality of resource flows to understand these relationships.

To address these limitations, the flow of resources has been a focal point throughout this thesis. The flow of resources entails the physical movements and transformations of resources in a single loop over time (Blomsma and Tennant, 2020; Stahel, 2019; Webster, 2013). This thesis allows us to outline early principles of a novel design philosophy that assigns a central role to the resource flow: *resource flow-centred design*. Similar to a user's role in user-centred design (Daae and Boks, 2015; Wever *et al.*, 2008), resource flow-centred design puts the resource flow at the centre stage during the entire design process. The design process must consider all the needs and constraints of the resource flow. Similar to the user-centred design philosophy, which emphasises user experience and the behaviour of the user (Norman and Draper, 1986), resource flow-centred design aims to improve the efficacy and efficiency of the resources' journey. Circular flow strategies, such as a slow, narrow or closed-loop resource flow (Bocken *et al.*, 2016), can be translated into this journey and expressed as the processes to physically move and transform resources.

Life cycle thinking is similar to this philosophy in that it reviews an entire journey of resources (Vogtländer, 2010). The philosophy is significantly different from a focus purely on integrating services with products to reduce life cycle impacts (Pieroni *et al.*, 2019; Tukker, 2004; Manzini *et al.*, 2001). The design scope is defined by the resource flow rather than a business objective. Flow-centred design implies a need for integrated design of the RFS and the resources as opposed to services or business models and products. The philosophy emphasises the actual ability of resources to flow (Charnley, 2017 and De los Rios) but incorporates the common need of narrowing flows through resource reduction (Bocken *et al.*, 2016). It shares the importance of keeping resources at their highest utility, not just to optimise yield (EMF, 2015), but also because it implies a minimisation of movements and transformations which would optimise resource flow efficacy and efficiency. Circular resource flows are characterised by pace and volumes (Allwood, 2014; Bocken *et al.*, 2016), but this granularity is insufficiently considered in conventional design for the CE. This thesis positions the needs and constraints of flows at the centre of design, suggesting a detailed consideration of the movements and transformations of resources and, therefore, moving away from conventional methods (Yuan *et al.*, 2006) to tackle challenges in the CE with new methods and skills.

Flowability as a driver for innovation

Although there is increasing pressure on the industry to pull their weight in the climate crisis (United Nations, 2016), reducing environmental impacts is still rarely a primary driver for innovation (Pieroni *et al.*, 2020a; Weetman, 2016). Sustainable innovation often competes with costs (Kim *et al.*, 2018), which is evident from strategically linking sustainable innovation to optimisations in the supply chain (Ashby and Johnson, 2002; Hunt and Franklin, 1996; Womack *et al.*, 1992) that directly result in costs reductions (Taylor, 2017). Reducing material and energy resources are important and necessary industrial developments that align with CE principles (Allwood, 2014; Bocken *et al.*, 2016). However, they merely reduce the consumption of resources, and actual physical flow can remain problematic (Braungart and McDonough, 2008). A flow-centred approach implies that the flow of resources or, more specifically, flowability, could be a driver for innovation. Expressing flow as a function and breaking it down into subfunctions using Flow Functions provides a consistent approach to develop and compare a variety of solutions to the problem (Stone and Wood, 2000). Using flowability to drive innovation could, thus, encourage stakeholders to explore different opportunities to innovate beyond the low-hanging fruits that immediately reduce costs. The ability of resources to flow depends on the compatibility between the resource and the RFS producing their movements and transformations. Therefore, flowability would encourage and guide the exploration of relationships between resource flows and economic factors (Raworth, 2017; Stahel, 2010). This type of exploration can lead to innovation in business models, such as a Material-Service System (MSS) in which materials, not products, are subject to service offerings (Aurisicchio *et al.*, 2020).

Hands-on collaboration in design

Collaboration between companies is considered a significant enabler for transitioning to the CE (Mishra *et al.*, 2019; Ellen MacArthur Foundation, 2016; Kraaijenhagen *et al.*, 2016). Collaboration is often sought early in the innovation process, allowing the co-development of the problem and solution (Brown *et al.*, 2019) but also requiring multi-disciplinary engagement on the practical level to develop in-depth insights on the systemic problem (De Koeijer *et al.*, 2017; Miser and Quade, 1985). The importance of multi-disciplinary collaboration for resource flow-centred design is stressed, as it is necessary that a team with views and expertise relevant to the system is assembled (Meyer and Norman, 2020). Regardless of their background or understanding of design (Flanagan, 2014), stakeholders must be enabled to contribute their views and expertise to all phases of the problem-solving process (De los Rios and Charnley, 2017; Norman and Stappers, 2015). The Flow Mapper and Flow-Causality Diagram allow all stakeholders to contribute to the innovation process through a hands-on process. The methods and tool provide visual and simple language to describe system elements, flow functions and processes. Moreover, the state model provides a visual representation of the resource flow and a means to guide and direct the collaboration.

8.2.2. Designing resources

Traditional design aims to deliver a product that performs well in production and in use. This implies changes for the physical design of products to align with specific types of flows, e.g., using compostable materials only in the biocycle (Corbin and Garmulewicz, 2018). Depending on journey, the performance of the resources in each of its three categorical forms (Blomsma and Tennant, 2020) is increasingly important. A resource may need to perform as a component in one moment and as a material in another. Nevertheless, these three categorical states of resources are often poorly considered in product design. Instead, the focus is usually on a few specific features of products, e.g., through guidelines for recyclability for material recycling and design for disassembly for the preservation of components and recovery of materials (Mestre and Cooper, 2017). However, this guidance typically focus on a single resource state, e.g., whether a resource can be recycled when it is in a MRF (WRAP, 2019a; 2019b), but not of the successive conditions of the resource, e.g., whether the recycled resource satisfies a demand (Zeeuw van der Laan and Aurisicchio, 2020). A lack of these considerations may unrightfully celebrate strategies for the CE. For example, material substitution with biodegradable materials as advocated by some in the FMCG sector often lacks consideration of the probability of material recovery (Lesteur *et al.*, 2010).

Resource flow-centred design implies designing *resources* instead of products. The resource is envisioned as the substance in a single flow (Stahel, 2019), in which the substance takes different shapes in different moments in the flow. The design of the resource as a material is, therefore, as important as designing the resource in the product form because it will have to perform in either state. The performance of the resource is, thus, interpreted both as its ability to flow and its ability to endure the movements and transformations that the flow entails.

This view extends the categorical view of resource states in which transitions between entropies are aligned to an industrial life cycle (Blomsma and Tennant, 2020). We propose that resources at various moments can be further characterised with detail beyond their geometric shape. Resources are enrolled in different settings in which they behave in specific ways that influence how consumers treat them (Baxter *et al.*, 2016; Hawkins, 2012). Therefore states of resources must be understood to determine their success in resource flows. From this perspective, it appears that the obsolete resource state has been considered rather proactively. For example, the obsolete resource state was enforced by selecting materials with inferior material quality (Packard, 1960), such as stockings prone to laddering. Resources that remind of disposability (Lucas, 2002), or look and behave like waste, are likely to be treated as such (Hawkins, 2012).

Features of resources

The consideration of granular resource states allows the identification of features of resources that may hinder, e.g., dirty packaging that is not identified in an MRF, (Ali and Courtenay, 2014) or favour resource flows, e.g., attributes of used-up packaging that encourage recycling behaviour (Baxter *et al.*, 2016). To identify and understand these features, resources in different states could be characterised. Characterisation methods are common in the field of materials science, in which they focus on the structure and behaviour of materials based on principles of chemistry, physics, biology, processing and engineering (Zhang *et al.*, 2008). The field delivers technical material properties used to predict which material allows a product to perform best in manufacturing and use (Ashby and Johnson, 2002). Materials can also be characterised experientially (Karana *et al.*, 2015) based on sensorial, interpretive, affective and performative dimensions (Giaccardi and Karana, 2015), which can be used to predict how humans will interact with products. Although this provides rich data on materials, it is often deemed incomplete for sustainable design (Prendeville, *et al.*, 2014; Sherwin and Evans, 1998). Besides the suggestion that designers need in-depth scientific material knowledge (De los Rios and Charnley, 2017), more topical, transparent and practical types of material information have been conceptualised that allow the adaptation of materials selection processes for sustainable design (Lilley *et al.*, 2019; Jensen and Remmen, 2017; Rau and Oberhuber, 2016; Prendeville, O'Connor *et al.*, 2014). However, such information is unconventional and not easily available

(Prendeville, O'Connor *et al.*, 2014) neither are the information systems to democratise aggregated material data (Corbin *et al.*, 2018). Moreover, such information still delivers incomplete characterisations of resources along the entire resource flow. Characterisations of the products in the form of products and component could easily be derived from product design and assessment methods.

Nevertheless, granular resource states, as proposed in this thesis, require consideration of more circumstantial factors rather than clean, isolated components and products. A state model, as integrated in the Flow Mapper (Chapter 7), would allow us to characterise resources in different circumstances. Contextual circumstances, such as those that influence the resource value (Zeeuw van der Laan and Aurisicchio, 2020), should be considered in relation to flow. A resource designer needs to consider, for example, whether the resource is mixed with another resource at any moment. Other methods could be used to extend the characterisation of resource states. For example, waste characterisations measure the fractions of individual materials in a flow to assess the economic value of the waste (Parajuly and Wenzel, 2017; Rada and Cioca, 2017). Therefore, resource designers would benefit from an active role in material characterisation in which broader and contextual characterisations can be made (Karana *et al.*, 2015), and novel insights can be generated on less conventional material properties based on what materials have to offer in different contexts (Barati and Karana, 2019).

8.2.3. Designing systems

Business models are believed to be insufficiently comprehensive when considered as system solutions to address problems to enable a transition to the CE (Ceschin and Gaziulusoy, 2016; Konietzko *et al.*, 2020b). Suggestions are emerging to go beyond business models, such as PSSs and behaviours, and instead consider designing the whole system to address complex problems (Charnley *et al.*, 2011). Systems thinking is suggested to provide a more inclusive way of thinking in design, enabling designers to further expand design boundaries. This holistic approach allows us to integrate and combine multiple domains through collaboration (Blizzard and Klotz, 2012; Dwyer, 2015; Miser and Quade, 1985). However, these larger systems often still include changes to products and introduction of services (Han *et al.*, 2016). Therefore, solutions still appear to be sought in isolation, either as subsystems or their elements, depending on the needs of single actors (Buede, 2009; Ceschin and Gaziulusoy, 2016). As a result, the CE solutions typically have a limited systemic span or reach and remain on a conceptual level or emerge with suboptimal flows.

Resource flow-centred design implies designing the *RFS* instead of a business model. The RFS is characterised by boundaries that are defined based on the purpose of flowing resources rather than business objectives. An interpretation of resource flow as a behaviour of the system over time (Meadows, 2008; Senge, 2006) implies that it is the entire system, instead of a subsystem or specific system elements, that is responsible for this behaviour (Dewberry and Monteiro de Barros, 2009). By defining that the overall function of the system is 'to flow resources', the boundaries of the system are set around all the structures that need to be in place to produce the flow of resources (de Weck *et al.*, 2011a). These structures involve carefully organised and interconnected elements (Buede, 2009) that span across the domains of a sociotechnical system (Hughes, 1987).

The RFS resembles a type of anthropogenic metabolism, which combines industrial and urban metabolisms to understand the flows of resources in the man-made world (Baccini and Brunner, 2012). However, anthropogenic metabolism aims to comprehend both energy and material resource flows (Baccini and Brunner, 2012), whereas the RFS revolves only around physical resources. Similar to the material flow analysis (MFA), the RFS focuses on a single resource. Nevertheless, the MFA looks into the entire volume of a single material resource and aims to capture all the journeys of that material within a geographically defined system (Brunner and Rechberger, 2004). Instead, the RFS looks into the flow of a single product resource. The significant difference with these methods is that rather than only interpreting the system as the physical containment of the flow, the flow is interpreted as the behaviour produced by the RFS over time (Dewberry and Monteiro de Barros, 2009; Meadows, 2008). Furthermore, the RFS encompasses all the structures that are in place to produce the resource flow, using causalities to link system elements to each other and to the processes that describe the flow.

System design methods

Developing system prototypes helps investigate the system and understand what it has to offer, such as identifying business opportunities (Houde and Hill, 1997). Both the system's model and the process to develop it are significant enablers for the design of system solutions (Charnley *et al.*, 2011). Nevertheless, the methods to model system solutions are typically complex and require skilled experts (De Haan and De Heer, 2017; Forrester, 1968a; Meadows, 2008), which is why prototyping sociotechnical systems is not yet a common practice in design. The challenges to prototype systems revolve around the difficulty of developing a mental model aligned between stakeholders (Senge, 2006) and the lack of methods and tools to visualise system concepts (Charnley *et al.*, 2011). The flow-causality diagram and the Flow Mapper are new methods allowing the collaborative development of an RFS model. These methods provide two equally important perspectives for designing systems solutions.

First, a holistic view of the RFS is important because the flow, i.e., its behaviour, emerges over time (Stahel, 2010; Meadows, 2008; Senge, 2006). Therefore, a holistic perspective is needed to understand the problem. This allows us to identify and include all the important structures and processes of the system (Jackson, 2006; Findeli, 2001). The holistic view allows us to critically analyse the system (Jackson, 2006) and identify patterns in systems that deliver satisfactory behaviour (Senge, 2006). It could, for example, be used to identify flow disruptions, pinpoint gaps in responsibility for flow and understand the positive (e.g., business) and negative (e.g., environmental) impacts of producing the flow. Thus, the holistic view allows the configuration of the elements in the RFS to manipulate the flow it produces.

Second, an in-depth understanding of the structure of RFSs provides insights into its elements, processes and interconnections (Kasser and Mackley, 2008). Understanding this structure allows an understanding of the system's workings, such as if it produces the desired behaviour of flowing resources (Meadows, 2008; Senge, 2006). Rather than its individual components, the way they are organised enables the system to deliver its overall function (Buede, 2009; Meadows, 2008; Pourdehnad *et al.*, 2011; Richmond, 1993; Seiffert and Loch, 2005). However, systems become increasingly complex when they span across multiple disciplines or domains (De Haan and De Heer, 2017). The RFS is a sociotechnical system (Hughes, 1987), which necessitates the consideration of multiple domains (Charnley *et al.*, 2011). Several elements of the RFS have emerged from this research, including roles of consumers and the dimensions that characterise them (Chapter 4), gateways and the dimensions that influence them (Chapter 4), PSSs elements that enable services to flow resources in a closed loop (Chapter 5), and a library of system elements for the flow-causality diagram (Chapter 6). These findings provide insights on the role of specific elements in the system's structure and, thus, deepen the understanding of how the system produces the flow (Aguirre Ulloa and Paulsen, 2017; Hughes, 1987). Expressing the resource flow as functions, e.g., using flow functions (Chapter 6) and the Flow Mapper's functional model (Chapter 7), allows us to define the system without reference to its elements (Kasser and Mackley, 2008) and, thus, configure and compare structures in a system's prototype to explore satisfactory behaviours (Aurisicchio *et al.*, 2012; Halbe *et al.*, 2014; Maussang *et al.*, 2007). These insights allow us to define operational requirements for the system, identify new research opportunities based on successful patterns of interrelated elements and develop insights on the root causes for closed-loop resource flows.

Practical value of system design methods

Evidence for commercial and economic success is one of the most effective drivers for a transition to the CE. The promise is that business value can be generated from flowing resources (EMF, 2012). However, whether resources flow often remains uncertain due to a lack of evidence for their success. This work has proposed methods that have been applied to a real-world design programme in the industry and have enabled the industrial users to gather evidence of the success (or failure) of systems proposed to produce flow. Such insights allow us to qualitatively reason if and how well the system produces flow. System performance can be investigated using non-functional system requirements or ilities (Burge, 2006). However, ilities typically relate to stakeholder objectives and, thus, indicate the amount of human effort and skill (Han, 2006) instead of the successful movement and transformation of resources. The flow functions and their respective processes provide concrete definitions of what the system must do (Stone *et al.*, 2000). These functions could be assessed against non-functional performance requirements, which set constraints that define how well the function must perform (Burge, 2006). This can provide further insights into whether and how well the functions are satisfied, which is useful and important to leverage system solutions (Seidel *et al.*, 2013). The prototype of the RFS can then enable an assessment of efficiency and efficacy, which enables stakeholders to gather and assess evidence for systems solutions.

8.3. Limitations and directions for future work

The limitations of the studies have been discussed in the respective chapters. However, there are a few limitations that apply to the thesis, which deserve to be highlighted. We address these and suggest directions for future work.

Methods and tools

This thesis developed a novel methodology to model an RFS. The studies described in Chapter 6 and Chapter 7 have been conducted in parallel. Although the methods follow the same theoretical background, the parallel execution was not permitted to implement all the learning from Chapter 6 into the application of the Flow Mapper in Chapter 7. Chapter 6 provides the most advanced version of the modelling method, and Chapter 7 provides the version of the modelling method that was more feasible to implement in industrial contexts. In future work, we plan to evolve the Flow Mapper to adopt the more advanced version of the method. Furthermore, both methods have limitations, such as the inability to model multi-material assemblies and variations of flow and distinguish between existing and novel system elements. P&G and other organisations have expressed interest in working with the Flow Mapper, which will provide further opportunities for using the tool in live projects to evaluate its usability and usefulness. Further research and industrial collaboration can lead to a better understanding of the limitations of conventional innovation processes for a CE design and allow the integration of the new methods in practice. Such research can also provide further insight into our aim to embed these methods into organisations rather than relying on consultancy and the role of designers in this proposition.

System elements and relations to flow

This work has produced insights into the role of several system elements in closed-loop systems for FMCGs. Although this research suggests a relationship between these elements and flow, further work is needed to understand these relations in more detail. For example, there is a need to examine the relation between the density of bins and consumer engagement. Such knowledge is valuable for the stakeholders tasked to design closed-loop systems, as it will allow in-depth and meaningful configurations. Forms of obsolescence, facilitators (incentives and investments), accessibility of gateways and entry requirements emerged as dimensions that influenced the role of consumers in Chapter 4. These and the PSS elements in Chapter 5 could be integrated into the library of system elements in Chapter 6 (section 5) to strengthen its use as a checklist and vocabulary for system designers. A thorough and exhaustive understanding could be used to draft an agenda for further research on the exact relations between elements and between elements and processes. Some of these relations might be expressible numerically, for example, by collecting and triangulating data, which provide an opportunity to develop a version of the Flow Mapper that simulates resource flows based on configurations of system elements and allow us to assess flow efficacy and efficiency.

Prioritisation of closed loops for FMCGs

Although the principles of resource flow-centred design are not exclusive to any flow, this thesis has predominantly focused on a closed loop, i.e., the output of a flow is input for the same flow (Braungart and McDonough, 2008; Geissdoerfer *et al.*, 2017; Konietzko *et al.*, 2020a). Concerns have been raised that a focus on closing loops in the CE might underestimate the dependency on energy resources to sustain such a journey (Allwood, 2014; Fiksel, 2006; Prendeville, Sanders, *et al.*, 2014). The criticism predominantly revolves around the justification of closed-loop flows in which resources transform from products to raw materials, which typically requires significant energy inputs (Allwood and Cullen, 2015; Blomsma, 2018). Establishing a closed loop, whether involving materials for recycling or components for reuse, emerged as the biggest challenge for FMCGs and was, therefore, adopted by this thesis. However, we acknowledge that a closed loop is not a dogma, and a balanced approach is needed for the best environmental and economic outcomes. We have confidence that the results of this thesis also apply to other types of resource flows and other sectors, but further work is recommended to explore this opportunity. We also acknowledge that work is needed to understand the non-material resource flows and the impacts caused by physically flowing resources. This work could support future assessment methods, as it allows a more detailed understanding that provides more accurate inputs into an assessment methodology. Further work is needed to investigate the relations between circularity indicators and the RFS.

8.4. Overview of the contributions

The overall aim of this research was to address practical knowledge gaps in the CE theory. We used qualitative research, systems thinking and industrial collaboration to develop knowledge and methods to address the challenges faced by the FMCG sector in its transition to a CE.

8.4.1. Main scientific contributions

The novelty of this thesis lies in the central position given to the physical flow of resources in research and design. This differs from other work in design and the CE, which typically prioritise synergies between CE objectives, value propositions and behaviour changes. The thesis provides contributions to research in the fields of design and the CE aligned to three underrepresented areas in the literature, as discussed in Chapter 3.

I) Resources are products, components and materials

Resources have been categorised into three states i.e., products, components and materials (Blomsma and Tennant, 2020). A general notion exists in the literature that flow can impact resources, e.g., the quality of a material resource is affected by recycling processes, and resources can impact the feasibility of flow, e.g., resources with compromised quality may be unable to satisfy manufacturing and consumption processes (Baxter *et al.*, 2014; Zink and Geyer, 2017). However, current understanding of resource states is still insufficient to build a comprehensive picture of how resources in flow. This thesis developed a novel method to characterise resources in different moments in time to inform the design of resources rather than products. The main contribution is:

- A State Model of key moments in the resource flow (operative, obsolete, recoverable, suppliable, market-ready and on market) that can be used to visualise the resource flow through Snapshots (Chapter 7).

II) Flow entails movements and transformations of resources

Resource flows involve tangible matter moving and transforming over time (Brunner and Rechberger, 2004). In design, resource flows are generally described as high level strategies, e.g., reuse and recycle (Ellen MacArthur Foundation, 2015b) and interpreted as product life cycles (Franconi *et al.*, 2019; Mestre and Cooper, 2017). However, current understanding of the physical movements and transformations that entail flow is not sufficiently rich. The thesis developed detailed understanding of resource flows going beyond typical life cycle phases, and offering a language to articulate flow as the physical movements and transformations of resources. The main contributions are:

- Four subfunctions that PSSs should satisfy to close loops; ‘intercept and transition obsolete resources’ are requirements demanded by PSSs to close loops and imply physical movement of resources; ‘state and govern resource lifetimes’ are requirements which PSSs should have to improve the likelihood of flowing resources (Chapter 5).
- A function tree and functional model based on Flow Functions, i.e., the processes that describe the physical movements and transformations of resources that

entail flow that are integrated in the Flow-Causality Diagram and the Flow Mapper (Chapter 6 and Chapter 7).

III) Systems produce resource flows

There appears to be a dominant focus on the role of design to integrate products and services in new business models for the CE (Bocken *et al.*, 2016; Guldmann *et al.*, 2019b; Pieroni *et al.*, 2019a). Despite the suggestion to broaden this focus to larger systems (Ceschin and Gaziulusoy, 2016; Charnley *et al.*, 2011), the approaches to investigate and design systems do not include resource flows in their entirety. Little is known about how systems produce flow, which limits our ability to design them and provide evidence for their success. This work interpreted resource flow as the behaviour of the system, allowing to define appropriate and inclusive boundaries to the system of interest (Meadows, 2008). The thesis produced novel insights on system elements and their interconnections, as well as novel methods and a tool to enable industrial users to adopt systems thinking in design practice. The main contributions are:

- Four archetypical roles of consumers i.e., keep, bring, consign and abandon obsolete resources, characterised by the form of obsolescence, the obsolete state change, prerequisite activities, and facilitators (incentives and investments) (Chapter 4).
- A conceptualisation of gateways as points where resources enter revalorisation systems and two factors that influence it (accessibility of gateways and resource entry criteria) (Chapter 4).
- A framework of twenty-one PSS elements organised in six architectural classes and mapped against the four subfunctions of PSS to close loops (Chapter 5).
- Circular Design Guidelines, which provide guidance on embedding PSS elements to close loops (Chapter 5).
- A conceptualisation of the RFSs as the system that encompasses interconnected system elements spanning across the sociotechnical system (Chapter 6).
- A library of System Elements that enable resource flows of FMCGs (Chapter 6).
- A method called Flow-Causality Diagram to model an RFS, which combines Flow Functions, System Elements and their causalities (Chapter 6).
- A tool called the Flow Mapper to model an RFS inclusive of a modelling method and the process to apply it and analyse the model (Chapter 7).

8.4.2. Industrial impact

The review presented in Chapter 2 suggests that the changes in the FMCG sector are primarily sustaining a linear business, rather than making structural changes to production and consumption systems. The adoption of the CE is predominantly encouraged by evidence for its success (Yuan *et al.*, 2006). Although case studies exist for the FMCG sector (e.g., EMF 2016), there is little knowledge of why these models are successful and how companies can adapt them for their business. The results of this research provide practical knowledge, applicable methods and a tool. The findings are relevant to several industrial sectors, but they have been specifically targeted at the FMCG sector. The FMCG sector praises itself for touching the lives of billions of people every day. This thesis aims to enable and encourage the sector to make systemic changes to current production and consumption systems on this scale.

Impact on the FMCG sector

There is increasing pressure from governments on the FMCG industry to change business as usual (e.g., European Commission, 2015), making research in the CE timely and relevant. Research on FMCGs and the CE typically focuses on specific system elements, such as those that relate to changing behaviour (Mugge, 2017; Daae and Boks, 2015; Lilley, 2009), provide guidance for product design features (e.g., Bakker *et al.*, 2014; Bhamra and Lofthouse, 2007; Mestre and Cooper, 2017) or explore the use of PSSs (Bocken *et al.*, 2016; Ceschin and Gaziulusoy, 2016; Tukker, 2004). There is a lack of methods and proven tools that provide an in-depth understanding of novel FMCG systems. Working closely with one of the largest players in the FMCG sector allowed us to evaluate the methods and tool in an industrial context. The results supported industrial users in gathering evidence for existing and novel system solutions, addressing the lack of evidence on CE business and enabling users to obtain it.

Impact on the industrial sponsor

Limited uptake of methods and tools by the industry is often attributed to a lack of involvement from future users in their development and the lack of evidence of their success (Bocken *et al.*, 2019; Peters *et al.*, 2020; Vallet *et al.*, 2013). The industrial collaboration has been invaluable to this research and has allowed the overcoming of both these challenges. Trust has been an enabling factor for this collaboration (Bruneel *et al.*, 2010). It has enabled us to learn from industrial users first hand, and it has provided several opportunities to validate our theories and findings in real-world settings and generate impact. For example, the PhD candidate has transferred CE knowledge to P&G employees through seminars, workshops, exhibitions and co-authorship of internal publications and engaged in live CE projects. More importantly, the development of the Flow Mapper tool was accelerated to generate an impact on the FMCG sector within the course of the PhD programme.

8.5. Conclusions

Despite sustainability efforts by the FMCG sector, systemic change to existing production and consumption systems has been minimal. This is a concern as it precludes the ability to establish closed-loop resource flows and transition to a CE. This thesis advanced our understanding of the relation between resource flows and FMCG systems and proposed methods to apply such knowledge to enable industry to design for circular systems. Design is considered a catalyst for the transition to a CE, but the literature on design and the CE does not provide sufficiently granular methods to consider the actual physical movements and transformations of resources in design. This doctoral research was initially focussed on the moment in which resources become obsolete, as this event poses a high risk of disrupting resource flows. System elements relevant to consumers' roles and the design of PSSs to close the loops of resource flows were identified and organised in frameworks. Subsequently, the focus of the research shifted to developing methods to understand how system elements are used to produce a flow of resources. Novel theory-based methods to model an RFS have been proposed. These methods allow to understand all the interconnected system elements that span across a sociotechnical system and must be in place to produce resource flow. A tool embedding the modelling methods was developed and evaluated by industrial users. It allows to obtain a holistic view and in-depth insights in the RFS informing its design. The thesis proposes a novel design philosophy called resource flow-centred design, which puts the flow of resources centre stage by designing resources and RFSs, rather than products and business models.

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List of Publications

Journal papers featuring work presented in this thesis

Zeeuw van der Laan, A. and Aurisicchio, M. (2020), “A framework to use product-service systems as plans to produce closed-loop resource flows”, *Journal of Cleaner Production*, Vol. 252, p. 119733.

Zeeuw van der Laan, A. and Aurisicchio, M. (2019), “Archetypical consumer roles in closing the loops of resource flows for Fast-Moving Consumer Goods”, *Journal of Cleaner Production*, Vol. 236,.

Conference papers featuring work presented in this thesis

Zeeuw van der Laan, A. and Aurisicchio, M. (2021), “The Flow Mapper : A Tool to Model Solutions for the Circular Economy and Put Systems Thinking into Action properties”, *PLATE Conference* 2021.

Zeeuw van der Laan, A. and Aurisicchio, M. (2019), “Gateways to Revalorisation in Future Circular Cities: A Vision for Closed-Loop Resource Flows”, Sustainable Innovation 22nd International Conference. Road to 2030: Sustainability, Business Models, Innovation and Design, The Centre for Sustainable Design, pp. 113–119.

Zeeuw van der Laan, A. and Aurisicchio, M. (2019), “Designing Product-Service Systems to Close Resource Loops: Circular Design Guidelines”, *Procedia CIRP*, Vol. 80, pp. 631–636.

Zeeuw van der Laan, A. and Aurisicchio, M. (2017), “Planned Obsolescence in the Circular Economy”, *PLATE Conference* 2017, pp. 446–452.

Other publications

Aurisicchio, M., Zeeuw van der Laan, A. and Tennant, M. (2020), “Material-Service Systems for Sustainable Resource Management”, EcoDesign and Sustainability, Vol. I, pp. 89–101.

Muranko, Ż., Tassell, C., Zeeuw van der Laan, A. and Aurisicchio, M. (2021), “Characterisation and Environmental Value Proposition of Reuse Models for Fast-Moving Consumer Goods: Reusable Packaging and Products”, *Sustainability,* Vol. 13 No. 2609.

Lists of acronyms, figures and tables

Acronyms

3R	Reduce, Reuse, Recycle
B2B	Business to Business
B2C	Business to Consumer
CE	Circular Economy
C2C	Cradle-to-Cradle
CJM	Customer Journey Map
CSR	Corporate Social Responsibility
DfS	Design for Sustainability
DfX	Design for X
D2C	Direct to Consumer
DRM	Design research Methodology
EMF	Ellen MacArthur Foundation
EPR	Extended Producer Responsibility
EOL	End-of-life
FCD	Flow-Causality Diagram
FM	Flow Mapper
GDP	Gross Domestic Product
GHG	Greenhouse Gas
FMCG	Fast-Moving Consumer Good
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
MRF	Material Recovery Facility
MSS	Material-Service System
P&G	Procter & Gamble
PCR	Post-Consumer Recycled
PSS	Product-Service System
SDG	Sustainable Development Goal

Figures

Tables

References

Acaroglu, L. (2018), *Circular Systems Design - A Toolkit for the Circular Economy,* Disrupt Design LLC, New York, United States.

Agrawal, S., Singh, R.K. and Murtaza, Q. (2015), “A literature review and perspectives in reverse logistics”, *Resources, Conservation and Recycling*, Vol. 97, pp. 76–92.

Agrawal, V. V, Kavadias, S. and Toktay, L.B. (2016), “The Limits of Planned Obsolescence for Conspicuous Durable Goods”, *Manufacturing & Service Operations Management*, Vol. 18 No. 2, pp. 216–226.

Aguirre Ulloa, M. and Paulsen, A. (2017), “Co-designing with relationships in mind”, *FormAkademisk - Forskningstidsskrift for Design Og Designdidaktikk*, Vol. 10 No. 1, pp. 1–14.

Ali, M. and Courtenay, P. (2014), “Evaluating the progress of the UK’s Material Recycling Facilities: A mini review”*, Waste Management and Research*, Vol. 32 No. 12, pp. 1149–1157.

Alliance to End Plastic Waste. (2019), “The Alliance to End Plastic Waste”.

Allwood, J.M. (2012), “Sustainable materials – with both eyes open”, *University of Cambridge - The Future in Practice*, pp. 3–5.

Allwood, J.M. (2014), “Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies”, in Worell;, E. and Reuter, M. (Eds.), *Handbook of Recycling*, pp. 445–477.

Allwood, J.M., Ashby, M.F., Gutowski, T.G. and Worrell, E. (2011), “Material efficiency: A white paper”, *Resources, Conservation and Recycling*, Vol. 55 No. 3, pp. 362–381.

Allwood, J.M. and Cullen, J.M. (2011), *Sustainable Materials: With Both Eyes Open*, UIT Cambridge

Allwood, J.M. and Cullen, J.M. (2015), *Sustainable Materials - without the Hot Air*, UIT Cambridge.

Alting, L. and Legarth, J.B. (1995), “Life Cycle Engineering and Design”, *CIRP Annals - Manufacturing Technology*, Vol. 44 No. 2, pp. 569–580.

Andrews, D. (2015), “The circular economy, design thinking and education for sustainability”, *Local Economy*, Vol. 30 No. 3, pp. 305–315.

Annamalai, G., Hussain, R., Cakkol, M., Roy, R., Evans, S. and Tiwari, A. (2010), *An Ontology for Product-Service Systems, Functional Thinking for Value Creation.*

Antikainen, M. and Paloheimo, H. (2017), “Creating value for consumers in CE-Tools as a service”, *XXVIII Innovation Conference - Composing the Innovation Symphony*

Anttonen, M. (2008), “Greening from the front to the back door? Investigating the varieties of chemical and resource management services”, *Business Strategy and the Environment*, Vol. 215 No. January 2009, pp. 199–215.

Arabi, M., Mansour, S. and Shokouhyar, S. (2017), “Optimizing a warranty–based sustainable product service system using game theory”, *International Journal of Sustainable Engineering*, Vol. 7038 No. January, pp. 1–12.

Armstrong, C.M., Niinimäki, K., Kujala, S., Karell, E. and Lang, C. (2015), “Sustainable product-service systems for clothing: Exploring consumer perceptions of consumption alternatives in Finland”, *Journal of Cleaner Production*, Vol. 97, pp. 30–39.

Ashby, M.F. and Johnson, K. (2002), *Materials and Design*, 7th (2007)., Oxford.

Attri, R., Dev, N. and Sharma, V. (2013), “Interpretive structural modelling (ISM) approach: an overview”, *Research Journal of Management Sciences*, Vol. 2319 No. 2, p. 1171.

Aurisicchio, M., Bracewell, R. and Armstrong, G. (2012), “The Function Analysis Diagram”, *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*.

Aurisicchio, M., Eng, N.L., Ortíz Nicolás, J.C., Childs, P.R.N. and Bracewell, R. (2011), “On the Functions of Products”, *International Conference on Engineering Design, ICED 2011*.

Aurisicchio, M., Zeeuw van der Laan, A. and Tennant, M. (2020), “Material-Service Systems for

Sustainable Resource Management", *EcoDesign and Sustainability*, Vol. I, pp. 89–101.

Ayala-Garcia, C., Rognoli, V. and Karana, E. (2017), "Five Kingdoms of DIY-Materials for Design", *EKSIG 2017: Alive. Active. Adaptive*, Delft, The Netherlands, pp. 222–234.

Babader, A., Ren, J., Jones, K.O. and Wang, J. (2016), "A system dynamics approach for enhancing social behaviours regarding the reuse of packaging", E*xpert Systems With Applications*, Vol. 46, pp. 417–425.

Baccini, P. and Brunner, P.H. (2012), *Metabolism of the Anthroposphere*, 2nd ed., MIT Press.

Bahrudin, F.I. Bin. (2019), *The Experiential Dimension of Sutainable Materials*, Imperial College London.

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., et al. (2007), "State-of-the-art in product-service systems", *Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 221 No. 10, pp. 1543–1552.

Baker, C., Wuest, J. and Stern, P.N. (1992), "Method slurring: the grounded theory/ phenomenology example", *Journal of Advanced Nursing*, Vol. 17 No. 11, pp. 1355–1360.

Bakker, C., Den Hollander, M.C., Hinte, E. van and Zijlstra, Y. (2014), *Products That Last: Product Design for Circular Business Models*, 1st ed., TU Delft Library, Delft.

Bakker, C., Wang, F., Huisman, J. and Den Hollander, M.C. (2014), "Products that go round: Exploring product life extension through design", *Journal of Cleaner Production*, Vol. 69, pp. 10–16.

Bakker, C., Hollander, M. Den, Peck, D. and Balkenende, R. (2019), "Circular Product Design: Addressing Critical Materials through Design", in Offerman, S.E. (Ed.), *Critical Materials - Underlying Causes and Sustainable Mitigation Strategies*, World Scientific Publishing, pp. 179–192.

Bakker, C., Wever, R., Teoh, C. and Clercq de, S. (2010), "Designing cradle-to-cradle products: a reality check", *International Journal of Sustainable Engineering*, Vol. 3 No. 1, pp. 2–8.

Bala, B.K., Arshad, F.M. and Noh, K.M. (2017), "Systems Thinking: System Dynamics", System Dynamics, pp. 15–35.

Baldassarre, B., Konietzko, J., Brown, P., Calabretta, G., Bocken, N., Karpen, I.O. and Hultink, E.J. (2020), "Addressing the design-implementation gap of sustainable business models by prototyping: A tool for planning and executing small-scale pilots", *Journal of Cleaner Production*, Vol. 255, p. 120295.

Bansal, P. and Corley, K. (2012), "What 's different about qualitative research?", *Academy of Management Journal*, Vol. 55 No. 3, pp. 509–513.

Barati, B. and Karana, E. (2019), "Affordances as Materials Potential : What Design Can Do for Materials Development", *International Journal of Design*, Vol. 13 No. 3, pp. 105–123.

Barles, S. (2015), "History of Waste Management and the Social and Cultural Representations of Waste", in Serneri, S. (Ed.), *The Basic Environmental History*, pp. 199–226.

Barquet, A.P.B., de Oliveira, M.G., Amigo, C.R., Cunha, V.P. and Rozenfeld, H. (2013), "Employing the business model concept to support the adoption of product-service systems (PSS)", *Industrial Marketing Management*, Vol. 42 No. 5, pp. 693–704.

Barr, S. (2007), "Factors Influencing Environmental Attitudes and Behaviors A U.K. Case Study of Household Waste Management", *Enviornment and Behavior*, Vol. 39, No. 4

Bartels, B., Ermel, U., Pecht, M. and Sandborn, P. (2012), "Introduction to Obsolescence Problems", *Strategies to the Prediction, Mitigation and Management of Product Obsolescence*.

Basow, S.A. (1991), "The hairless ideal", *Psychology of Women Quarterly*, Vol. 15 No. March 1990, pp. 83–96.

Baum, F., MacDougall, C. and Smith, D. (2006), "Participatory action research", *Journal of Epidemiology and Community Health*, Vol. 60 No. 10, pp. 854–857.

Baxter, W.L. (2017), *Designing Circular Possessions Exploring Human - Object Relationships in*

the Circular Economy, Imperial College London.
Baxter, W.L., Aurisicchio, M. and Childs, P.R.N. (2014), "Materials, use and contaminated interaction", *Materials and Design*, Vol. 90, pp. 1218–1227.
Baxter, W.L., Aurisicchio, M. and Childs, P.R.N. (2015), "A psychological ownership approach to designing object attachment", *Journal of Engineering Design*, Vol. 26 No. 4–6, pp. 140–156.
Baxter, W.L., Aurisicchio, M. and Childs, P.R.N. (2016), "Tear Here: the Impact of Object Transformations on Proper Disposal", *20th World Conference on Packaging, IAPRI World Conference on Packaging*.
Baxter, W.L., Aurisicchio, M. and Childs, P.R.N. (2017), "Contaminated Interaction Another Barrier to Circular Material Flows", *Journal of Industrial Ecology*, Vol. 21 No. 3, pp. 507–516.
Bellos, I. and Ferguson, M. (2017), "Moving from a Product-Based Economy to a Service-Based Economy for a More Sustainable Future", *Sustainable Supply Chains*, Springer, Vol. 4.
Benyus, J.M. (1998), Biomimicry: Innovation Inspired by Nature.
Berger, K.R. (2003), "A Brief History of Packaging", *EDIS*, Vol. 17.
Berry, L.L., Seiders, K. and Grewal, D. (2002), "Understanding Service Convenience", *Journal of Marketing*, Vol. 66 No. 3, pp. 1–17.
Besch, K. (2005), "Product-service systems for office furniture: Barriers and opportunities on the European market", *Journal of Cleaner Production*, Vol. 13 No. 10–11, pp. 1083–1094.
Bettencourt, L.A. and Ulwick, A.W. (2008), "The Customer-Centered Innovation Map", *Harvard Business Review*, Vol. 86 No. 5, pp. 109–114.
Beuren, F.H., Gomes Ferreira, M.G. and Cauchick Miguel, P.A. (2013), "Product-service systems: A literature review on integrated products and services", *Journal of Cleaner Production*, Vol. 47, pp. 222–231.
Bhamra, T. and Lofthouse, V.A. (2007), *Design for Sustainability: A Practical Approach*, Gower Publishing Limited, Aldershot.
Bhardwaj, V. and Fairhurst, A. (2010), "Fast fashion: Response to changes in the fashion industry", *International Review of Retail, Distribution and Consumer Research*, Vol. 20 No. 1, pp. 165–173.
Bihouix, P. (2020), *The Age of Low Tech: Towards a Technologically Sustainable Civilization*, Policy Press.
Bijl-Brouwer, M. van der and Malcolm, B. (2020), "Systemic Design Principles in Social Innovation: A Study of Expert Practices and Design Rationales", *She Ji*, Vol. 6 No. 3, pp. 386–407.
Bindel, A., Rosamond, E., Conway, P. and West, A. (2012), "Product Life Cycle Information Management in the Electronics Supply Chain", *Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 226.
Blessing, L.T.M. and Chakrabarti, A. (2009), *DRM, a Design Research Methodology*.
Blizzard, J.L. and Klotz, L.E. (2012), "A framework for sustainable whole systems design", *Design Studies*, Vol. 33 No. 5, pp. 456–479.
Blomsma, F. (2018), "Collective 'action recipes' in a circular economy – On waste and resource management frameworks and their role in collective change", *Journal of Cleaner Production*, Vol. 199, pp. 969–982.
Blomsma, F. and Brennan, G. (2017), "The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity", *Journal of Industrial Ecology*, Vol. 21 No. 3, pp. 603–614.
Blomsma, F. and Brennan, G. (2018), "Circularity Thinking", in Charter, M. (Ed.), *Designing for the Circular Economy*, Routledge, pp. 133–145.
Blomsma, F., Kjaer, L., Pigosso, D., McAloone, T.C. and Lloyd, S. (2018), "Exploring Circular Strategy Combinations - towards Understanding the Role of PSS", *Procedia CIRP*, Vol. 69

No. May, pp. 752–757.
Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D.C.A., Hildenbrand, J., Kristinsdottir, A.R., Kristoffersen, E., et al. (2019), “Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation”, *Journal of Cleaner Production*, Vol. 241, p. 118271.
Blomsma, F. and Tennant, M. (2020), “Circular economy: preserving particles or products? Introducing the Resource States framework”, *Resources, Conservation and Recycling*.
Blomsma, F., Tennant, M. and Brennan, G. (2020), “Beyond Product / Service Systems - towards a system view of circular strategies , circular business models , and circular value chains”, *IS4CE2020 Conference of the International Society for the Circular Economy*.
Blythe, R.A. and Macphee, C.E. (2013), “The Life and Death of Cells”, Physics, Vol. 6.
Bocken, N.M.P., de Pauw, I., Bakker, C. and van der Grinten, B. (2016), “Product design and business model strategies for a circular economy”, *Journal of Industrial and Production Engineering*, Vol. 33 No. 5, pp. 308–320.
Bocken, N.M.P., Short, S., Rana, P. and Evans, S. (2013), “Value mapping for business models”, *Corporate Governance*, Vol. 13 No. 5, pp. 482–497.
Bocken, N.M.P. and Short, S.W. (2016), “Towards a sufficiency-driven business model: Experiences and opportunities”, *Environmental Innovation and Societal Transitions*, Vol. 18, pp. 41–61.
Bocken, N.M.P., Strupeit, L., Whalen, K. and Nußholz, J. (2019), “A Review and Evaluation of Circular Business Model Innovation Tools”*, Sustainability,* Vol. 11 No. 8, p. 2210.
Bocken, N.M.P., Ritala, P. and Huotari, P. (2017), “The Circular Economy: Exploring the Introduction of the Concept Among S&P 500 Firms”, *Journal of Industrial Ecology*, Vol. 21 No. 3, pp. 487–490.
Boehm, M. and Thomas, O. (2013), “Looking beyond the rim of one’s teacup: A multidisciplinary literature review of Product-Service Systems in Information Systems, Business Management, and Engineering & Design”, *Journal of Cleaner Production*, Vol. 51, pp. 245–260.
Bofylatos, S. and Spyrou, T. (2016), “Supporting Design Dialogue through a Communication Framework Using Four Layers of Abstraction”, *Design Journal*, Routledge, Vol. 19 No. 2, pp. 269–282.
Boks, C. and Daae, J.Z. (2017), “Design for sustainable use using principles of behaviour change”, in Chapman, J. (Ed.), *Routledge Handbook of Sustainable Product Design*, 1st ed., Routledge, pp. 316–334.
Boons, F. and Howard-Grenville, J. (2009), *The Social Embeddedness of Industrial Ecology*,.
Borrego, M., Foster, M.J. and Froyd, J.E. (2014), “Systematic literature reviews in engineering education and other developing interdisciplinary fields”, *Journal of Engineering Education*, Vol. 103 No. 1, pp. 45–76.
Boudling, K.E. (1970), “Fun and Games with the Gross National Product - The Role of Misleading Indicators in Social Policy”, in Helfrich, Jr., H.W. (Ed.), *The Environmental Crisis*, Yale University, New Haven, pp. 157–170.
Boulding, K.E. (1966), *The Economics of the Coming Spaceship Earth*, Johns Hopkins University Press, Baltimore.
Braungart, M. and McDonough, W. (2008), *Cradle to Cradle: Re-Making the Way We Make Things*, Vintage Books, London.
Breen, L. (2006), “Give me back my empties or else! A preliminary analysis of customer compliance in reverse logistics practices (UK)”, *Management Research News*, Emerald Group Publishing Limited, Vol. 29 No. 9, pp. 532–551.
Bressanelli, G., Adrodegari, F., Perona, M. and Saccani, N. (2018), “Exploring how usage-focused business models enable circular economy through digital technologies”*, Sustainability,*

MDPI, Vol. 10 No. 3.
British Plastics Federation (BPF). (2018), *Plastics : A Vision for a Circular Economy*.
Brooks, A.L., Wang, S. and Jambeck, J.R. (2018), "The Chinese import ban and its impact on global plastic waste trade", *Science Advances*, Vol. 4 No. 6, pp. 1–8.
Brown, P., Bocken, N.M.P. and Balkenende, R. (2019), "Why Do Companies Pursue Collaborative Circular Oriented Innovation ?", *Sustainability,* Vol. 11 No. 635, pp. 1–23.
Brown, T. (2008), "Design Thinking", *Harvard Business Review*, No. June.
De Bruijn, H. and Herder, P.M. (2009), "System and actor perspectives on sociotechnical systems", *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans*, Vol. 39 No. 5, pp. 981–992.
Brundtland, G.H. (1987), *Our Common Future*, Oslo.
Bruneel, J., D'Este, P. and Salter, A. (2010), "Investigating the factors that diminish the barriers to university-industry collaboration", *Research Policy,* Vol. 39 No. 7, pp. 858–868.
Brunner, P.H. and Rechberger, H. (2004), *Practical Handbook of Material Flow Analysis*, CRC Press LCC.
Buede, D.M. (2009), *The Engineering Design of Systems - Models and Methods*, 2nd ed., John Wiley & Sons Inc.
Buijs, J. (2003), "Modelling Product Innovation Processes, from Linear Logic to Circular Chaos", *Creativity and Innovation Management*, Vol. 12 No. 2, pp. 76–93.
Burge, S. (2006), "Holistic Requirements Model (HRM)", *The Systems Engineering Tool Box*.
Burge, S. (2011), "Functional Modelling (FM)", *The Systems Engineering Tool Box.*
Burns, B. (2010), "Re-evaluating Obsolescence and Planning for It", in Cooper, T. (Ed.), *Longer Lasting Products: Alternatives To The Throwaway Society*, Gower Publishing Ltd., pp. 39–60.
Butler, D. and Tischler, L. (2015), *Design to Grow: How Coca-Cola Learned to Combine Scale and Agility (and How You Can, Too)*, edited by 1, Simon & Schutser, New York.
Butler, J. and Hooper, P. (2005), "Dilemmas in optimising the environmental benefit from recycling : A case study of glass container waste management in the UK", Vol. 45, pp. 331–355.
Camillus, J.C. (2008), "Strategy as a wicked problem", *Harvard Business Review*, Vol. 86 No. 5.
Catlin, J.R. and Wang, Y. (2012), "Recycling Gone Bad: When the Option to Recycle Increases Resource Consumption Jesse", *Journal of Consumer Psychology*, Vol. 23 No. 1, pp. 122–127.
Ceschin, F. (2013), "Critical factors for implementing and diffusing sustainable product-Service systems: insights from innovation studies and companies' experiences", *Journal of Cleaner Production*, Vol. 45, pp. 74–88.
Ceschin, F. and Gaziulusoy, I. (2016), "Evolution of design for sustainability: From product design to design for system innovations and transitions", *Design Studies*, Vol. 47, pp. 118–163.
Ceschin, F. and Gaziulusoy, I. (2020), *Design for Sustainability - A Multi-Level Framework from Products to Socio-Technical Systems, Routledge*, New York.
Chang, M.M.L., Ong, S.K. and Nee, A.Y.C. (2017), "Approaches and Challenges in Product Disassembly Planning for Sustainability", *Procedia CIRP*, The Author(s), Vol. 60, pp. 506–511.
Chapman, J. (2009), "Design for (Emotional) Durability", *Design Issues*, Vol. 25 No. 4, pp. 29–35.
Charnley, F., Lemon, M. and Evans, S. (2011), "Exploring the process of whole system design", *Design Studies*, Vol. 32, pp. 156–179.
Charnley, F., Walker, D. and Kuzmina, K. (2015), Fast-Moving Circular Goods 2025, Vol. 006.
Chattopadhyay, G. and Rahman, A. (2008), "Development of lifetime warranty policies and models for estimating costs", Reliability Engineering and System Safety, Vol. 93 No. 4,

pp. 522–529.
Chaudhary, K. and Vrat, P. (2020), "Circular economy model of gold recovery from cell phones using system dynamics approach: a case study", *Environment, Development and Sustainability*, Vol. 22 No. 1, pp. 173–200.
Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. and Sovacool, B. (2018), "Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework", *Energy Research and Social Science*, Vol. 37 No. November 2017, pp. 175–190.
Chertow, M.R. (2000), "Industrial Symbiosis: Literature and Taxonomy", *Annual Review Energy Environment*, Vol. 25, pp. 313–337.
Chileshe, N., Jayasinghe, R.S. and Rameezdeen, R. (2019), "Information flow-centric approach for reverse logistics supply chains", *Automation in Construction*, Vol. 106 No. June, p. 102858.
Choi, Y.J., Stevens, J. and Brass, C. (2018), "Carative Factors in the Design Development Process: Towards Understanding Owner-Object Detachment and Promoting Object Longevity", The *Design Journal*, Vol. 21 No. 4, pp. 477–497.
Coles, R., McDowell, D. and Kirwan, M.J. (2003), *Food Packaging Technology*, Vol. 5, Blackwell Publishing.
Cooper, T. (2004), "Inadequate Life? Evidence of Consumer Attitudes to Product Obsolescence", *Journal of Consumer Policy*, Vol. 27 No. 4, pp. 421–449.
Cooper, T. (2005), "Slower Consumption ' Throwaway Society '", *Journal of Industrial Ecology*, Vol. 9 No. 1, pp. 51–67.
Cooper, T. (2010), "The Significance of Product Longevity", in Cooper, T. (Ed.), *Longer Lasting Products: Alternatives To The Throwaway Society, Gower Publishing Limited*, pp. 3–36.
Copeland, M.T. (1923), "Relation of consumers' buying habits to marketing methods", *Harvard Business Review*, Vol. 1 No. 3, pp. 282–289.
Corbin, L. and Garmulewicz, A. (2018), "Circularity through local abundance: tapping the potential of the biocycle", No. September, pp. 1–17.
Corbin, L., Gladek, E. and Tooze, J. (2018), "Materials Demcoracy: An action plan for realising a redistributed materials economy", *Making Futures*, Vol. 5, pp. 1–30.
Corvellec, H. and Stål, H.I. (2017), "Evidencing the waste effect of Product-Service Systems (PSSs)", *Journal of Cleaner Production*, Vol. 145, pp. 14–24.
Costa, F., Prendeville, S., Beverley, K., Teso, G. and Brooker, C. (2015), "Sustainable product-service systems for an office furniture manufacturer: How insights from a pilot study can inform PSS design", *Procedia CIRP*, Vol. 30, pp. 66–71.
Creswell, J. (2007), *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, SAGE Publications, Inc, Thousand Oaks.
Creswell, J.W., Hanson, W.E., Clark Plano, V.L. and Morales, A. (2007), "Qualitative Research Designs: Selection and Implementation", *The Counseling Psychologist*, Vol. 35 No. 2, pp. 236–264.
Crosier, A. and Handford, A. (2012), "Customer Journey Mapping as an Advocacy Tool for Disabled People: A Case Study", *Social Marketing Quarterly*, Vol. 18 No. 1, pp. 67–76.
Curtin, S. (2016), "The effect of British natural history television programmes: Animal representations and wildlife tourism", *Mediating the Tourist Experience: From Brochures to Virtual Encounters*, Edited by Jo-Anne Lester and Caroline Scarles, pp. 75–90.
Daae, J. and Boks, C. (2015), "A classification of user research methods for design for sustainable behaviour", *Journal of Cleaner Production*, Vol. 106, pp. 680–689.
Dahlén, L. (2008), *Household Waste Collection: Factors and Variations,* Luleå University of Technology Department of Civil, Mining and Environmental Engineering.
Dahlén, L. and Lagerkvist, A. (2010), "Evaluation of recycling programmes in household waste

collection systems”, *Waste Management & Research*, Vol. 28, pp. 577–586.

Demirel, P. and Kesidou, E. (2011), “Stimulating different types of eco-innovation in the UK: Government policies and firm motivations”, *Ecological Economics*, Vol. 70 No. 8, pp. 1546–1557.

Derksen, L. and Gartrell, J. (1993), “The Social Context of Recycling”, *American Sociological Review,* Vol. 58, pp. 434–442.

Detzel, A. and Mönckert, J. (2009), “Environmental evaluation of aluminium cans for beverages in the German context”, *International Journal of Life Cycle Assessment*, Vol. 14 No. SUPPL. 1, pp. 70–79.

Dewberry, E.L. and Monteiro de Barros, M. (2009), “Exploring the Need for More Radical Sustainable Innovation - What Does it Look Like and Why?”, *International Journal of Sustainable Engineering*, Vol. 2 No. 1, pp. 28–39.

Dewberry, E.L., Sheldrick, L., Moreno, M., Sinclair, M. and Makatsoris, C. (2017), “Developing Scenarios for Product Longevity and Sufficiency”.

Dhall, R.K., Sharma, S.R. and Mahajan, B.V.C. (2012), “Effect of shrink wrap packaging for maintaining quality of cucumber during storage”, *Journal of Food Science and Technology*, Vol. 49 No. 4, pp. 495–499.

Dobbs, R., Oppenheim, J., Kendall, A., Thompson, F., Bratt, M. and van der Marel, F. (2013), *Reverse the Curse: Maximizing the Potential of Resource-Driven Economies*.

Domina, T. and Koch, K. (2002), “Convenience and Frequency of Recycling. Implications for Including Textiles in Curbside Recycling Programs”, *Environment and Behavior*, Vol. 34, pp. 216–38.

Dora, M., Bhatia, S. and Gallear, D. (2016), *Supply Chain in a Circular Economy: A Multidimensional Research Agenda*.

Dorst, K. (2019), “What Design Can’t Do”, *She Ji*, Vol. 5 No. 4, pp. 357–359.

Dorst, K. and Cross, N. (2001), “Creativity in the design process: Co-evolution of problem-solution”, *Design Studies*, Vol. 22 No. 5, pp. 425–437.

Dou, K., Wang, X., Tang, C., Ross, A. and Sullivan, K. (2015), “An evolutionary theory-systems approach to a science of the ilities”, *Procedia Computer Science*, Vol. 44 No. C, pp. 433–442.

Dwyer, C. (2015), “Socio-technical Systems Theory and Environmental Sustainability”, *Proceedings of SIGGreen Workshop, Sprouts: Working Papers on Information Systems,* Vol. 11 No. 3.

Eastman, C.M. (2012), *Design for X: Concurrent Engineering Imperiatives*, edited by Huang, G.Q., Springer.

Elia, V., Gnoni, M.G. and Tornese, F. (2017), “Measuring circular economy strategies through index methods: A critical analysis”, *Journal of Cleaner Production*, Vol. 142, pp. 2741–2751.

Ellen MacArthur Foundation. (2012), *Towards the Circular Economy (Volume 1): Economic and Business Rationale for an Accelerated Transition.*

Ellen MacArthur Foundation. (2013), *Towards the Circular Economy (Volume 2): Opportunities for the Consumer Goods Sector.*

Ellen MacArthur Foundation. (2014), *Towards the Circular Economy (Volume 3): Accelerating the Scale-up across Global Supply Chains.*

Ellen MacArthur Foundation. (2015a), *Towards a Circular Economy: Business Rationale for an Accelerated Transition.*

Ellen MacArthur Foundation. (2015b), *Circularity Indicators : An Approach to Measuring Circularity.*

Ellen MacArthur Foundation. (2016), *The New Plastics Economy: Rethinking the Future of Plastics.*

Ellen MacArthur Foundation. (2017a), *The New Plastics Economy: Catalysing Action.*
Ellen MacArthur Foundation. (2017b), *Urban Biocycles.*
Ellen MacArthur Foundation. (2019a), *Completing the Picture: How the Circular Economy Tackles Climate Change*, No. September, pp. 1–60.
Ellen MacArthur Foundation. (2019b), *HolyGrail : Tagging Packaging for Accurate Sorting and High-Quality Recycling.*
Ellen MacArthur Foundation. (2019c), *Reuse - Rethinking Packaging*
Engelhardt, F. (2000), "Improving systems by combining axiomatic design, quality control tools and designed experiments", *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, Vol. 12 No. 4, pp. 204–219.
Eppler, M.J. and Bresciani, S. (2013), "Visualization in management: From communication to collaboration. A response to Zhang", *Journal of Visual Languages and Computing*, Vol. 24 No. 2, pp. 146–149.
European Commission. (2011), *Roadmap to a Resource Efficient Europe*.
European Commission. (2014), "Towards a circular economy: A zero waste programme for Europe", European Commission, Vol. 398, pp. 1–14.
European Commission. (2015a), *Closing the Loop - Helping Consumers Choose Sustainable Products and Services.*
European Commission. (2015b), C*losing the Loop - Clear Targets and Tools for Better Waste Management.*
European Commission. (2018a), *On the Implementation of the Circular Economy Package: Options to Address the Interface between Chemical, Product and Waste Legislation* (Accompanying the Document).
European Commission. (2018b), *A European Strategy for Plastics in a Circular Economy.*
European Commission. (2018c), *On a Monitoring Framework for the Circular Economy.*
European Union. (2008), *Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directives.*
European Union. (2019), *Directive of the European Parliament and the Council on the Reduction of the Impact of Ceratin Plastic Products on the Environment.*
Farrell, R. and Hooker, C. (2013), "Design, science and wicked problems", *Design Studies*, Vol. 34 No. 6, pp. 681–705.
Favi, C., Marconi, M., Germani, M. and Mandolini, M. (2019), "A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling", *Advanced Engineering Informatics*, Vol. 39, pp. 62–79.
Fearnley-Whittingstall, H. and Rani, A. (2019), "War on plastics", BBC One.
Feldman, K. and Sandborn, P. (2007), "Integrating Technology Obsolescence Considerations into Product Design Planning", *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference.*
Fiksel, J. (2006), "A Framework for Sustainable Materials Management", *Journal of the Minerals, Metals and Materials*, No. August, pp. 15–22.
Filimonau, V. (2016), "The Life Cycle Thinking Approach and the Method of Life Cycle Assessment (LCA)", *Life Cycle Assessment (LCA) and Life CYcle Analysis in Tourism*, pp. 9–43.
Findeli, A. (2001), "Rethinking Design Education for the 21st Century: Theoretical, Methodological, and Ethical Discussion", *Design Issues*, Vol. 17 No. 1, pp. 5–17.
Finnveden, G. (2000), "On the Limitations of Life Cycle Assessment and Environmental Systems Analysis Tools in General", *The International Journal of Life Cycle Assessment*, Vol. 5 No. 229.
Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., et al. (2011), "Methodology and indicators of economy-wide material flow accounting: State of the art and reliability across sources", *Journal of Industrial Ecology*, Vol. 15 No.

6, pp. 855–876.
Fishbein, B.K. (1996), *Germany, Garbage, and the Green Dot: Challenging the Throwaway Society*, Vol. 50.
Fletcher, A.J. (2017), "Applying critical realism in qualitative research: methodology meets method", *International Journal of Social Research Methodology*, Vol. 20 No. 2, pp. 181–194.
Flanagan, T.R. (2014), "Systemic Design Principles for Complex Social Systems", *Social Systems and Design*, Vol. 1, pp. 147–166.
Flood, R.L. (2010), "The Relationship of 'Systems Thinking' to Action Research", *Systemic Practice and Action Research*, Vol. 23, pp. 269–284.
Forrester, J.W. (1968a), *Principles of Systems*, 6th ed., Wright-Allen Press Inc.
Forrester, J.W. (1968b), *Industrial Dynamics*, 5th ed., The MIT Press.
Fortune. (2019), "Global Fortune 500".
Fragala, M.S. (2015), "The physiology of aging and exercise", in Sullivan, G.M. and Pomidor, A.K. (Eds.), *Exercise for Aging Adults*, pp. 1–11.
Franconi, A., Badalucco, L., Peck, D. and Nasr, N. (2019), "A multi-hierarchical ' Design for X ' framework for accelerating circular economy", *PLATE Conference*, pp. 18–20.
Freeman, C. (2001), *As Time Goes by : From the Industrial Revolutions to the Information Revolution*, Oxford University Press, Oxford.
Gallagher, R. and Appenzeller, T. (1999), "Beyond Reductionism", *Science Magazine*, Vol. 284, p. 79.
Galvao, A.B. and Sato, K. (2005), "Affordances in product architecture: Linking technical functions and users' tasks", *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conferenc*, Vol. 5, pp. 143–153.
Gedell, S., Michaelis, M.T. and Johannesson, H. (2011), "Integrated model for co-development of products and production systems - A systems theory approach", *Concurrent Engineering Research and Applications*, Vol. 19 No. 2, pp. 139–156.
Geissdoerfer, M., Savaget, P., Bocken, N.M.P. and Hultink, E.J. (2017), "The Circular Economy – A new sustainability paradigm?", *Journal of Cleaner Production*, Vol. 143, pp. 757–768.
Gelbmann, U. and Hammerl, B. (2015), "Integrative re-use systems as innovative business models for devising sustainable product-service-systems", *Journal of Cleaner Production*, Vol. 97 No. 2015, pp. 50–60.
Geng, Y., Sarkis, J., Bleischwitz, R., Sarkis, J. and Bleischwitz, R. (2019), "How to globalize the circular economy".
Gertner, D., Robertes, J. and Charles, D. (2011), "University-Industry Collaboration: A CoPs Approach to KTPs Drew", *Journal of Knowledge Management*.
Geyer, R., Jambeck, J.R. and Law, K.L. (2017), "Production, use, and fate of all plastics ever made", *Science Advances*, Vol. 3 No. e1700782.
Ghisellini, P., Cialani, C. and Ulgiati, S. (2016), "A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems", *Journal of Cleaner Production*, Vol. 114, pp. 11–32.
Giaccardi, E. and Karana, E. (2015), "Foundations of Materials Experience", *Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, pp. 2447–2456.
Gibson, J. j. (1977), "The Theory of Affordances", The Ecological Approach to Visual Perception.
Gioia, D.A., Corley, K.G. and Hamilton, A.L. (2013), "Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology", *Organizational Research Methods*, Vol. 16 No. 1, pp. 15–31.
Goedkoop, M.J., Van Halen, C.J.G., Te Riele, H.R.M. and Rommens, P.J.M. (1999), *Product Service Systems, Ecological and Economic Basics, Economic Affairs*, Vol. 36.
Goldsworthy, K. (2014), "Design for Cyclability: Pro-active approaches for maximising material

recovery", *Making Futures* Journal, Vol. 3, pp. 2042–1664.
Goldsworthy, K. (2017), "The Speedcycle: a design-led framework for fast and slow circular fashion lifecycles", The *Design Journal*, Vol. 20 No. 1, pp. S1960–S1970.
Gottberg, A., Longhurst, P.J. and Cook, M.B. (2010), "Exploring the potential of Product Service Systems to achieve household waste prevention on new housing developments in the UK", *Waste Management & Research*, Vol. 28 No. 3, pp. 228–235.
Govindan, K. and Hasanagic, M. (2018), "A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective", *International Journal of Production Research*, Vol. 56 No. 1–2, pp. 278–311.
Govindan, K., Soleimani, H. and Kannan, D. (2015), "Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future", *European Journal of Operational Research*, Vol. 240 No. 3, pp. 603–626.
Graedel, T.E. and Allenby, B.R. (1995), Industrial Ecology, Prentice-Hall, Upper Saddle River, N.J.
Grant, D.B. and Banomyong, R. (2010), "Design of closed-loop supply chain and product recovery management for fast-moving consumer goods: The case of a single-use camera", Asia Pacific *Journal of Marketing* and Logistics, Vol. 22 No. 2, pp. 232–246.
Greenpeace. (2018), *A Crisis of Convenience - The Corporations Behind the Plastic Pollution Pandemic*.
Guagnano, G.A., Stern, P.C. and Dietz, T. (1995), "Influences on Attitude-Behavior Relationships: A Natural Experiment with Curbside Recycling", *Environment and Behavior*, Vol. 27 No. 5, pp. 699–718.
Guba, E.. and Lincoln, Y.. (1994), "Competing Paradigms in Qualitative Research", *Handbook of Qualitative Research 2*
Guide Jr, V.D.R., Harrison, T.P. and Van Wassenhove, L.N. (2003), "The Challenge of Closed-Loop Supply Chains", *Interfaces*, Vol. 33 No. 6.
Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., et al. (2011), "Life cycle assessment: Past, present, and future", *Environmental Science and Technology*, Vol. 45 No. 1, pp. 90–96.
Guldmann, E., Bocken, N.M.P. and Brezet, H. (2019a), "A Design Thinking Framework for Circular Business Model Innovation", *Journal of Business Models*, Vol. 7 No. 1, pp. 39–70.
Guldmann, E., Bocken, N.M.P. and Brezet, H. (2019b), "A Design Thinking Framework for Circular Business Model Innovation", *Journal of Business Models*, Vol. 7 No. 1, pp. 39–70.
De Haan, A. and De Heer, P. (2017), *Solving Complex Problems*, Boom uitgevers, Amsterdam.
Haase, R.P., Pigosso, D.C.A. and McAloone, T.C. (2017), "Product/Service-System Origins and Trajectories: A Systematic Literature Review of PSS Definitions and their Characteristics", *Procedia CIRP*, The Author(s), Vol. 64, pp. 157–162.
Haber, N. and Fargnoli, M. (2017), "Design for product-service systems: a procedure to enhance functional integration of product-service offerings", *International Journal of Product Development*, Vol. 22 No. 2, p. 135.
Haffmans, S., Gelder, M. van, Hinte, E. van and Zijlstra, Y. (2018), *Products That Flow*, 1st ed., BIS Publishers.
Halbe, J., Adamowski, J., M. Bennett, E., Pahl-Wostl, C. and Farahbakhsh, K. (2014), "Functional organization analysis for the design of sustainable engineering systems", *Ecological Engineering*, Vol. 73, pp. 80–91.
Han, L. (2006), "Measuring 'ilities' is a Hopeless Task".
Han, S.L.-C., Hall, N., Apeagyei, P.R. and Tyler, D. (2016), "Whole Systems Thinking for Circular Economy Design Practice", *Circular Transitions: A Mistra Future Fashion Conference on Textile Design and the Circular Economy*, pp. 1–18.
Hartson, H.R., Andre, T.S. and Williges, R.C. (2003), "Criteria for evaluating usability evaluation methods", *International Journal of Human-Computer Interaction*, Vol. 15 No. 1, pp. 145–

181.
Hawkins, G. (2012), "The Performativity Of Food Packaging: Market Devices*, Waste* Crisis And Recycling", *Sociological Review*, Vol. 60 No. SUPPL.2, pp. 66–83.
Heiskanen, E. (2002), "The institutional logic of life cycle thinking", *Journal of Cleaner Production*, Vol. 10 No. 5, pp. 427–437.
Hemmert, M., Bstieler, L. and Okamuro, H. (2014), "Bridging the cultural divide: Trust formation in university-industry research collaborations in the US, Japan, and South Korea", *Technovation*, Vol. 34 No. 10, pp. 605–616.
Henry, M., Schraven, D., Bocken, N., Frenken, K., Hekkert, M. and Kirchherr, J. (2021), "The battle of the buzzwords: A comparative review of the circular economy and the sharing economy concepts", *Environmental Innovation and Societal Transitions*, Vol. 38 No. October 2020, pp. 1–21.
Hertzum, M. and Jacobsen, N.E. (2003), "The evaluator effect: A chilling fact about usability evaluation methods", *International Journal of Human-Computer Interaction*, Vol. 15 No. 1, pp. 183–204.
Hirsch, G.B., Levine, R. and Miller, R.L. (2007), "Using system dynamics modeling to understand the impact of social change initiatives", *American Journal Community Psychology*, No. 39, pp. 239–253.
Hirtz, J., Stone, R.B., Mcadams, D.A., Szykman, S. and Wood, K.L. (2002), "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts", *Research in Engineering Design*, Vol. 13 No. 2, pp. 65–82.
Den Hollander, M.C. (2018), *Design for Managing Obsolescence: A Design Methodology for Preserving Product Integrity in a Circular Economy*, Delft University of Technology.
Den Hollander, M.C., Bakker, C. and Hultink, E.J. (2017), "Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms", *Journal of Industrial Ecology*, Vol. 21 No. 3, pp. 517–525.
Holt, R. and Barnes, C. (2010), "Towards an integrated approach to 'design for X': An agenda for decision-based DFX research", *Research in Engineering Design*, Vol. 21 No. 2, pp. 123–136.
Homrich, A.S., Galvão, G., Abadia, L.G. and Carvalho, M.M. (2018), "The circular economy umbrella: Trends and gaps on integrating pathways", *Journal of Cleaner Production*.
Hoover, S.P., Rinderle, J.R. and Finger, S. (1991), "Models and abstractions in design", *Design Studies*, Vol. 12 No. 4, pp. 237–245.
Hopewell, J., Dvorak, R. and Kosior, E. (2009), "Plastics recycling: challenges and opportunities.", *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences,* Vol. 364 No. 1526, pp. 2115–26.
Hornbæk, K. (2010), "Dogmas in the assessment of usability evaluation methods", *Behaviour and Information Technology*, Vol. 29 No. 1, pp. 97–111.
Huang, C.L., Vause, J., Ma, H.W. and Yu, C.P. (2012), "Using material/substance flow analysis to support sustainable development assessment: A literature review and outlook", *Resources, Conservation and Recycling*, Vol. 68, pp. 104–116.
Huang, Y.C., Tu, J.C. and Kuo, K.P. (2017), "Establishing sustainable design and development for plastic mold under product service system", *Advances in Mechanical Engineering*, Vol. 9 No. 7, pp. 1–19.
Hubka, V. and Eder, W.E. (2012), *Theory of Technical Systems: A Total Concept Theory for Engineering Design, Springer Science & Business Media*.
Hughes, T.P. (1987), "The evolution of large technological systems", *The Social Construction of Technological Systems.*
Hunt, R.G. and Franklin, W.E. (1996), "LCA - How it Came about - Personal Reflections on the Origin and the Development of LCA in the USA", *International Journal of Life Cycle Assessment*, Vol. 1, pp. 4–7.

Hussain, R., Lockett, H., Vijaykumar, G. and Vasantha, A. (2012), “A framework to inform PSS Conceptual Design by using system-in-use data”, *Computers in Industry*, Vol. 63 No. 4, pp. 319–327.

IDEO and Ellen MacArthur Foundation. (2016), “Circular Design Guide”.

Islam, M.T. and Huda, N. (2018), “Reverse logistics and closed-loop supply chain of Waste Electrical and Electronic Equipment (WEEE)/E-waste: A comprehensive literature review”, *Resources, Conservation and Recycling*, Vol. 137, pp. 48–75.

Iturrioz, C., Aragón, C. and Narvaiza, L. (2015), “How to foster shared innovation within SMEs’ networks: Social capital and the role of intermediaries”, *European Management Journal*, Vol. 33 No. 2, pp. 104–115.

Jackson, M.C. (2006), “Creative Holism: A Critical Systems Approach to Complex Problem Situations”, *Systems Research and Behavioral Science*, Vol. 23, pp. 647–657.

Jackson, T. (2009), *Prosperity without Growth: Economics for a Finite Planet, Prosperity without Growth: Economics for a Finite Planet.*

Jambeck, J., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., et al. (2015), “Plastic waste inputs from land into the ocean”*, Science,* Vol. 347 No. 6223, pp. 3–6.

Jenkins, R.R., Martinez, S.A., Palmer, K. and Podolsky, M.J. (2003), “The determinants of household recycling: a material-specific analysis of recycling program features and unit pricing”, *Journal of Environmental Economics and Management*, Academic Press, Vol. 45 No. 2, pp. 294–318.

Jensen, J.P. and Remmen, A. (2017), “Enabling Circular Economy Through Product Stewardship”, *Procedia Manufacturing*, The Author(s), Vol. 8 No. October 2016, pp. 377–384.

Johnston, R. and Kong, X. (2011), “The Customer Experience : A Road Map for Improvement”, *Managing Service Quality*, Vol. 21 No. 1, pp. 5–24.

Josefsson, T. and Thuvander, L. (2020), “Form Follows Availability: The Reuse Revolution”, *IOP Confernece Series: Earth and Environmental Science*, p. 588.

Jurisch, M.C., Wolf, P. and Krcmar, H. (2013), “Using the Case Survey Method for Synthesizing Case Study Evidence in Information Systems Research”, *Americas Conference on Information Systems.*

Kamigaki, K., Matsumoto, M. and Fatimah, Y.A. (2017), “Remanufacturing and Refurbishing in Developed and Developing Countries in Asia - A Case Study in Photocopiers”, *Procedia CIRP*, Vol. 61, pp. 645–650.

Karana, E. (2009), *Meanings of Materials*, Delft University of Technology, Delft.

Karana, E., Barati, B., Rognoli, V. and Zeeuw van der Laan, A. (2015), “Material driven design (MDD): A method to design for material experiences”, *International Journal of Design*, Vol. 9 No. 2, pp. 35–54.

Karana, E., Pedgley, O. and Rognoli, V. (2014), *Materials Experience*, Butterwort-Heinemann, Oxford.

Kasser, J. and Mackley, T. (2008), “Applying systems thinking and aligning it to systems engineering”, *INCOSE International Symposium*, Vol. 18 No. 1, pp. 1389–1405.

Katz, J.S. and Martin, B.R. (1997), “What is research collaboration?”, *Research Policy,* Vol. 26 No. 1, pp. 1–18.

Kirchherr, J., Reike, D. and Hekkert, M. (2017), “Conceptualizing the circular economy: An analysis of 114 definitions”, *Resources, Conservation and Recycling*, Vol. 127 No. April, pp. 221–232.

Kim, H., Lee, C., Kim, H. and Lee, C.W. (2018), “The Effects of Customer Perception and Participation in Sustainable Supply Chain Management: A Smartphone Industry Study”*, Sustainability,* Multidisciplinary Digital Publishing Institute, Vol. 10 No. 7.

Kjaer, L.L., Pigosso, D.C.A.A., Niero, M., Bech, N.M. and McAloone, T.C. (2018), “Product/Service-

Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption?", *Journal of Industrial Ecology*, Vol 23 No. 1, p. 22-35

De Koeijer, B., Wever, R. and Henseler, J. (2017), "Realizing Product-Packaging Combinations in Circular Systems: Shaping the Research Agenda", *Packaging Technology and Science,* Vol. 30, pp. 443–460.

Konietzko, J., Bocken, N. and Hultink, E.J. (2020a), "Circular ecosystem innovation: An initial set of principles", *Journal of Cleaner Production*, Vol. 253,

Konietzko, J., Bocken, N.M.P. and Hultink, E.J. (2020b), "A Tool to Analyze, Ideate and Develop Circular Innovation Ecosystems", *Sustainability,* Vol. 12 No. 1.

Koppius, O., Özdemir-Akyıldırım, Ö. and Van der Laan, E. (2014), "Business Value from Closed-Loop Supply Chains", *International Journal Supply Chain Management,* Vol. 3 No. 4, pp. 107–120.

Kopytoff, I. (1986), "The cultural biography of things: commoditization as process", *The Social Life of Things - Commodities in Cultural Perspective*, Cambridge University Press, pp. 64–92.

Kraaijenhagen, C., van Oppen, C. and Bocken, N.M.P. (2016), *Circular Business: Collaborate and Circulate*, 1st ed.

Krueger, R.A. (2014), *Focus Groups: A Practical Guide for Applied Research*, Sage publications.

Kuo, T.C., Ma, H.Y., Huang, S.H., Hu, A.H. and Huang, C.S. (2010), "Barrier analysis for product service system using interpretive structural model", *International Journal of Advanced Manufacturing Technology*, Vol. 49 No. 1–4, pp. 407–417.

Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C. and Wiktorsson, M. (2015), "Waste flow mapping to improve sustainability of waste management: a case study approach", *Journal of Cleaner Production*, Vol. 98, pp. 304–315.

Kuzmina, K., Prendeville, S., Walker, D. and Charnley, F. (2019), "Future scenarios for fast-moving consumer goods in a circular economy", *Futures*, Pergamon, Vol. 107, pp. 74–88.

Lambert, S., and Wagner, M. (2017). Environmental performance of bio-based and biodegradable plastics: the road ahead. *Chemical Society reviews*, 46(22), 6855–6871.

Laufer, W.S. (2003), "Social Accountability and Corporate Greenwashing", *Journal of Business Ethics*, Vol. 43 No. 3, pp. 253–261.

Lee, H.M., Lu, W.F., Song, B., Shen, Z., Yang, Z. and Gay, R.K.L. (2007), "A framework for integrated manufacturing and product service system: integrating service operations into product life cycle", *International Journal of Services Operations and Informatics*, Vol. 2 No. 1, p. 81.

Lesteur, M., Bellon-Maurel, V., Gonzalez, C., Latrille, E., Roger, J.M., Junqua, G. and Steyer, J.P. (2010), "Alternative methods for determining anaerobic biodegradability: A review", *Process Biochemistry*, Vol. 45, pp. 431–440.

Lewandowski, M. (2016), "Designing the business models for circular economy-towards the conceptual framework", *Sustainability,* Vol. 8 No. 1, pp. 1–28.

Lewis, H. and Gertsakis, J. (2009), *Design + Environment : A Global Guide to Designing Greener*, Greenleaf Publishing, Sheffield.

Lewis, H., Verghese, K. and Fitzpatrick, L. (2010), "Evaluating the sustainability Impacts of packaging: the plastic carry bag dilemma", *Packaging and Technology and Science*, Vol. 23, pp. 145–160.

Liao, T. (1996), "A fuzzy multicriteria decision-making method for material selection", *Journal of Manufacturing Systems*, Vol. 15 No. l, pp. 1–12.

Lilley, D. (2009), "Design for susstainable behaviour: strategies and perceptions", *Design Studies*, Vol. 30 No. 6, pp. 704–720.

Lilley, D., Bridgens, B., Davies, A. and Holstov, A. (2019), "Ageing (dis)gracefully: Enabling designers to understand material change", *Journal of Cleaner Production*, Vol. 220, pp. 417–430.

Lim, Y.K., Stolterman, E. and Tenenberg, J. (2008), "The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas", *ACM Transactions on Computer-Human Interaction*, Vol. 15 No. 2.

Lindahl, M., Sundin, E. and Sakao, T. (2014), "Environmental and economic benefits of Integrated Product Service Offerings quantified with real business cases", *Journal of Cleaner Production*, Vol. 64, pp. 288–296.

Lindahl, P., Robèrt, K.H., Ny, H. and Broman, G. (2014), "Strategic sustainability considerations in materials management", *Journal of Cleaner Production*, Vol. 64, pp. 98–103.

Lindgaard, G. (2014), "The usefulness of traditional usability evaluation methods", *Interactions*, Vol. 21 No. 6, pp. 80–82.

Lindgreen, A. and Swaen, V. (2010), "Corporate social responsibility", *International Journal of Management Reviews*, Vol. 12 No. 1, pp. 1–7.

Lindström, J. (2016), "Extending the Functional Products definition with additional through-life-cycle aspects", *International Journal of Product Development*, Vol. 21 No. 4, p. 288.

Liu, J., Mooney, H., Hull, V., Davis, S.J., Gaskell, J., Hertel, T., Lubchenco, J., et al. (2015), "Systems integration for global sustainability", *Science,* Vol. 347 No. 6225

Lofthouse, V. (2006), "Ecodesign tools for designers: defining the requirements", *Journal of Cleaner Production*, Vol. 14 No. 15–16, pp. 1386–1395.

Lofthouse, V. and Prendeville, S. (2018), "Human-Centred Design of Products And Services for the Circular Economy–A Review", *Design Journal*, Routledge, Vol. 21 No. 4, pp. 451–476.

Lofthouse, V.A. and Bhamra, T. (2006a), "Investigation into the drivers and barriers affecting refillable packaging", *Waste* 2006, pp. 1–8.

Lofthouse, V.A. and Bhamra, T.A. (2006b), "Refillable packaging systems: design considerations", *International Design Conference*.

Lofthouse, V.A. and Prendeville, S. (2017), "Considering the user in the circular economy", *PLATE Conference*, pp. 213–216.

Lofthouse, V.A., Trimingham, R.L. and Bhamra, T.A. (2009), "Investigating consumer perceptions of refillable packaging and assessing business drivers to their use", *Packaging Technology and Science,* No. May, pp. 335–348.

Longhurst, R. (2003), "Semi-Structured Interview and Focus Group", Key Methods in Geography.

Longmuss, J. and Poppe, E. (2017), "Planned obsolescence: who are those planners?", *PLATE Conference*, pp. 217–221.

De los Rios, I.C. and Charnley, F.J.S. (2017), "Skills and capabilities for a sustainable and circular economy: The changing role of design", *Journal of Cleaner Production*, Vol. 160, pp. 109–122.

Lüdeke-Freund, F., Gold, S. and Bocken, N.M.P. (2018), "A Review and Typology of Circular Economy Business Model Patterns", *Journal of Industrial Ecology*, Wiley/Blackwell (10.1111), Vol. 23 No. 1, pp. 36–61.

Lucas, G. (2002), "Disposability and Dispossession in the Twentieth Century", *Journal of Material Culture*, Vol. 7 No. 1, pp. 5–22.

Lueb, M. (2014), *Modeling Production Sequences in the Fast Moving Consumer Goods Industry*, Technical University of Berlin.

Lyons, T.W., Guironnet, D., Findlater, M. and Brookhart, M. (2012), "Synthesis of p-xylene from ethylene", *Journal of the American Chemical Society*, Vol. 134 No. 38, pp. 15708–15711.

Mackenzie, J., Tan, P.L., Hoverman, S. and Baldwin, C. (2012), "The value and limitations of Participatory Action Research methodology", *Journal of Hydrology,* Vol. 474, pp. 11–21.

Macleod, J. (2017), *Ends. Why We Overlook Endings for Humans, Products, Services and Digital. And Why We Shouldn't.*

Magnier, L., Mugge, R. and Schoormans, J. (2019), "Turning ocean garbage into products – Consumers' evaluations of products made of recycled ocean plastic", *Journal of Cleaner*

Production, Vol. 215, pp. 84–98.
Magnier, L. and Schoormans, J. (2015), “Consumer reactions to sustainable packaging: The interplay of visual appearance, verbal claim and environmental concern”, *Journal of Environmental Psychology*, Vol. 44, pp. 53–62.
Magnier, L. and Schoormans, J. (2017), “How Do Packaging Material, Colour and Environmental Claim Influence Package, Brand and Product Evaluations?”, *Packaging Technology and Science*.
Mahrinasari, M.S. (2019), “Determinants of brand equity: Communication of corporate social responsibility (CSR) versus csr itself and company credibility”, *Contemporary Economics,* Vol. 13 No. 3, pp. 317–334.
Maier, J.R.A. and Fadel, G.M. (2009), “Affordance based design: A relational theory for design”, *Research in Engineering Design*, Vol. 20 No. 1, pp. 13–27.
Maletz, R. (2017), “Success Factors for the Implementation of Separate Collection Systems”, in Maletz, R., Dornack, C. and Ziyang, L. (Eds.), *Source Separation and Recycling. The Handbook of Environmental Chemistry*, Vol 63., Cham, pp. 297–313.
Manzini, E. (1994), “Design, Environment and Social Quality: From ‘Existenzminimum’ to ‘Quality Maximum’”, *Design Issues*, Vol. 10 No. 1, pp. 37–43.
Manzini, E. (2009), “New design knowledge”, *Design Studies*, Vol. 30 No. 1, pp. 4–12.
Manzini, E. and Vezzoli, C. (2003), “A strategic design approach to develop sustainable product service systems: Examples taken from the ‘environmentally friendly innovation’ Italian prize”, *Journal of Cleaner Production*, Vol. 11 No. 8 SPEC., pp. 851–857.
Manzini, E., Vezzoli, C. and Clark, G. (2001), “Product-Service Systems. Using an Existing Concept as a New Approach to Sustainability”, *Journal of Design Research*, Vol. 1 No. 2, pp. 1–13.
Maussang, N., Sakao, T., Zwolinski, P. and Brissaud, D. (2007), “A Model for Designing Product-Service Systems Using Functional Analysis and Agent Based Model”, *ICED’07.*
Mashhadi, A.R., Esmaeilian, B. and Behdad, S. (2016), “Simulation modeling of consumers’ participation in product take-back systems”, *Journal of Mechanical Design*, *Transactions of the ASME*, Vol. 138 No. 5
Maycroft, N. (2009), *Consumption, Planned Obsolescence and Waste.*
Maussang, N., Zwolinski, P. and Brissaud, D. (2009), “Product-service system design methodology: from the PSS architecture design to the products specifications”, *Journal of Engineering Design*, Vol. 20 No. 4, pp. 349-366.
McAloone, T.C. and Pigosso, D.C.A. (2018), “Designing Product Service Systems for a Circular Economy”, in Charter, M. (Ed.), *Designing for the Circular Economy*, Routledge, pp. 102–112.
McDonald, M.H.B., de Chernatony, L. and Harris, F. (2001), “Corporate marketing and service brands: Moving beyond the fast-moving consumer goods model”, European *Journal of Marketing*, Vol. 35 No. 3/4, pp. 335–352.
McDonough, W. and Braungart, M. (1998), *The NEXT industrial revolution*, The Atlantic.
McDonough, W. and Braungart, M. (2013), *The Upcycle: Beyond Sustainability - Designing for Abundance*, 1st ed., North Point Press.
McKechnie, L. (2000), “Ethnographic Observation of Preschool Children”, *Library and Information Science Research*, Vol. 22 No. 1, pp. 61–76.
McKinsey & Company. (2010), *The Decade Ahead: Trends That Will Shape the Consumer Goods Industry.*
McKinsey Global Institue. (2011), *Resource Revolution: Meeting the World’s Energy, Materials, Food, and Water Needs.*
Meadows, D.H. (2008), *Thinking in Systems - A Primer*, edited by Wright, D., 1st ed., Chelsea Green Publishing.
Mestre, A. and Cooper, T. (2017), “Circular Product Design. A Multiple Loops Life Cycle Design

Approach for the Circular Economy", The *Design Journal*, Vol. 20 No. sup1, pp. S1620-1635.

Meyer, M.W. and Norman, D. (2020), "Changing Design Education for the 21st Century", *She Ji*, Vol. 6 No. 1, pp. 13–49.

Michelini, G., Moraes, R.N., Cunha, R.N., Costa, J.M.H. and Ometto, A.R. (2017), "From Linear to Circular Economy: PSS Conducting the Transition", *Procedia CIRP*, The Author(s), Vol. 64, pp. 2–6.

Middlemiss, N. (2003), "Authentic not cosmetic: CSR as brand enhancement", *Journal of Brand Management*, Vol. 10 No. 4, pp. 353–361.

Miser, H.J. and Quade, E.S. (1985), "The Context, Nature and Use of Systems Analysis", *Handbook of Systems Analysis*, John Wiley & Sons.

Mishra, J.L., Chiwenga, K.D. and Ali, K. (2019), "Collaboration as an enabler for circular economy: a case study of a developing country", *Management Decision*.

Mishra, J.L., Hopkinson, P.G. and Tidridge, G. (2018), "Value creation from circular economy-led closed loop supply chains: a case study of fast-moving consumer goods", *Production Planning & Control*, Vol. 29 No. 6, pp. 509–521.

Modaff, J. V and Modaff, D.P. (2010), "Technical Notes on Audio Recording", *Language*, Vol. 1813 No. 918974596.

Møller, A. and Myles, P. (2016), "What makes a good systematic review and meta-analysis?", *British Journal of Anaesthesia*, Vol. 117 No. 4, pp. 428–430.

Monat, J. and Gannon, T. (2018), "Applying Systems Thinking to Engineering and Design", *Systems*, Vol. 6 No. 3.

Mont, O. (2002), "Clarifying the concept of product – service system", *Journal of Cleaner Production*, Vol. 10, pp. 237–245.

Mont, O., Palgan, Y.V., Bradley, K. and Zvolska, L. (2020), "A decade of the sharing economy: Concepts, users, business and governance perspectives", *Journal of Cleaner Production*, Vol. 269, p. 122215.

Mont, O. and Tukker, A. (2006), "Product-Service Systems: reviewing achievements and refining the research agenda", *Journal of Cleaner Production*, Vol. 14 No. 17, pp. 1451–1454.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., et al. (2019), "Circular economy indicators: What do they measure?", *Resources, Conservation and Recycling*, Vol. 146, pp. 452–461.

Moreau, V., Sahakian, M., Van Griethuysen, P. and Vuille, F. (2017), "Coming Full Circle: Why Social and Institutional Dimensions Matter for the Circular Economy", *Journal of Industrial Ecology*, Vol. 21 No. 3, pp. 497–506.

Morelli, N., Issues, S.D., Summer, N. and Morelli, N. (2002), "Designing Product / Service Systems : A Methodological Exploration", *Design Issues*, The MIT Press, Vol. 18 No. 3, pp. 3–17.

Moreno, M., De los Rios, C., Rowe, Z. and Charnley, F. (2016), "A conceptual framework for circular design", *Sustainability,* MDPI, Vol. 8 No. 9.

Moreno, P.R., Rohmer, S., Ma, H.-W., Rodriguez Moreno, P., Rohmer, S. and Ma, H.-W. (2015), "Analysis of Potential Relationships between Functional Analysis and Life Cycle Assessment", *Procedia CIRP*, Vol. 29, pp. 390–395.

Morgan, G. and Smircich, L. (1980), "The case for qualitative research", *Academy of Management Review,* Vol. 5 No. 4, pp. 491–500.

Moriguchi, Y. (2007), "Material flow indicators to measure progress toward a sound material-cycle society", *Journal of Material Cycles and Waste Management*, Vol. 9, pp. 112–120.

Morlet, A., Blériot, J., Opsomer, R., Linder, M., Henggeler, A., Bluhm, A. and Carrera, A. (2016), "Intelligent Assets: Unlocking the Circular Economy Potential",

Mugge, R. (2017), "A consumer's perspective on the circular economy", *Routledge Handbook of Sustainable Product Design*, pp. 374–390.

Mugge, R., Massink, T., Hultink, E.J. and van den berg-Weitzel, L. (2014), “Designing a premium package: Some guidelines for designers and marketers”, *Design Journal*, Vol. 17 No. 4, pp. 583–605.

Mugge, R. and Schoormans, J.P.L. (2012), “Product design and apparent usability. The influence of novelty in product appearance”, *Applied Ergonomics*, Vol. 43 No. 6, pp. 1081–1088.

Müller, P. and Stark, R. (2008), “Detecting and structuring requirements for the development of product-service systems”, *DFX 2008: Symposium on Design for X.*

Müller, P. and Stark, R. (2010), “A Generic PSS Development Process Model Based on Theory and an Empirical Study”, *International Design Conference*, pp. 361–370.

Murakami, S., Oguchi, M., Tasaki, T., Daigo, I. and Hashimoto, S. (2010), “Lifespan of Commodities, Part I”, *Journal of Industrial Ecology*, Vol. 14 No. 4, pp. 598–612.

Muranko, Ż., Aurisicchio, M., Baxter, W. and Childs, P. (2020), “Behaviour chains in circular consumption systems : the reuse of FMCGs Behaviour chains in circular consumption systems : the reuse of FMCGs”, No. June.

Muranko, Ż., Tassell, C., Zeeuw van der Laan, A. and Aurisicchio, M. (2021), “Characterisation and Environmental Value Proposition of Reuse Models for Fast-Moving Consumer Goods: Reusable Packaging and Products”*, Sustainability,* Vol. 13 No. 2609.

Murphy, P.E. and Enis, B.M. (1986), “Classifying Products Strategically”, *Journal of Marketing*, Vol. 50 No. 3, pp. 24–42.

Murray, A., Skene, K. and Haynes, K. (2017), “The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context”, *Journal of Business Ethics*, Vol. 140 No. 3, pp. 369–380.

Mr Green Africa (2020), https://www.mrgreenafrica.com/

Nassour, A., Hemidat, S., Lemke, A., Elnaas, A. and Nelles, M. (2017), “Separation by Manual Sorting at Home: State of the Art in Germany”, in Maletz, R., Dornack, C. and Ziyang, L. (Eds.), *Source Separation and Recycling. The Handbook of Environmental Chemistry,* Vol 63., Cham, pp. 67–87.

Van Nes, N., Cramer, J. and Stevels, A. (1999), “A practical approach to the ecological lifetime optimization of electronic products”, *International Symposium on Environmentally Conscious Design and Inverse Manufacturing, IEEE*, pp. 108–111.

Nestlé. (2019), *Progress Report* 2019.

Niero, M., Hauschild, M.Z., Hoffmeyer, S.B. and Olsen, S.I. (2017), “Combining Eco-Efficiency and Eco-Effectiveness for Continuous Loop Beverage Packaging Systems: Lessons from the Carlsberg Circular Community”, *Journal of Industrial Ecology*, John Wiley & Sons, Ltd (10.1111), Vol. 21 No. 3, pp. 742–753.

Norman, D.A. (1998), *The Design of Everyday Things*, MIT Press.

Norman, D.A. and Draper, S.W. (1986), U*ser Centered System Design : New Perspectives on Human-Computer Interaction*, CRC, Boca Raton, Fla.

Norman, D.A. and Stappers, P.J. (2015), “DesignX: Complex Sociotechnical Systems”, *She Ji*, Vol. 1 No. 2, pp. 83–106.

Nußholz, J.L.K. (2017), “Circular business models: Defining a concept and framing an emerging research field”, *Sustainability*, Vol. 9 No. 10, pp. 14–17.

Nyberg, D. and Wright, C. (2013), “Corporate corruption of the environment: Sustainability as a process of compromise”, *British Journal of Sociology*, Vol. 64 No. 3, pp. 405–424.

O’Reilly, K., Paper, D., Marx, S., Watling, C.J., Lingard, L., Matavire, R., Brown, I., et al. (2015), “Grounded Theory as a General Research Methodology”, *Organizational Research Methods*, Vol. 18 No. 4, pp. 305–323.

OC&C Strategy Consultants. (2019), *The FMCG Global 50* 2019.

OECD. (1993), *System of National Accounts*, Vol. SNA93.

OECD. (2008), “Measuring Material Flows and Resource Productivity”, Volume 1, Vol. III, pp.

1–164.
Oguchi, M., Murakami, S., Tasaki, T., Daigo, I. and Hashimoto, S. (2010), “Lifespan of commodities, part II: Methodologies for estimating lifespan distribution of commodities”, *Journal of Industrial Ecology*, Vol. 14 No. 4, pp. 613–626.
Ogunmakinde, O.E. (2019), “A review of circular economy development models in China, Germany and Japan”*, Recycling*, Vol. 4 No. 3.
Oliva, R. and Kallenberg, R. (2003), “Managing the transition from products to services”, *International Journal of Service Industry Management,* Vol. 14 No. 2, pp. 160–172.
Orgel, L.E. (1973), “Ageing of Clones of Mammalian Cells”, Nature, Vol. 243, pp. 441–445.
Van Ostaeyen, J., Van Horenbeek, A., Pintelon, L. and Duflou, J.R. (2013), “A refined typology of producte-service systems based on functional hierarchy modeling”, *Journal of Cleaner Production*, Vol. 51, pp. 261–276.
Östlin, J., Sundin, E. and Björkman, M. (2008), “Importance of closed-loop supply chain relationships for product remanufacturing”, *International Journal of Production Economics,* Vol. 115 No. 2, pp. 336–348.
Oxfam. (2013), *Behind the Brands: Food Justice and the “Big 10” Food and Beverage Companies.*
Packard, V. (1960), *The Waste Makers*, Longmans, Green.
Pagoropoulos, A., Andersen, J.A.B., Kjær, L.L., Maier, A. and McAloone, T.C. (2014), “Building an ontology of Product/Service-Systems: Using a maritime case study to elicit classifications and characteristics”, *IFIP Advances in Information and Communication Technology*, Vol. 434, pp. 119–126.
Pahl, G., Beitz, W., Feldhusen, J. and Grote, K.H. (2007), *Engineering Design: A Systematic Approach*, 3rd ed., Springer.
Papanek, V. (1985), *Design for the Real World*, 2nd ed., Thames and Hudson, London.
Parajuly, K. and Wenzel, H. (2017), “Potential for circular economy in household WEEE management”, *Journal of Cleaner Production*, Vol. 151, pp. 272–285.
Park, C. (2015), *Influencing Factors for Sustainable Design Implementation in the Front-End of New Product Development Process within the Fast-Moving-Consumer-Goods Sector,* Carnfield University.
Pedgley, O., Şener, B., Lilley, D. and Bridgens, B. (2018), “Embracing Material Surface Imperfections in Product Design”, *International Journal of Design*, Vol. 12 No. 3, pp. 21–33.
Peeters, J.R., Vanegas, P., Dewulf, W. and Duflou, J.R. (2017), “Economic and environmental evaluation of design for active disassembly”, *Journal of Cleaner Production*, Vol. 140, pp. 1182–1193.
Peters, D., Loke, L. and Ahmadpour, N. (2020), “Toolkits, cards and games–a review of analogue tools for collaborative ideation”, *CoDesign*, Vol. 00 No. 00, pp. 1–25.
Peters, S. (2014), “Sustainable Multipurpose Materials and Desi”, in Karana, E., Pedgley, O. and Rognoli, V. (Eds.), *Materials Experience,* 1st ed., Butterwort-Heinemann (Elsevier), pp. 169–196.
Petersen, T.B. and Riisberg, V. (2017), “Cultivating User-ship? Developing a Circular System for the Acquisition and Use of Baby Clothing”, *Fashion Practice*, Routledge, Vol. 9 No. 2, pp. 214–234.
Phillips, R., Freeman, R.E. and Wicks, A.C. (2003), “What Stakeholder Theory is Not”, *Business Ethics Quarterly,* Vol. 13 No. 4, pp. 479–502.
Phillips, R.A. and Reichart, J. (1997), “The Environment as a Stakeholder? A Fairness-Based Approach”, *Business Strategy Review,* Vol. 8 No. 2, pp. 25–28.
Pialot, O., Millet, D. and Bisiaux, J. (2017), “‘Upgradable PSS’: Clarifying a new concept of sustainable consumption/production based on upgradablility”, *Journal of Cleaner Production*, Vol. 141, pp. 538–550.

Pieroni, M.P., McAloone, T.C. and Pigosso, D.C. (2019a), "Configuring New Business Models for Circular Economy through Product–Service Systems", *Sustainability,* Multidisciplinary Digital Publishing Institute, Vol. 11 No. 13, p. 3727.

Pieroni, M.P.P., McAloone, T.C. and Pigosso, D.C.A. (2019b), "Business model innovation for circular economy and sustainability: A review of approaches", *Journal of Cleaner Production*, Vol. 215, pp. 198–216.

Pieroni, M.P.P., McAloone, T.C. and Pigosso, D.C.A. (2020a), "Circular Economy business model innovation: sectorial patterns within manufacturing companies", *Journal of Cleaner Production* (under Review)., p. 124921.

Pieroni, M.P.P., McAloone, T.C. and Pigosso, D.C.A. (2020b), "From theory to practice: systematising and testing business model archetypes for circular economy", *Resources, Conservation and Recycling*, Vol. 162 No. June, p. 105029.

Pigosso, D. and McAloone, T.C. (2017), "How can design science contribute to a circular economy?", *International Conference on Engineering Design*, Vol. 5 No. DS87-5, pp. 299–307.

Pigosso, D.C.A.A., McAloone, T.C. and Boucher, X. (2015), "Supporting the development of environmentally sustainable PSS by means of the ecodesign maturity model", *Procedia CIRP*, Vol. 30, pp. 173–178.

Pine II, J.B. and Gilmore, J.H. (2013), "The experience economy: past, present and future", in Sundbo, J. and Sërensen, F. (Eds.), *Handbook on the Experience Economy*, Edward Elgar Publishing, pp. 21–44.

Pinkston, T.S. and Carroll, A.B. (1996), "A Retrospective Examination of CSR Orientations : Have They Changed ?", *Journal of Business Ethics*, Vol. 15, pp. 199–206.

Pomponi, F. and Moncaster, A. (2017), "Circular economy for the built environment: A research framework", *Journal of Cleaner Production*, Vol. 143, pp. 710–718.

Poortinga, W. and Whitaker, L. (2018), "Promoting the use of reusable coffee cups through environmental messaging, the provision of alternatives and financial incentives", *Sustainability,* Vol. 10 No. 3.

Pourdehnad, J., Wexler, E.R. and Wilson, D. V. (2011), "Systems & design thinking: A conceptual framework for their integration", *55th Annual Meeting of the International Society for the Systems Sciences 2011*, No. April, pp. 807–821.

Prendeville, S., O'Connor, F. and Palmer, L. (2014), "Material selection for eco-innovation: SPICE model", *Journal of Cleaner Production*, Vol. 85, pp. 31–40.

Prendeville, S., Sanders, C., Sherry, J. and Costa, F. (2014), *Circular Economy: Is It Enough?.*

Pringle, T., Barwood, M. and Rahimifard, S. (2016), "The Challenges in Achieving a Circular Economy within Leather Recycling", *Procedia CIRP*, Vol. 48, pp. 544–549.

Procter & Gamble. (2015), *Sustainability Report.*

Procter & Gamble. (2018), *Ambition 2030.*

Procter & Gamble. (2019), *2019 Citizenship Report.*

Quariguasi Frota Neto, J. and Van Wassenhove, L.N. (2013), "Original Equipment Manufacturers' Participation in Take-Back Initiatives in Brazil: An Analysis of Engagement Levels and Obstacles Quariguasi and Van Wassenhove OEM Participation in Take-back Initiatives in Brazil", *Journal of Industrial Ecology*, Vol. 17 No. 2, pp. 238–248.

Rabnawaz, M., Wyman, I., Auras, R. and Cheng, S. (2017), "A roadmap towards green packaging: The current status and future outlook for polyesters in the packaging industry", *Green Chemistry, Royal Society of Chemistry*, Vol. 19 No. 20, pp. 4737–4753.

Rada, E. and Cioca, L. (2017), "Optimizing the Methodology of Characterization of Municipal Solid Waste in EU Under a Circular Economy Perspective", *Energy Procedia*, Vol. 119, pp. 72–85.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., et al. (2021), "Plasticenta: First evidence of microplastics in human placenta", *Environment International,* Vol. 146, p. 106274.

Rahimi, A. and García, J.M. (2017), "Chemical recycling of waste plastics for new materials production", *Nature Reviews Chemistry, Nature Publishing Group,* Vol. 1 No. 46.

Rahimifard, S. and Sheldrick, L. (2015), "Ubiquitous sustainability: a multidisciplinary approach towards the second generation of sustainability research", *International Journal of Sustainable Engineering*, Vol. 8 No. March, pp. 1–4.

Rau, T. and Oberhuber, S. (2016), *Material Matters - Het alternatief Voor Onze Roofbouwmaatschappij*, 5th ed., Bertram + de Leeuw Uitgevers.

Raworth, K. (2017), *Doughnut Economics: Seven Ways to Think like a 21st-Century Economist*, Chelsea Green Publishing.

RECOUP. (2019), *Core Principles for Plastic Packaging Recyclability.*

Reijnders, L. (2008), "Are emissions or wastes consisting of biological nutrients good or healthy?", *Journal of Cleaner Production*, Vol. 16 No. 10, pp. 1138–1141.

Reim, W., Parida, V. and Örtqvist, D. (2015), "Product-Service Systems (PSS) business models and tactics - A systematic literature review", *Journal of Cleaner Production*, Vol. 97, pp. 61–75.

Retamal, M. (2017), "Product-service systems in Southeast Asia: Business practices and factors influencing environmental sustainability", *Journal of Cleaner Production*, Vol. 143, pp. 894–903.

Richmond, B. (1993), "Systems thinking: Critical thinking skills for the 1990s and beyond", *System Dynamics Review*, Vol. 9 No. 2, pp. 113–133.

del Rio-Roberts, M. (2011), "How I Learned to Conduct Focus Groups", *Qualitative Report*, Vol. 16 No. 1, pp. 312–315.

Risch, S.J. (2009), "Food Packaging History and Innovations", *Journal of Agricultural and Food Chemistry*, Vol. 57 No. 18, pp. 8089–8092.

Ritch, E., Brennan, C. and Macleod, C. (2009), "Plastic bag politics: modifying consumer behaviour for sustainable development", *International Journal of Consumer Studies,* Vol. 33, pp. 168–174.

Rittel, H.W.J. and Webber, M.M. (1973), "Dilemmas in a General Theory of Planning", *Policy Sciences*, Vol. 4, pp. 155–169.

Roberts, N. (2000), "Wicked Problems and Network Approaches to Resolution", *International Public Management Review,* Vol. 1 No. 1, pp. 1–19.

Robotham, A.J. (2002), "The use of function/means trees for modelling technical, semantic and business functions", *Journal of Engineering Design*, Vol. 13 No. 3, pp. 243–251.

Robson, C. (2011), *Real world research*, Blackwell Publishing. Malden.

Rodrigues, S., Martinho, G. and Pires, A. (2016), "Waste collection systems. Part A: a taxonomy".

Romero, D. and Rossi, M. (2017), "Towards Circular Lean Product-Service Systems", *Procedia CIRP*, The Author(s), Vol. 64, pp. 13–18.

Romero Rojo, F.J., Roy, R., Shehab, E., Cheruvu, K. and Mason, P. (2012), "A cost estimating framework for electronic, electrical and electromechanical (EEE) components obsolescence within the use-oriented product-service systems contracts", *Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 226 No. 1, pp. 154–166.

Roozenburg, N.F.M. and Eekels, J. (1998), *Produktontwerpen, Structuur En Methoden*, 2nd ed., Uitgeverij Lemma, Utrecht.

Rossi, M., Germani, M. and Zamagni, A. (2016), "Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies", *Journal of Cleaner Production*, Vol. 129, pp. 361–373.

Rousta, K., Bolton, K., Lundin, M. and Dahlén, L. (2015), "Quantitative assessment of distance to

collection point and improved sorting information on source separation of household waste".
Rousta, K. and Dahlén, L. (2015), "Source Separation of Household Waste Materials", in Taherzadeh, M.J. and Richards, T. (Eds.), *Resource Recovery to Approach Zero Municipal Waste*, CRC, pp. 61–76.
Roy, R., Mehnen, J., Addepalli, S., Redding, L., Tinsley, L. and Okoh, C. (2014), "Service knowledge capture and reuse", *Procedia CIRP*, Vol. 16, pp. 9–14.
Russo, D., Birolini, V. and Ceresoli, R. (2016), "FIT: A TRIZ Based Failure Identification Tool for Product-Service Systems", *Procedia CIRP*, The Author(s), Vol. 47, pp. 210–215.
Ryan, A.J. (2014), "A Framework for Systemic Design", F*ORMakademisk: Relating Systems Thinking and Design II*, Vol. 7, pp. 1–14.
Saidani, M., Yannou, B., Leroy, Y. and Cluzel, F. (2017), "How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework", *Recycling*, MDPI, Vol. 2 No. 6, p. 18.
Saldaña, J. (2013), *The Coding Manual for Qualitative Researchers* (2nd Ed.), SAGE Publications Inc.
Scheepens, A.E., Vogtländer, J.G. and Brezet, H.C. (2016), "Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable", *Journal of Cleaner Production*, Vol. 114, pp. 257–268.
Schenkel, M., Caniëls, M.C.J., Krikke, H. and van der Laan, E. (2015), "Understanding value creation in closed loop supply chains – Past findings and future directions", *Journal of Manufacturing Systems*, Vol. 37, pp. 729–745.
Schlosser, E. (2012), *Fast Food Nation: The Dark Side of the All-American Meal*, Houghton Mifflin Harcourt.
Seidel, S., Recker, J. and Vom Brocke, J. (2013), "Sensemaking and sustainable practicing: Functional affordances of information systems in green transformations", *MIS Quarterly: Management Information Systems*, Vol. 37 No. 4, pp. 1275–1299.
Seiffert, M.E.B. and Loch, C. (2005), "Systemic thinking in environmental management: Support for sustainable development", *Journal of Cleaner Production*, Vol. 13 No. 12, pp. 1197–1202.
Selvefors, A., Rexfelt, O., Renström, S. and Strömberg, H. (2019), "Use to use – A user perspective on product circularity", *Journal of Cleaner Production*, Vol. 223, pp. 1014–1028.
Senge, P.M. (2006), *The Fifth Discipline*, 2nd ed., Currency.
Sharken Simon, J. (1999), "How to conduct a focus group", *The Grantsmanship Center Magazine*, No. 800, pp. 1–10.
Sheehy, B. (2014), "Defining CSR: Problems and Solutions", *Journal of Business Ethics*, Vol. 131 No. 3, pp. 625–648.
Sherwin, C. and Evans, S. (1998), "Ecodesign innovation: is 'early' always 'best'?", *IEEE,* Vol. 44, pp. 112–117.
Shi, X., Wu, Y. and Fu, D. (2020), "Does University-Industry collaboration improve innovation efficiency? Evidence from Chinese Firms", *Economic Modelling*, Vol. 86 No. May 2019, pp. 39–53.
Shih, B.-Y., Chen, C.-Y. and Chen, Z.-S. (2006), "An Empirical Study of an Internet Marketing Strategy for Search Engine Optimization", *Human Factors and Ergonomics in Manufacturing*, Vol. 16 No. 1, pp. 61–81.
Shih, L.H. (2001), "Reverse logistics system planning for recycling electrical appliances and computers in Taiwan", *Resources, Conservation and Recycling*, Vol. 32 No. 1, pp. 55–72.
Shipton, J. and Fisher, T. (2010), "There are Times and Places: Systems and Practices in the Domestic Processing and Reuse of Pacakging", in Fisher, T. (Ed.), *Longer Lasting Products:*

Alternatives To The Throwaway Society, Gower Publishing Ltd., pp. 267–392.

Sidique, S.F., Lupi, F. and Joshi, S. V. (2010), “The effects of behavior and attitudes on drop-off recycling activities”, Vol. 54, pp. 163–170.

Sinclair, M., Sheldrick, L., Moreno, M. and Dewberry, E. (2018), “Consumer Intervention Mapping—A Tool for Designing Future Product Strategies within Circular Product Service Systems”*, Sustainability,* MDPI, Open Access Journal, Vol. 10 No. 6, pp. 1–21.

Singh, J. and Ordoñez, I. (2016), “Resource recovery from post-consumer waste: important lessons for the upcoming circular economy”, *Journal of Cleaner Production*, Vol. 134, pp. 342–353.

Singhirunnusorn, W., Donlakorn, K. and Kaewhanin, W. (2012), “Contextual Factors Influencing Household Recycling Behaviours: A Case of Waste Bank Project in Mahasarakham Municipality-review under responsibility of Centre for Environment-Behaviour Studies (cE-Bs), Faculty of Architecture, Planning & Surveying, Universiti Teknologi MARA, Malaysia”, Procedia-Social and Behavioral Sciences, Vol. 36, pp. 688–697.

Sinha, R., Laurenti, R., Singh, J., Malmström, M.E. and Frostell, B. (2016), “Identifying ways of closing the metal flow loop in the global mobile phone product system: A system dynamics modeling approach”, *Resources, Conservation and Recycling*, Vol. 113, pp. 65–76.

Sjöö, K. and Hellström, T. (2019), “University–industry collaboration: A literature review and synthesis”, *Industry and Higher Education*, Vol. 33 No. 4, pp. 275–285.

Smets, M., Morris, T. and Greenwood, R. (2012), “From Practice to Field: A Multilevel Model of Practice Driven institutional Change”, *Academy of Management Journal*, Vol. 55 No. 4, pp. 877–904.

Sorrell, S., Gatersleben, B. and Druckman, A. (2020), “The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change”, *Energy Research and Social Science*, Vol. 64 No. January, p. 101439.

Sousa-Zomer, T.T., Magalhães, L., Zancul, E. and Cauchick-Miguel, P.A. (2017), “Lifecycle Management of Product-service Systems: A Preliminary Investigation of a White Goods Manufacturer”, *Procedia CIRP*, The Author(s), Vol. 64, pp. 31–36.

Souza, G.C. (2013), “Closed-Loop Supply Chains: A Critical Review, and Future Research”, *Decision Sciences*, Vol. 44 No. 1, pp. 7–38.

Spangenberg, J.H. (2013), “Design for sustainability (DfS): Interface of sustainable production and consumption”, *Handbook of Sustainable Engineering*, No. October, pp. 575–595.

Spinuzzi, C. (2005), “The Methodology of Participatory Design”, *Technical Communication*, Vol. 52 No. 2, pp. 163–174.

Stahel, W.R. (1982), “The product life factor”, *An Inquiry Into the Nature of Sustainable Societies: The Role of the Private Sector*, pp. 72–105.

Stahel, W.R. (1994), “The Utilization-Focused Service Economy: Resource Efficiency and Product-Life Extension”, *The Greening of Industrial Ecosystems*, pp. 178–190.

Stahel, W.R. (1997), “The service economy: ‘Wealth without resource consumption’?”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 355 No. 1728, pp. 1309–1319.

Stahel, W.R. (2010), *The Performance Economy*, 2nd ed., Palgrave Macmillan, Basingstoke.

Stahel, W.R. (2013), “Policy for material efficiency — sustainable taxation as a departure from the throwaway society Subject Areas ”:, *Philosophical Transactions of the Royal Society A*, Vol. 371 No. 20110567.

Stahel, W.R. (2016), “Circular Economy”, *Nature*, pp. 6–9.

Stahel, W.R. (2019), *The Circular Economy: A User’s Guide*, 1st ed., Routledge, London.

Stahel, W.R. and Clift, R. (2016), “Stocks and Flows in the Performance Economy”, in Clift, R. and Druckman, A. (Eds.), *Taking Stock of Industrial Ecology*, Spring, Cham, pp. 1–362.

Stål, H.I. and Corvellec, H. (2018), “A decoupling perspective on circular business model implementation: Illustrations from Swedish apparel”, *Journal of Cleaner Production*, Vol. 171, pp. 630–643.

Stål, H.I. and Jansson, J. (2017), “Sustainable Consumption and Value Propositions: Exploring Product-Service System Practices Among Swedish Fashion Firms”, *Sustainable Development*, Vol. 25, pp. 546–558.

Starik, M. (1995), “Should Trees Have Managerial Standing? Toward Stakeholder Status for Non-Human Nature”, *Journal of Business Ethics*, Vol. 14, pp. 2017–2017.

Stark, J. (2011), *Product Lifecycle Management : 21st Century Paradigm for Product Realisation*, 2nd ed., Springer.

Steg, L. and Vlek, C. (2008), “Encouraging pro-environmental behaviour: An integrative review and research agenda”, *Journal of Environmental Psychology*, Vol. 29, pp. 309–317.

Stein, A. and Ramaseshan, B. (2016), “Towards the identification of customer experience touch point elements”, *Journal of Retailing and Consumer Services*, Vol. 30, pp. 8–19.

Stein, R.S. (2002), “Plastics Can Be Good for the Environment”, *The NEACT Journal*, Vol. 21 No. 1.

Steinder, M. and Sethi, A.S. (2001), “Non-deterministic diagnosis of end-to-end service failures in a multi-layer communication system”, *International Conference on Computer Communications and Networks,* pp. 374–379.

Sterman, J.D. (2001), “System Dynamics Modeling: Tools for Learning in a Complex World”, *California Management Review*, Vol. 43 No. 4, pp. 8–25.

Sterman, J.D. (2002), Business Dynamics, System Thinking and Modeling for a Complex World.

Stetler, C.B., Legro, M.W., Wallace, C.M., Bowman, C., Guihan, M., Hagedorn, H., Kimmel, B., et al. (2006), “The role of formative evaluation in implementation research and the QUERI experience”, *Journal of General Internal Medicine*, Vol. 21 No. SUPPL. 2, pp. 1–8.

Stewart, R. and Niero, M. (2018), “Circular economy in corporate sustainability strategies: A review of corporate sustainability reports in the fast-moving consumer goods sector”, *Business Strategy and the Environment*, pp. 1–18.

Stickdorn, M., Hormess, M.E., Lawrence, A. and Schneider, J. (2016), *This Is Service Design Doing*, 1st ed., O’Reilly Media.

Stone, R.B. and Wood, K.L. (2000), *Development of a Functional Basis for Design.*

Stone, R.B., Wood, K.L. and Crawford, R.H. (2000), “A heuristic method for identifying modules for product architectures”, *Design Studies*, Vol. 21 No. 1, pp. 5–31.

Suckling, J. and Lee, J. (2015), “Redefining scope: the true environmental impact of smartphones?”, *International Journal of Life Cycle Assessment*, Vol. 20 No. 8, pp. 1181–1196.

Sundin, E. and Lindahl, M. (2008), “Rethinking product design for remanufacturing to facilitate integrated product service offerings”, *IEEE International Symposium on Electronics and the Environment*, No. May 2014.

Sundin, E., Lindahl, M. and Ijomah, W. (2009), “Product design for product / service systems Design experiences from Swedish industry”, *Journal of Manufacturing Technology Management*, Vol. 20 No. 5, pp. 723–753.

Sushil. (2012), “Interpreting the interpretive structural model”, *Global Journal of Flexible Systems Management*, Vol. 13 No. 2, pp. 87–106.

Tasaki, T., Hashimoto, S. and Moriguchi, Y. (2006), “A quantitative method to evaluate the level of material use in lease/reuse systems of electrical and electronic equipment”, *Journal of Cleaner Production*, Vol. 14 No. 17, pp. 1519–1528.

Taylor, D. (2017), “A brief history of (un)sustainable design”, in Chapman, J. (Ed.), *Routledge Handbook of Sustainable Product Design*, 1st ed., Routledge, pp. 11–24.

Tennant, M. (2013), *Sustainability and Manufacturing, Foresight, Government Office for Science.*

Terracycle (2020), https://www.terracycle.com/en-GB/

Thain, G. and Bradley, J. (2014), *FMCG The Power of Fast-Moving Consumer Goods*, First Edition Design Publishing, Sarasota, FL.

Thevenot, H.J. and Simpson, T.W. (2009), "A product dissection-based methodology to benchmark product family design alternatives", *Journal of Mechanical Design*, Transactions of the ASME, Vol. 131 No. 4, pp. 0410021–0410029.

Thomsen, B., Kokkolaras, M., Månsson, T. and Isaksson, O. (2016), "Quantitative Assessment of the Impact of Alternative Manufacturing Methods on Aeroengine Component Lifing Decisions", *Journal of Mechanical Design*, Vol. 139 No. 2, p. 021401.

Timmermans, R.W. and Witjes, S. (2016), "Circular Business: Collaborate and Circulate; a bookreview", edited by Bernasco, C. and Goodchild-van Hilten, L.*Journal of Cleaner Production*, Circular Collaboration, Vol. 135, pp. 699–700.

Toba, A.L. and Seck, M. (2016), "Modeling Social, Economic, Technical & Environmental Components in an Energy System", *Procedia Computer Science*, The Author(s), Vol. 95, pp. 400–407.

Toffel, M.W., Stein, A., Lee, K.L. and Lee, K.L. (2008), *Extending Producer Responsibility : An Evaluation Framework for Product Take- Back Policies Extending Producer Responsibility,* Harvard Business School.

Tonelli, F., Taticchi, P. and Sue, E.S. (2009), "A framework for assessment and implementation of product-service systems strategies: Learning from an action research in the health-care sector", *WSEAS Transactions on Business and Economics*, Vol. 6 No. 7, pp. 303–319.

Tonglet, M., Phillips, P.S. and Read, A.D. (2004), "Using the Theory of Planned Behaviour to investigate the determinants of recycling behaviour: a case study from Brixworth, UK", Vol. 41, pp. 191–214.

Tseng, F.C., Huang, M.H. and Chen, D.Z. (2020), "Factors of university–industry collaboration affecting university innovation performance", *Journal of Technology Transfer*, Vol. 45 No. 2, pp. 560–577.

Tukker, A. (2004), "Eight types of product-service system: Eight ways to sustainability? Experiences from suspronet", *Business Strategy and the Environment*, Vol. 13 No. 4, pp. 246–260.

Tukker, A. (2015a), "Product services for a resource-efficient and circular economy - A review", *Journal of Cleaner Production*, Vol. 97, pp. 76–91.

Tukker, A. (2015b), "Priorities for Sustainable Consumption Policies", in Reisch, L.A. and Thøgersen, J. (Eds.), *Handbook of Research on Sustainable Consumption,* Edward Elgar Publishing, Cheltenham, pp. 145–160.

Tukker, A. and Tischner, U. (2006), "Product-services as a research field: past, present and future. Reflections from a decade of research", *Journal of Cleaner Production*, Vol. 14 No. 17, pp. 1552–1556.

Twede, D. (2002), "Commercial Amphoras: The Earliest Consumer Packages?", *Journal of Macromarketing*, Vol. 22 No. 1, pp. 98–108.

Ullman, D. (2016), *The Mechanical Design Process*, Fifth edit., McGraw-Hill Education, New York.

Umeda, Y., Nonomura, A., Tomiyama, T. and Nonomura, A. (2000), "Study on life-cycle design for the post mass production paradigm", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM,* Vol. 14 No. 2, pp. 149–161.

UNEP. (2014), *Valuing Plastics: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry.*

Unilever. (2019), *Annual Report and Accounts.*

United Nations. (2016), *Paris Agreement.*

United Nations. (2018a), *Classification of Individual Consumption According to Purpose (COICOP)*, New York.

United Nations. (2018b), *Single-Use Plastics - A Roadmap for Sustainability.*

Vallet, F., Eynard, B., Millet, D., Mahut, S.G., Tyl, B. and Bertoluci, G. (2013), “Using eco-design tools: An overview of experts’ practices”, *Design Studies*, Vol. 34 No. 3, pp. 345–377.

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., et al. (2017), “Ease of disassembly of products to support circular economy strategies”, *Resources, Conservation and Recycling*.

Vasantha, G.V.A., Roy, R., Lelah, A. and Brissaud, D. (2012), “A review of product-service systems design methodologies”, *Journal of Engineering Design*, Vol. 23 No. 9, pp. 635–659.

Venable, J., Pries-Heje, J. and Baskerville, R. (2016), “FEDS: A Framework for Evaluation in Design Science Research”, *European Journal of Information Systems*, Vol. 25 No. 1, pp. 77–89.

Vezzoli, C., Ceschin, F., Diehl, J.C. and Kohtala, C. (2012), “Why have ‘Sustainable Product-Service Systems’ not been widely implemented? Meeting new design challenges to achieve societal sustainability”, *Journal of Cleaner Production*, No. 35, pp. 288–290.

Vezzoli, C., Kohtala, C., Srinivasan with Diehl, A.J., Moi Fusakul, S., Xin, L., Sateesh Vezzoli, D. and Publishing, G. (2014), *Product-Service System Design for Sustainability*, Greenleaf Publishing Limited.

Vick, T.E. and Robertson, M. (2018), “A systematic literature review of UK university- industry collaboration for knowledge transfer: A future research agenda”, *Science and Public Policy*, Vol. 45 No. 4, pp. 579–590.

Voet, E. van der. (2002), “Substance flow analysis methodology”, *A Handbook of Industrial Ecology*, Edward Elgar Publishing Limited, pp. 91–101.

Vogtländer, J.G. (2010), *A Practical Guide to LCA for Students Designers and Business Managers*, VVSD, Delft.

Walker, R.A. (2008), “Is there a Service Economy? the Changing Capitalist Division of Labor”, *Reading Economic Geography*, pp. 97–110.

Wastling, T., Charnley, F. and Moreno, M. (2018), “Design for Circular Behaviour: Considering Users in a Circular Economy”*, Sustainability,* Vol. 10 No. 6, p. 1743.

Webster, K. (2013), “What might we say about a circular economy? Some temptations to avoid if possible”, World Futures: *Journal of General Evolution*, Vol. 69 No. 7–8, pp. 542–554.

De Weck, O.L., Roos, D. and Magee, C.L. (2011), *Engineering Systems: Meeting Human Needs in a Complex Technological World*, MIT Press.

Van Weelden, E., Mugge, R. and Bakker, C. (2016), “Paving the way towards circular consumption: Exploring consumer acceptance of refurbished mobile phones in the Dutch market”, *Journal of Cleaner Production*, Vol. 113, pp. 743–754.

Weetman, C. (2016), *A Circular Econmy Handbook for Business and Supply Chains: Repair, Remake, Redesign, Rethink*, 1st ed., Kogan Page.

Welink, J.-H. (2019), “How to Get Stuff Back?”, in Offerman, S.E. (Ed.), Critical Materials - Underlying Causes and Sustainable Mitigation Strategies, World Scientific Publishing, pp. 267–288.

Wever, R., van Kuijk, J. and Boks, C. (2008), “User-centred design for sustainable behaviour”, *International Journal of Sustainable Engineering*, Taylor & Francis , Vol. 1 No. 1, pp. 9–20.

Whalen, K.A., Berlin, C., Ekberg, J., Barletta, I. and Hammersberg, P. (2017), “‘All they do is win’: Lessons learned from use of a serious game for Circular Economy education”, *Resources, Conservation and Recycling*, No. January, pp. 0–1.

Wholey, J.S. (1996), “Formative and summative evaluation: Related issues in performance measurement”, *American Journal of Evaluation*, Vol. 17 No. 2, pp. 145–149.

Wholey, J.S. (2010), “Exploratory Evaluation”, in Wholey, J.S., Hatry, H.P. and Newcomer, K.E. (Eds.), *Handbook of Practical Program Evaluation*, 3rd ed., Jon Wiley & Sons, pp. 81–99.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J. and Kanemoto, K. (2015), “The material footprint of nations”, *Proceedings of the National Academy of Sciences of*

the United States of America, Vol. 112 No. 20, pp. 6271–6276.
Wieser, H. (2016), "Beyond planned obsolescence: Product lifespans and the challenges to a circular economy", *Gaia*, Vol. 25 No. 3, pp. 156–160.
Williams, A. (2007), "Product service systems in the automobile industry: contribution to system innovation?", *Journal of Cleaner Production*, Vol. 15 No. 11–12, pp. 1093–1103.
Williams, H., Wikström, F., Wetter-Edman, K. and Kristensson, P. (2018), "Decisions on recycling or waste: How packaging functions affect the fate of used packaging in selected Swedish households", *Sustainability*, Vol. 10 No. 12, pp. 1–19.
Wilson, G.T., Bhamra, T. and Lilley, D. (2015), "The considerations and limitations of feedback as a strategy for behaviour change", *International Journal of Sustainable Engineering*, Vol. 8 No. 3, pp. 186–195.
Wilson, G.T., Smalley, G., Suckling, J.R., Lilley, D., Lee, J. and Mawle, R. (2017), "The hibernating mobile phone: Dead storage as a barrier to efficient electronic waste recovery", *Waste* Management, The Authors, Vol. 60, pp. 521–533.
Woldemichael, D.E. and Hashim, F. M.(2011), "A framework for function-based conceptual design support system", *Journal of Engineering, Design and Technology*, Vol. 9 No. 3, pp. 250–272.
Womack, J.P. and Jones, D.T. (2005), "Lean Consumption", *Harvard Business Review*.
Womack, J.P., Jones, D.T. and Roos, D. (1992), "The machine that changed the world", *Business Horizons,* Vol. 35 No. 3, pp. 81–82.
World Bank Group. (2018), *What a Waste 2.0 - A Global Snapshot of Solid Waste Management to 2050.*
WRAP. (2019a), *Defining What's Recyclable and Best in Class Polymer Choices for Packaging.*
WRAP. (2019b), *Design Tips for Recycling - Paper and Card Packaging.*
Wrigley, E.A. (2015), "Energy and the English industrial revolution", *Energy and the English Industrial Revolution,* pp. 1–272.
Yin, R.K. (2018), *Case Study Research and Applications : Design and Methods, Case Study Research and Applications: Design and Methods*, 6th ed., SAGE Publications, Inc, Thousand Oaks.
Yong, R. (2007), "The circular economy in China", *Journal of Material Cycles Waste Management,* Vol. 9, pp. 121–129.
Yoo, M.J., Grozel, C. and Kiritsis, D. (2016), "Closed-loop lifecycle management of service and product in the internet of things: Semantic framework for knowledge integration", *Sensors*, Vol. 16 No. 7.
Yuan, Z., Bi, J. and Moriguichi, Y. (2006), "The Circular Economy: A New Development Strategy in China", *Journal of Industrial Ecology*, Vol. 10 No. 1–2, pp. 4–8.
Zalewska-Kurek, K. and Harms, R. (2020), "Managing autonomy in university–industry research: a case of collaborative Ph.D. projects in the Netherlands", *Review of Managerial Science,* Vol. 14 No. 2, pp. 393–416.
Zeeuw van der Laan, A. and Aurisicchio, M. (2017), "Planned Obsolescence in the Circular Economy", *PLATE Conference*, pp. 446–452.
Zeeuw van der Laan, A. and Aurisicchio, M. (2019a), "Archetypical consumer roles in closing the loops of resource flows for Fast-Moving Consumer Goods", *Journal of Cleaner Production*, Vol. 236.
Zeeuw van der Laan, A. and Aurisicchio, M. (2019b), "Gateways to Revalorisation in Future Circular Cities: A Vision for Closed-Loop Resource Flows", *Sustainable Innovation 22nd International Conference. Road to 2030: Sustainability, Business Models, Innovation and Design, The Centre for Sustainable Design,* pp. 113–119.
Zeeuw van der Laan, A. and Aurisicchio, M. (2019d), "Designing Product-Service Systems to Close Resource Loops: Circular Design Guidelines", *Procedia CIRP*, Vol. 80, pp. 631–636.
Zeeuw van der Laan, A. and Aurisicchio, M. (2020), "A framework to use product-service systems

as plans to produce closed-loop resource flows", *Journal of Cleaner Production*, Vol. 252, p. 119733.
Zeeuw van der Laan, A. and Aurisicchio, M. (2021), "The Flow Mapper: A Tool to Model Solutions for the Circular Economy and Put Systems Thinking into Action", *4th PLATE 2021 Virtual Conference.*
Zhang, S., Li, L., Kumar, A., Li, L. and Kumar, A. (2008), *Materials Characterization Techniques,* CRC Press.
Zhou, C.-C., Yin, G.-F. and Hu, X.-B. (2009), "Multi-objective optimization of material selection for sustainable products: Artificial neural networks and genetic algorithm approach", *Materials and Design*, Vol. 30 No. 4, pp. 1209–1215.
Zink, T. and Geyer, R. (2017), "Circular Economy Rebound", *Journal of Industrial Ecology*, Vol. 21 No. 3, pp. 593–602.
Zink, T. and Geyer, R. (2018), "Material Recycling and the Myth of Landfill Diversion", *Journal of Industrial Ecology*, Wiley/Blackwell, Vol. 23 No. 3, pp. 541–548.

Appendices

Appendix A. Study 1 Customer Journey Maps

	PURCHASE STAGE						USE STAGE				DISPOSAL STAGE				
	VISIT(WEB) SHOP	CHOOSE PRODUCT	PREPARE	PURCHASE	BECOME OWNER	STOCK	REMOVE	PREPARE	CONSUME	MAINTAIN	REMOVE	STOCK	PREPARE	TRANSIT	DETACH

state changing activity

first prerequisite activity

P resource in operative state
P resource in affected state
P resource in obsolete state
S service
C collect-and-return product

1. KEEP OBSOLETE RESOURCES

	PURCHASE						USE				DISPOSE				
SPLOSH	visit Splosh website	choose refills	PREPARE	make purchase	receive refills in post	store refills until a bottle is yempty	REMOVE	mix refill with water in bottle	pour Splosh detergents	contain Splosh detergents	REMOVE	keep empty Splosh bottles	PREPARE	TRANSIT	DETACH
DOPPER	open app to see refill points	choose refill point	refill bottle at refill point	PURCHASE	take filled bottle	STOCK	REMOVE	PREPARE	drink water	contain water	REMOVE	retain empty bottle	remember to take bottle	take bottle on the move	DETACH
ECOVER	visit retail with refill station	choose Ecover detergent	refill bottle	make purchase	take bottle home	keep in storage until use	REMOVE	PREPARE	pour out detergent	close lid for storage	REMOVE	retain empty bottle	remember to take bottle	take to retailer	DETACH

2. BRING OBSOLETE RESOURCES

	PURCHASE						USE				DISPOSE				
BOLDKING	visit Boldking website	choose cartridges	choose return envelope	subscribe to purchase	receive order	store until use	take from pack	assemble cartridge to handle	use the blade (until wear)	rinse and clean the blade	disassemble from handle	keep cartridges (until 12)	remember to take to post box	take to post box	drop in post box
GROLSCH	visit retailer	choose bottles with deposit	PREPARE	make purchase & pay deposit	take product home	store the beer until needed	open bottle	PREPARE	drink the beer	MAINTAIN	REMOVE	collect the bottles in crate	remember to take bottles	take bottles to retailer	place in reverse vending
MLIK&MORE	visit Milk&More website	choose milk in reusable bottle	PREPARE	make purchase & pay deposit	receive bottles on doorstep	keep in refrigerator until use	REMOVE	PREPARE	use product	close lid and refrigerate to preserve	clean bottles	store bottles	remember to organise return	take bottles to doorstep	leave bottles for collection (deposit)
REPACK	VISIT(WEB) SHOP	opt-in during E-shopping	PREPARE	make purchase & pay Repack	receive e-commerce in Repack	STOCK	REMOVE	PREPARE	unpack purchase from Repack	MAINTAIN	REMOVE	keep Repack envelope	reveal label and remember	take to post box	drop in post box (voucher)
HP	visit retailer	choose cartridge	PREPARE	make purchase	take cartridge home	store until replacement indicated	unpack cartridge (envelope)	place in printer	use until replacement indicated	MAINTAIN	remove cartridge from printer	collect until 3 cartridges in envelope	remember to take	take to post box	drop in post box
NESPRESSO	visit Nespresso brand store	choose preferred capsules	ask for collection envelope	make purchase	take capsules home	store capsules until use	take capsules from sleeve	place in Nespresso machine	run Nespresso machine	MAINTAIN	remove capsule from machine	collect until 200 capsules in envelope	remember to take envelope	take to post box	drop in post box
BIC	visit retailer	choose BIC pens	PREPARE	purchase pens	take the pens home	store pens until use	take a pen from pack	PREPARE	use the pen (until wear)	close lid of pen	REMOVE	collect until going to TC	remember to take	take pens to school	drop in TC box (points)
DRINKFINITY	visit Drinkfinity webshop	choose pods	PREPARE	place order	receive order	keep pods until use	take a pod from the pack	assemble pod with bottle	drink infused water	MAINTAIN	disassemble from bottle	store used pods	print, pack and remember	take to post box	drop in post box (points)
GARNIER	visit retailer	choose product	PREPARE	make purchase	take product home	store until needed for use	REMOVE	PREPARE	use product	close lid and contain	remove excess product	store bottles	print, pack and remember	take to post box	drop in post box (points)
JACOB'S	visit retailer	choose biscuits	PREPARE	make purchase	take biscuits home	store until use	REMOVE	PREPARE	eat biscuits	close pack to preserve biscuits	REMOVE	collect until 1kg of wrappers	print, pack and remember	take to post box	drop in post box (points)
LUSH	visit Lush brand store	choose product in black pots	PREPARE	make purchase	take product home	keep product until use	REMOVE	PREPARE	use product	close lid to preserve product	remove excess product	collect until 5 pots	remember to take	take to Lush store	hand in at Lush counter (face mask)
MAC	visit MAC brand store	choose MAC product	PREPARE	make purchase	take product home	keep product until use	REMOVE	PREPARE	use product	close lid to preserve product	REMOVE	collect until 6 items	remember to take	take to MAC store	hand in at MAC counter (lipstick)
PRESERVE	visit Preserve website	choose toothbrush	PREPARE	make purchase	receive toothbrush in parcel	keep product until use	remove outer packaging	PREPARE	use toothbrush	rinse and use until worn	REMOVE	store until 5 items collected	print, pack and remember	take to post box	drop in post box (points)

3. CONSIGN OBSOLETE RESOURCES

	PURCHASE						USE				DISPOSE				
FUJI	visit retailer	choose Fuji disposable camera	PREPARE	make purchase	take camera home	store until event to take pictures	unpack from sleeve	PREPARE	take 27 photos	MAINTAIN	REMOVE	retain camera	remember to take	take to photo service	hand in camera (photos)

4. ABANDON OBSOLETE RESOURCES

	PURCHASE						USE				DISPOSE				
KARTENT	visit festival website	opt-in during booking	PREPARE	pay for the tent online	go to festival	STOCK	REMOVE	PREPARE	sleep in tent during festival	MAINTAIN	remove everything from tent	STOCK	PREPARE	TRANSIT	leave tent at festival site

Appendix B. Study 2 Dataset

The abbreviations used in this table refer to:

Sta.	State resource lifetime
Gov.	Govern resource lifetime
Int.	Intercept obsolete resources
Tra.	Transition obsolete resources

Quote	Ref	Sta.	Gov	Int.	Tra.	Guideline
MSDS (Material Safety Data Sheet) management applications can be termed the core of the services in this profile [IT Focused safety and supply management]. (…) included tools for chemical usage and inventory value follow-up, inspection and audit management, toxic or hazardous waste inventories, chemical tracking in single or multiple locations and labelling applications.	[1]				X	Understand the value of obsolete resources.
The KIES service is mainly about operating and managing industrial waste sludge and water for the company's customers. The aim is to recover or reclaim chemical substances [in-house] back to the customer's own manufacturing process [or other local customers' processes].	[1]				X	Establish demand for obsolete resources
The company offers closed container systems, and its solvents and service network partners offer cleaning equipment, distribution and logistics services, and waste management. (…) its service entails co-operation and co-production of a service package with [third parties].	[1]			X		Lure obsoletes to gateways.
The fourth, integral or full service, model combines chemical management and waste management in order to streamline the customers' processes starting from downstream or by wrapping the customer with inbound and outbound supply management. It seems to be a profile for large companies that are able to offer all the services either by themselves or through subsidiaries and different business units.	[1]			X		Provide gateways for obsolete resources.
A method to optimise the warranty time to minimise the provider's costs; how to estimate out of warranty time up until a form of relative obsolescence is reached and the product is disposed of.	[2]	X				Make lifetime specific
Table 1 presents a brief summary of the reviewed literature. As shown in the table, several papers explore the effect of warranty by considering the producer and customer's costs. But none of them have simultaneously considered warranty, out of warranty and EOL phase to minimise the total cost of usage and EOL phase of product from viewpoint of customer and producer. (...) a model that						
integrates several considerations that many researchers have addressed separately, including optimisation of warranty and out of warranty period form producer and customer's point of view with respect to sustainable product service system.	[2]	X				Make lifetime specific
One logical approach to achieve sustainability is extending the product's life by warranty and services. Customer's decisions during the 'usage' phase of a product on whether to repair or throw items away affect the product life span (and thus the rate of waste generation). The E-SCOPE survey (King et al. 2006) found that 68% of respondents have cited cost as a reason why they did not get items repaired: a factor borne out by the fact that while new washing machine prices increased by only 40% during the 1980s–1990s, repair costs over this period increased by 165%. However, little research has been conducted to understand the advantages of this closed loop option with respect to sustainability.	[2]			X		Lure obsoletes to gateways.
Services such as take-back are increasing, though sometimes utilized in exchange for discounts and not always implemented to close the material loop.	[3]			X		Lure obsoletes to gateways.
MaryAnn visits her local department store. She discovers a collection of one-of-a-kind pieces created from old garments. The collection is the result of a new take-back service. Used clothing items can be brought back in exchange for a coupon for new purchases. The store recycles used clothing fibres or redesigns garments for resale.	[3]				X	Establish demand for obsolete resources
Despite this, respondents readily identified several PSS features such as extending use time, *Recycling*, rede- sign, and take-back as being good for the environment. The environmental benefits of selling clothing products with redesign and repair services (Scenario 1) or renting (Scenario 6) options made these concepts attractive. Respondents	[3]				X	Understand the value of obsolete resources.
suspicion about the effort required and anticipated benefits was raised in discussion: for instance, how expensive the garment would have to be to merit the effort made to take it back to the shop for modifications or repair. Clearly, it was not entirely transparent to participants what the real advantages would be, in light of their historical consumption habits.	[3]				X	Optimise the value of obsolete resources
The development of clothing-related PSS may be most ideal for a company with a well-established brand image. For example, Marks and Spencer has begun to offer similar services, such as take-back. A smaller boutique may have a more difficult time earning the consumer's trust. Acceptance of experiential schemes hinge on the company's ability to educate and provide support and reassurance to the customer in the design process.	[3]			X		
Product-oriented services sell a product and a product-related service that adds value to the sale, such as maintenance, financing, take-back schemes or consultancy while	[3]			X		Provide gateways for obsolete resources.

The following is the basic idea of the proposed PSS						
scenario: The furniture manufacturer offers products for renting. The customer rents the furniture and the service includes maintenance, repairing and up-grading by the manufacturer. At the end of the renting period the customer returns the furniture and receives remanufactured furniture if s/he wants to continue the renting contract. The old furniture is remanufactured and rented to another (or the same) customer. The	[4]	X				Reveal or communicate obsolescence
During the interviews, logistics emerged as another						
important factor with regard to the economic feasibility of the PSS scenario. The cost effectiveness of the PSS scenario significantly depends on the transport distance between the service provider and the customer, as well as the amount of furniture serviced by one provider. It seems only decentralized organization would make economic sense. Transport of office furniture seems to be too expensive to facilitate transport back to the production facility. Once the furniture has reached the customer it should be transported as little as possible for both environmental and economic reasons. Regional or local service providers seem to be the best solution in order to provide an economically feasible renting service. These providers should be responsible for repair, maintenance, customer consultancy, relocations, reorganizations and remanufacturing. Another	[4]			X		Understand the value of obsolete resources.
The profitability of material recycling from office furniture is closely dependent on the volume of waste: the more office furniture is transported and disassembled together, the more profit- able the process becomes [1]. In	[4]				X	
The problem is that there is no market for recycled materials and no interest from the customers' side to pay for material recycling. Under the current legislative conditions in the EU it is cheaper and easier to burn or dispose old furniture.	[4]				X	
Witte [1] calculated that the utilization of old parts in new office furniture could lead to cost reductions of up to 35%. One problem for the implementation of this strategy is the development of a take back system that ensures producers a constant reflow of office furniture or furniture parts in good condition. Witte	[4]				X	
The interviewed manufacturers and experts pointed to the strong competition from low-cost countries, which could destroy the possibility to remanufacture furniture, since the remanufacturing of used furniture in western European countries would always be more expensive than the production of new furniture in low-cost countries. Nevertheless, western European countries will most probably lose the price war against low-cost countries, even if they rationalize production processes, just because of the difference in labour costs. Therefore,	[4]				X	
The take back and remanufacturing of used office furniture can facilitate a second or third usage period. Office furniture is a simple product that in principle does not lose its function over many decades. Both the SYSKREIS project [3] and Witte [1] stated that a major fraction of production costs for office furniture is raw material costs. Therefore, it seems promising to remanufacture office furniture. According to a case study [1], office chair remanufacturing could be realized economically but difficulties remained in finding a market for secondhand chairs.	[4]			X		Establish demand for obsolete resources
By embedding the RFID into the PCB it is physically embedded in the product and stored information travels with the product through the supply chain and throughout the product lifecycle to the user and the recycler. (...) New life cycle monitoring system approaches, as discussed above, have been proposed to overcome the information boundary between the supply chain and the end user and recycler. (...) The uncertainty of network availability introduces a risk of losing visibility during the product life cycle. In contrast, the proposed system with an embedded RFID tag offers ready visibility of relevant product data across the whole life cycle of the product. Only additional operational data is reliant on network connectivity, whilst relevant data is directly accessible from the product itself.	[5]		X			Monitor resources in use.
Life cycle information is central to PSS implementation. Furthermore, performance data collected during customer usage can help to provide a better understanding of the product during its life, to enable optimisation of servicing and maintenance plans, improve overall product quality and wear characteristics and hence the increase value of the service supplied. With product ownership and subsequent investments being the responsibility of the OEM, quality and reliability are key to reducing running costs, retain brand reputation and to maximising return on investment.	[5]		X			Align changes to the obsolete state with moments of interaction

However, costs incurred during the use phase of a product / service include those for root cause analysis and repair, which occur during servicing and maintenance. Uncertainties exist here, as MTBF and MTTR are also strongly dependent on the scenarios and the efficiency in responding to events (e.g. failures). The need for improvements in life cycle monitoring to enable and timely more accurately and timely prediction of these variables is vital for PSS adaptation	[5]				X	
Finally, through the IoT technology, companies can access real-time product location and condition. This information may be used for a better execution of end-of-life collection, refurbishment, remanufacturing, and recycling activities (#8) [12,23].	[6]			X		
Moreover, companies through IoT may monitor the product condition, status, location, and usage						
(Table 2, #3) [12,52], thus discouraging careless users' behavior that may lead to quicker wear and tear—therefore, product lifespan is extended. This	[6]				X	
During the use stage, suitable sensors required to capture relevant users' data and part conditions will be identified for a family of products.	[7]		X			
These sensors can communicate with the manufacturers and other stakeholders to provide the necessary data automatically for disassembly planning during maintenance.	[7]				X	Optimise the value of obsolete resources
Disassembly planning focuses on the components and product levels to generate the most optimal disassembly route of a specific product. Meanwhile, disassembly sequencing focuses on the task planning and inventory flow to systematically disassemble batches of products. Reported	[7]				X	Optimise the value of obsolete resources
To address uncertainties due to EOL conditions of the products, dynamic disassembly planning methods that take into account real time conditions, such as broken parts and severely corroded components, have emerged as a challenging field to assist human operators in retrieving the core efficiently in real life conditions.						
For	[7]		X			
However, a reasonable assumption of lifetime warranty						
is that it does not cease before the statutory warranty period ends and it does not exceed the technical or physical life of the product. Changes	[8]	X				Make lifetime specific
The waste effect of a PSS is independent of its being product-oriented, use-oriented or result-oriented. Rather the effect depends on how the business model of the PSS organises material flows at production, distribution, use and post consumption stages in relationship to prevailing waste regimes where the PSS operate.	[9]				X	Understand the value of obsolete resources.
Likewise again, second largest global clothing retailer H&M has set up a take-back system, mostly oriented toward recycling. H&M lets I:CO, part of the used textile and recycling SOEX group, run a collection system in its stores and accepts any textiles regardless of origin, providing consumers with a fixed discount for their next purchase according to I:CO's slogan: Rethink, Recycle, Reward.	[9]			X		Provide gateways for obsolete resources.
Danish Vigga can be considered a result-oriented PSS that offers customers the possibility to focus on the result of having their babies dressed in chemical-free and organic clothes (GOTS-certified organic cotton) rather than on any specific pieces of clothing. To achieve this result, Vigga puts together packages of clothes for its consumers based on baby's size; replaces these packages with new packages as the child grows; then washes and prepares used clothes for reuse by other consumers; and, eventually, recycles worn out pieces. Likewise, Filippa K has started providing customers with advice and products to deliver a "curated wardrobe" that could be considered an embryo of a result-oriented PSS as it focuses on outcomes rather than on means.	[9]	X				Reveal or communicate obsolescence
For instance, the Swedish premium clothing and interior design company Boomerang has offered since 2008 a service offline store take-back in its Swedish stores that aims at reuse and recycling. (…)						
Other companies offer similar take-back services. For example,						
Indiska, a medium life-style brand, also offers a take-back service oriented toward reuse and recycling. The company collects used textiles on behalf of Myrorna, a second-hand retailer owned by the Salvation Army; Indiska has even started selling in its own shops a limited amount of selected jeans with a Myrorna tag. Likewise, the premium Swedish brand Filippa K offers a combination of reuse, collecting used garments of its own brand to sell some of them in a second-hand Filippa K store, and gives the rest to charity for recycling.	[9]			X		Provide gateways for obsolete resources.
Likewise, the premium Swedish brand Filippa K offers a combination of reuse, collecting used garments of its own brand to sell some of them in a second-hand Filippa K store, and gives the rest to charity for recycling. Likewise	[9]				X	Establish demand for obsolete resources

For instance, there is no discussion of the nature of the substances referred to as waste or how differently various waste management options affect the environment. A more efficient management of waste has not been high on the PSS research agenda except as an ideal environmental benefit, a potential for cost reduction, and away to comply with EU regulations such as the recast of the Restriction of Hazardous Substances Directive (RoHS 2; The European Parliament and the Council of the European Union, 2011/65/ EU) or the Waste Electrical and Electronic Equipment (WEEE) Directive (The European Parliament and the Council of the European Union, 2012/19/EU). Expanding	[9]		X		
Another finding is that the European waste hierarchy model (The European Parliament and the Council of the European Union, 2008/98/EC), or an equivalent model outside the European context, creates a clarity among waste treatment alternatives that may serve as strategies for reducing waste effects. Such strategies would also gain in precision if PSS managers adopted a broad understanding of waste, one that runs along the whole value chain and internalizes its total environmental costs (Watson et al., 2014), including less visible costs such as the negative environmental impacts of recycling activities in poor countries or the lasting emissions of methane in landfills. Such strategies would even benefit from institutional incentives such as raw material taxes, extended producer responsibility (EPR) systems, and other ways to replace cur- rent valuation practices and bring along waste regimes where it makes good economic and environmental sense to learn from and account for waste. On this account, PSS designers may gain from collaborating more tightly with waste specialists early in the PSS development process to imagine ways of reducing the residual material impacts of their creations	[9]			X	
Upon handing a piece of Boomerang clothing back, a consumer receives a 10% discount for the next purchase, which can have a substantial impact on the profitability of single sales if the purchased product is significantly cheaper than the retuned one. The	[9]		X		Lure obsoletes to gateways.
For instance, the Swedish premium clothing and interior design company Boomerang has offered since 2008 a service offline store take-back in its Swedish stores that aims at reuse and recycling. Named the Boomerang-effect, the initiative came from one of the designers who found it problematic that a new winter jacket for kids would cost as much as an adult jacket even though it would be quickly outgrown. She argued that Boomerang should offer consumers the possibility of returning the jacket to the store. Today, the company presents the service as a way to communicate long-lasting quality and strengthen the Boomerang brand.	[9]		X		
UFD has designed an original collection system geared toward reuse. UFD is a premium brand that mostly uses up-cycled mate- rials and aspires to design and produce the most environmentally friendly fashion garments on the market and lead a movement for a changing industry. The company has introduced a shopping bag that, if turned inside out, becomes a "rag-bag" that can be stuffed with an old item and mailed directly to a charity free-of-charge.	[9]	X			Reveal or communicate obsolescence
Waste collection and treatment is an industry in its own right, and it is far from obvious for a company to build closed material loops with their own products. It is even far from obvious how to exploit the information potential of used products to learn how to improve the reuse and recycling of the products that firms put on the market. There are many differences among firms that have set up PSSs when it comes to engaging with repair or resale, monitoring the waste that they produce, and following the processing of waste after having helped to collect it. Different PSSs expose decision makers to different waste knowledge and create more or less favorable positions for them to monitor the residual material effect of these PSS	[9]		X		Provide gateways for obsolete resources.
In the case of the use-oriented PSS, clear specification of the exact points at which the product is to be returned at EOL are specified and compliance is encouraged through a pay per use purchase process.	[10]		X		Lure obsoletes to gateways.
The involvement of a third party would remove the responsibility for storage and refurbishment or remanufacturing [i.e. The focal company was not equipped for handling excess stock]	[10]			X	
In the case of a product-oriented PSS, ownership is transferred to the customer, who enters a contract with the company through which they are committed to take-back.	[10]		X		Provide gateways for obsolete resources.
The ECO-WISE staff have very specific training needs, and these will need to be met by the focal company if the project is to be scaled up. They also lack remanufacturing equipment and do not have the means to purchase it. Therefore, the focal company will need either to carry out some of					

the remanufacturing at their own facility, or support the ECO- WISE in purchasing the relevant equipment. Transfer of the chairs from the first customer to the ECO-WISE and subsequent storage has also proved problematic. They are a very small enterprise and only have storage capacity for a small number of chairs. In the pilot case, the chairs have already been decommissioned and are stored in the corporate client's warehousing facility. This has allowed the focal company to combine phased collection with existing delivery schedules, thereby reducing transport costs. However, this reliance on the corporate client limits the degree to which the take-back scheme can be extended.	[10]	X		Provide gateways for obsolete resources.
A product-oriented PSS is much less predictable in terms of material flow than a use-oriented PSS. Problems arise in recovering the chairs at EOL; the company is reliant on their customers being motivated to return the chairs at two points in the overall lifetime.	[10]		X	
A third party is currently selling into a market that does not expect comparable quality to the original product, however, the quality is crucial for the focal company to have the best possible standard.	[10]		X	Understand the value of obsolete resources.
The low uptake of the				
company's current take-back				
scheme highlights that				
customers do not currently have sufficient incentive to return chairs. If the chairs are not refurbished and remanufactured at the appropriate times, it may become economically unviable to undertake the process. The	[10]	X		Lure obsoletes to gateways.
In order to achieve the focal company's objective, it is				
necessary to design a PSS that ensures that the chair is used for the fifteen-year period.	[10]	X		
(…) and especially making use of commercial waste companies' knowledge on collecting items that should no longer be regarded as waste.	[11]		X	Understand the value of obsolete resources.
Today, the range of goods provided spans clearing-out and pick- up-at-home services, sorting and cleaning of e.g. clothes, repairing of e.g. household appliances, refurbishing of e.g. furniture and dismantling and reassembling goods (Neitsch et al., 2010). Re-use ECO-WISEs like Heidenspass have also gone about re-design with a plethora of ideas like bags, furniture or decorative items. All these features, including labour-intensive services like take-back systems, repair/refurbishment, or disassembly, conform to Mont's (2002) definition of SPSS. (...) Activities that have to be extended pertain to e.g. installing "re-use corners" in community waste centres, establishing co-operation with trade companies as to take-back systems (e.g. for furniture, clothes, or sports gear)(...)	[11]	X		Lure obsoletes to gateways.
Procurement refers to the collection of reusable items from private households, companies and (public) organisations. Heidenspass procures items via a bonus system for re-use products and is hence placed outside the waste regime, as a donation is central to the transaction. Mostly procurement takes place within the waste regime and requires the recipient to possess a waste collector's license, which all Austrian re-use ECO-WISEs do.	[11]		X	Establish demand for obsolete resources
Activities involved in preparing for re-use (cf. Fig. 2)are repairing, refurbishing and to some extent re-assembling of still functional or interesting parts into new products. (…) Accordingly, quality criteria are needed (…)	[11]		X	Optimise the value of obsolete resources
retail activities can differ significantly from "classical" sales marketing: Mostly retail takes place in re-use ECO-WISEs that are run with the help of transit workers. The range of products offered depends on the amount and quality of reusable items made available by procurement and preparing for re-use. Sales and price policy can also differ, but at any rate re-use shops strive to provide good-quality and low-price offerings in an appealing setting	[11]		X	Understand the value of obsolete resources.
The main problem is that (except for textiles and WEEE) there is				
no separate collection established in the waste regime. Accordingly the items often become residual waste and can no longer be re- used (due to e.g. hygiene reasons). In reality, hence, only a fractional amount is retrieved as re-use goods. This will change significantly in phase 6 of waste management development with the self-perception of the waste industry shifting from that of a disposal service to that of a supplier of goods, thus substantiating that re-use systems feature SPSS characteristics (Klampfl-Pernold et al., 2011). And it will change with the emergence of a new kind of waste enterprise: re-use ECO-WISEs.				
3.3.	[11]		X	Establish demand for obsolete resources

Items can be donated or sold to/in second-hand shops, bric-a- brac markets or internet platforms. (…) Secondly, items can be brought to “community waste management and recycling centres” (referred to as community waste centres), re-use enterprises or inserted into special containers.	[11]			X		Lure obsoletes to gateways.
PSS can prevent waste when a certain proportion of households on new housing developments consume PSS as a complement to self-service. However this only arises when households select lightweight goods to support their self service activities and retain these for 15 years.	[12]	X				
Rather than utilising just product in-use-data, the framework utilises system-in-use data which is data collected from the various elements in a system in which a PSS or a product is embedded (...) [e.g.] Interviews, in-service records or ethnographic means to create a picture of the task devised to meet that customer's need (...)	[13]		X			Monitor resources in use.
Formerly, aging planes were defined by calendar years and operating hours but today, sophisticated models analyse the relative value of an aircraft to determine service life. (…) The first major study on aircraft recycling was initiated by Airbus in 2005. PAMELA was a dismantling						
demonstration project carried out with support from several partners and the European Commission. The objectives of PAMELA were to: 1) demonstrate full-scale experimentation on aircraft where 85% could be recycled, reused or recovered, 2) set up a standard for environmentally responsible management at the end-of-life, and 3) develop an international network of partners to further disseminate this topic.	[14]	X				Reveal or communicate obsolescence
The valuation of a ship as it ages is complex but the European Commission states that ‘freight rates determine when to scrap; labour costs determine where to scrap; steel prices determine the size of the ship owner's profit’. [43]	[14]				X	Understand the value of obsolete resources.
a management information system can help handle the exchange of information along the product life cycle. New technologies have the potential to improve the efficiency of doing business including improved management of products and resources. [66] Digitalization and end-to-end optimization opens new possibilities - from automation of many work steps to decision support in situations like reuse and recycling. It calls for new data streams to be managed and central tools to handle information. Product	[14]		X			
The project showed that a material mapping in the design phase would support high value recycling and would eliminate the need for spectrometric analysis.	[14]				X	Understand the value of obsolete resources.
Maersk Line, has been working on a ‘cradle2cradle’ (C2C) passport for their Triple-E fleet. The aim of the passport is to create a document that marks the materials into different material categories as well location of all materials in addition to dismantling and recycling instructions. The expectation is that the salvage value can increase up to 10 % due to the increased knowledge of the ship.	[14]				X	Understand the value of obsolete resources.
The IDIS database was created to assist in dismantling of parts in the quickest and least complicated way – and thereby most economical. One of the key features is the identification of economically recyclable plastic parts as all plastic parts exceeding 100 grams are coded to ensure systematic recycling. This has fostered innovations in the automotive industry that support ‘closed-loop-recycling’, where some materials go back into the automobiles as secondary raw material [38] and helped to: (1) Prevent use hazardous materials (reduction of 96-99,99%), (2) Code and/or inform on parts and components, (3) Ensure information for consumers and treatment organizations (achieved, but criticized for being too bureaucratic and costly) and (4) Achieve reuse, *Recycling* and recovery performance targets (significantly improved and increased willingness to integrate recycled materials in design). [37]	[14]				X	Understand the value of obsolete resources.
including an inventory of hazardous materials [IHM] that should enable a ‘cradle-to-grave’ approach for ship recycling, with focus on avoiding hazardous materials in new ships. [43] The IHM is central in the HKC as a document containing an inventory of the materials used in ship manufacturing, including materials that are potentially hazardous to humans or the environment. The IHM accompanies the ship throughout its service life and changes are recorded. The final owner is expected to deliver the IHM with the ship to the recycler and virtually all materials can be recycled or utilized locally. [44-45]	[14]		X			Monitor resources in use.
Haigh and Griffiths (2009) notify that a sustainable strategy signifies a company’s relationship to nature is integrated and managed throughout the value chain, where information and control systems that support life-cycle thinking are central components of the strategy. [3] However, companies are often motivated by legislative or competitive factors rather than by integrated sustainability values. [4]	[14]	X				

A part of customers prefers purchasing (or leasing) remanufactured products, and such customers are increasing, however still such demands are limited. Remanufactured products are often bundled to newly manufactured products with a large-lot customers purchases.	[15]			X	Optimise the value of obsolete resources
They will take back the computers after the usage by the consumers. This is to ensure that the computers are being used up to the optimal lifespan and being properly managed as E-waste instead of being disposed into the general waste stream. (…) the manufacturers will take back the computer and parts for appropriate EOL actions. Through this system, the manufacturers have greater flexibility of managing the hardware resources at different stages and thus optimising the use of the resources. (...) environmental benefits will be yielded as E-waste will be handled properly and materials will make their way to the recovery plants	[16]			X	Understand the value of obsolete resources.
Perhaps, the most significant challenge of these directives is to create an effective take back system. Taking back products will enable the manufacturers to better manage and manipulate used items for proper EOL treatment or repair services. This can maximise the utilisation of					
resources, help to achieve					
dematerialisation and alleviate the problems of Electronic waste (E-waste)	[16]		X		
To further highlight the problem, it has been reported that in the computer industry, one of the major obstacles in encouraging sustainability is the absence of accurate information flow of material through the industry supply chain. Hence it is required to design an infrastructure suitable for implementing a new framework that promotes communication, interactions and exchanges among the different actors from various stages in order to form a closed product life cycle loop both in terms of information and physical products.	[16]			X	Optimise the value of obsolete resources
These require ontology for relationships between design and EOL, design and maintenance, design and marketing, resource provision and EOL, usage and EOL as well as manufacturing and EOL. This is unique to the discrete manufacturing industry as they involved both the hardware and software feedback to the earlier stages and each stage is rather modular.	[16]			X	Optimise the value of obsolete resources
In the event of repair, upgrade and maintenance, the products must be arranged					
A framework for IMPSS 93					
to be collected at the service centre for assessment and then be dispatched to the appropriate substages, either take-back, repair, maintenance (including upgrading) or cleaning for the respective services. (...)					
Through this system, the manufacturers have greater flexibility of managing the hardware resources at different stages and thus optimising the use of the resources.	[16]		X		
[includes many things but also planning for obsolescence - e.g. proactiveness for maintenance and recycling purposes]	[17]	X			
[Several through life-cycle aspects are introduced] Remote and offline monitoring and planned maintenance (pre-determined and condition-based) are likely to be improved and operational losses minimised.					
related) activities. Further, how to run, maintain, update and patch software over time needs to be considered as well. The service-support system can in an FP context span a number of assets such as online and offline monitoring systems, analytic systems, warning/notification systems, maintenance and support instructions/manuals, information and information systems, knowledge					
(...)					
In particular, it is necessary to be able to manage the through-life-cycle aspects where large costs and risks are involved, e.g. asset management, and do it in an elaborately considered manner. Monitoring is also a key aspect which facilitates other aspects such as proactive/predictive maintenance and availability management.	[17]	X			Monitor resources in use.
Risks of entering the global market. E.g. Lower take-back of used product in some counties due to customer preferences.	[17]			X	Understand the value of obsolete resources.
The profit margins of remanufactured goods are as high as that of newly manufactured products, although it depends on the conditions. If the number of remanufactured increases, it becomes difficult to collect used products in sufficiently high quantities and thus remanufacturing costs increases., which then increase incentive to create new product.	[17]			X	

In PSS business models for circular economy, firms re-use parts (also modules and product components) as far as possible after the end of the product's life. This is possible because the producer reclaims the ownership of the product.	[18]				X	Optimise the value of obsolete resources
The results shown in Fig. 5 demonstrate that the environmental impact and the CRR on investment in design for remanufacturing strongly dependents on both the product properties and type of active fasteners.	[19]				X	Optimise the value of obsolete resources
For all products in this first cluster manual disassembly was, before the implementation of design for remanufacturing, not the most profitable EoL treatment due to high product complexity and, accordingly, high disassembly time. After the implementation of active fasteners a disassembly-based treatment becomes substantially more profitable, resulting in a high return on investment for the products in this firs cluster.	[19]				X	Optimise the value of obsolete resources
Furthermore, the following factors were identified to significantly influences the value of design for remanufacturing: (…) 4.) The collection rate at EoL, since investments in design for demanufacturing only make sense from an economic perspective when the products will be demanufactured by the company or society that invested in the improved product design	[19]				X	Understand the value of obsolete resources.
Furthermore, the following factors were identified to significantly influences the value of design for demanufacturing: (…) 5.) The product knowledge at EoL, since disassembly operations are more cost efficient with good product knowledge, which results in lower potential economic benefits of implementing design for active disassembly. For example, for the Yomani payment terminal, the medical monitor, the V3 setup-box and the B-Box modem, good product knowledge, which avoids the time required to localize and identify the type of fasteners, is evaluated to result in a decrease in disassembly time of up to 68%.	[19]				X	Understand the value of obsolete resources.
Furthermore, the following factors were identified to significantly influences the value of design for demanufacturing: (…) 2.) The product lifetime, as the CRR on investments in design for demanufacturing is negatively related with the average product lifetime, since a longer product lifetime results in a later return on investment.	[19]				X	Understand the value of obsolete resources.
Furthermore, the following factors were identified to significantly influences the value of design for demanufacturing: (…) 3.) The labor cost, since the economic benefits of design for demanufacturing are mainly obtained by reducing the labor intensity of repair, remanufacturing, cannibalization and recycling processes, while increasing the material recovery efficiency at EoL. 4.)	[19]				X	Optimise the value of obsolete resources
The color scheme would gradually be developed through the addition of brighter and carefully selected accent colors as the child grew, thereby slowly creating changes in the collection. This design strategy might be seen as a way of making the garments withstand the psychological obsolescence of fashion as well as to appeal to a large number of subscribers.						
(...)						
A service that leases-out baby clothing uses a changing colour-scheme to avoid aesthetic obsolescence and keep customers engaged.						
(This color scheme would gradually be developed through the addition of brighter and carefully, selected accent colors as the child grew, thereby slowly creating changes in the collection. This design strategy might be seen as a way of making the garments withstand the psychological obsolescence of fashion as well as to appeal to a large number of subscribers.) VIGGA, a baby clothing lease-company: Because the economic viability of the concept depended on how many times a garment could be circulated to new users, primary importance was placed on the material and aesthetic longevity of the garments. The business model was built around the assumption that garments could be circulated five to eight times before they would have to be discarded, and much effort was made to select durable textiles, which would be able to withstand circulation among multiple users. [Petersen]	[20]	X				Reveal or communicate obsolescence
Upgradability is used to respond to local technical problems (updating norms, update because of a broken component etc.) or as an end-of-life option	[21]			X		Lure obsoletes to gateways.
In our previous studies on remanufacturing (Pialot et al., 2012), well defined cycles were considered; these were constrained by the lifetimes of essential components and by the costs and environmental impacts of changing modules and returning them to the factory for renovation. In the more accessible configuration of upgradability (modules being changed by a technician or even by the client, with no return to factory necessary), the definition of "cycle" becomes less constraining so that it is possible to imagine cycles that are not prescribed in advance.	[21]		X			Align changes to the obsolete state with moments of interaction

In the more accessible configuration of upgradability (modules being changed by a technician or even by the client, with no return to factory necessary), the definition of “cycle” becomes less constraining (…)	[21]		X			Align changes to the obsolete state with moments of interaction
From the point of view of business model, upgradability implies that the manufacturer reconsiders customer relationships, adds one or several potential partners to materialize the support services for upgradability and imagines several modes of contract to be able to build a strategy to lead consumer towards offers without ownership transfer.	[21]		X			Communicate and agree on moments of interaction.
(...) in other words a product whose end-of-life would be projected over a longer term through optimal modularity. With such products, any technical, functional or visual improvement could be “easily” integrated, and could even depend on the changing needs of each user.	[21]				X	Optimise the value of obsolete resources
(…) keystone of an Up-PSS is an environmental gain derived from the hybridisation of rationalisation strategies in the use of the material relative to extended life time, optimisation of end-of-life and dematerialisation (hypothesis of Up-PSS in section 2.2). (...) an optimised end-of-life. This schedule of upgrades, carried out by a support service that collects worn modules at the same time as it implants “improved” modules, facilitates the end-of-life processing of these modules for the following reasons: flows are known (no uncertainty), the state of the modules is known (they thus do not have to be sorted) and the dismantling has already been done. Moreover, this scheduling of worn out modules for processing forms a perennial network of actors in end-of-life channel and facilitates the end-of-life pro- cessing of the product structure.	[21]			X		Lure obsoletes to gateways.
The tool rental business owner reported that he cleans and oils his products in between customers, and for small tools and equipment, he would normally change the motor and parts himself. However, for large construction equipment, he would usually sell them after 3 years of rental, where they could be repaired or rebuilt for the second hand market. However, if he expects something to break, he is likely to sell it before that happens. If a tool breaks while being rented, they usually repair the tool and take the repair cost from the deposit.	[22]				X	Understand the value of obsolete resources.
‘Repair, take back and recycling’ is particularly important for goods that have high environmental impacts during the production and disposal phase, such as electrical and electronic goods.	[22]				X	Understand the value of obsolete resources.
The baby equipment rental business explained that some baby equipment items need to be replaced after a certain period of time due to safety concerns. For example, a car seat needs to be retired after 5e6 years. Accordingly, they tend not to repair their equipment and often sell equipment to friends before it becomes worn. In this situation, repair of rental goods is not desirable, but professional recycling may still be possible.	[22]	X				Reveal or communicate obsolescence
However, when major repairs are likely to be required, it seems that most businesses sell their products and the responsibility for recycling gets passed on. In all of the examples above (except fashion rental which was relatively new), the businesses described selling their stock second-hand. This suggests that rental businesses are unlikely to be directly involved with recyclers, due to the thriving second hand markets in these cities. None of the businesses interviewed were involved with recycling or remanufacturing goods, which may be a lost opportunity.	[22]		X			Align changes to the obsolete state with moments of interaction
Owing to the high costs and long life- times associated with technology insertion and design refresh, these systems often fall behind the technology wave [4, 5]. This explains why many com- ponents are reaching their end of life at increased rates in many avionics and military systems [6, 7]. Therefore, one of the main problems that these systems unquestionably face during their lifetime is obsolescence [8, 9]. A component becomes obsolete when it is no longer available from stock of its own spares, procurable or produced by its manufacturer or suppliers [10, 11].	[23]	X				
defence environment is moving towards new types of agreement, such as capability- and availability-based contracts, which are enabled by product–service system (PSS) business models. (…) increased level of service provides the customer with higher value at reduced through-life cost. Therefore the framework presented in this paper enables the transition from traditional to availability contracts, including obsolescence in the contractual terms.	[23]		X			Align changes to the obsolete state with moments of interaction

Most of the research carried out so far on obsolescence has focused primarily on how to manage, mitigate and resolve it [17, 18]. For instance, some studies have been carried out on uprating electronic components, testing them beyond their designed operational characteristics (e.g. temperature), in order to replace obsolete components with an alternative [19, 20]. Significant emphasis has been placed on the need to manage obsolescence proactively, and to prepare an obsolescence management plan (OMP) to reduce the impact of obsolescence issues [21]. Many authors have indicated that collaboration among different projects and organizations, by sharing data about common obsolescence problems, is the next step required to reduce obsolescence costs further [18, 22]. Additionally,	[23]		X			
Some authors have done research on the effects that component standardization may have on the life-cycle cost of systems, concluding that it will mitigate the impact of obsolescence and hence reduce its cost [25]. There is also research on the interchangeability of components, which supports the selection of replacements for the obsolete component [21, 26].	[23]	X				Reveal or communicate obsolescence
This allowed the identification of key factors and cost drivers for obsolescence, together with the type of information available at different stages of the life cycle of the system. (…) The predicted end of life (obsolescence date) may come from an obsolescence-monitoring tool, or from the use of obsolescence-forecasting algorithms.	[23]		X			Monitor resources in use.
Automated techniques for non-destructive testing are currently being developed which will quantify service damages occurring in high-value components that will predict the remaining life of components.	[24]		X			Monitor resources in use.
An instrument (FIT, Fault Investigator Tool) has been						
developed to avoid this type of process and allow Fassi service network to rapidly and accurately diagnose the failure cause in case of crane malfunctions.	[25]		X			Monitor resources in use.
In this way, time for diagnosis is reduced and useless and expensive trial-and-error interventions of component replacement are prevented.	[25]				X	Optimise the value of obsolete resources
Mobile phone use time makes a large contribution to closing the loop efficiently	[26]		X			
Two indicators were chosen to define the closed loop system. One was Loop efficiency, which is based on the C2C indicator, which determines how efficiently the resources are utilised in the system. In this case, efficiency indicates the efficient use without hibernation of resources. (...) hibernation of phones resulted in a decreased leakage, with increased hibernation. longer hibernation of phones also decreases efficiency. Thus the model indicates that short duration of phone storage increases loop efficiency. (...) authors suggest shorter hibernation time.	[26]		X			
The analysis revealed that the accessibility of collection pathways (..) made one of the largest contributions to closing the loop efficiently (...) the collection of phones in the model was estimated by access to collection pathways, consumer motivation and awareness, incentives for consumer. The accessibility made a large contribution to the closed loop system, a higher collection rate can be achieved by incentives to consumers or by educating them to increase awareness.	[26]			X		Lure obsoletes to gateways.
Two indicators were chosen to define the closed loop system. One was Loop leakage, based on the linear flow index by EMF, determines the resource fraction leaving the product system. i.e. it indicates to what extend the loop is closed and metals are preserved in the system.	[26]				X	
According to the model, consumers buy new phones by comparing price and utility of a new phone and a second hand phone. Among cheaper phones, consumers generally prefer buying new phones over second-hand phones and this decreases the use of phones.	[26]				X	Understand the value of obsolete resources.
The provider manages the recycling process (a specialized company was established to deal with EoL recycling) and the recyclers that work as partners should provide evidence that the materials are recycled through the provision of a document certifying the components correct final destination.	[27]				X	Understand the value of obsolete resources.
The internal components that are replaced periodically (e.g. the filter) are strategically positioned allowing the easy access during the maintenance process. This allows the product life extension and slowing resource loops, corroborating with CE concerns during the design process [6]. In	[27]				X	Optimise the value of obsolete resources
FilippaK (..) On their own, over-the-counter, provides 15% discount.						
Boomerang (…) Collects on their own, over-the-counter, provides 10% discount.						
(Table 1)	[28]			X		Lure obsoletes to gateways.

Adoption of a certain type of practices, for instances take-back systems, influences just what an appropriate response, in that particular industry, entails. Thus firms can collectively choose a form of implementation that does not cost too much and allows them to continue to operate in a linear fashion	[28]				X	Establish demand for obsolete resources
clothing for second-use following repair and upgrading. Add-ons in product oriented, integrated in use- and result-oriented.	[29]			X		
when a take-back service is not fully integrated in a business model, there is a risk to remain in linear business models	[29]			X		
The demand for used and remanufactured products can be uncertain.	[29]				X	
Although challenges remain, in principle, it may be utilised, leading to potential simplification of the handset itself and reduction in energy consumption by outsourcing the in- tensive computation resources to hardware across a network. The reduction of energy consumption and greater robustness of any take-back scheme has the potential to reduce environ- mental impact. The simplification of the mobile handset and outsourcing of heavy processing could lead to an increased lifetime of the handset with further associated reduction in environmental impact. It	[30]	X				Reveal or communicate obsolescence
In addition to the lifetime, the user behaviour can lead to a strong variation of impact. The precise user distribution can never be fully understood and is one of the main sources of estimate within an LCA. Manufacturers' declarations are based upon an assumed typical user (Nokia 2013a, b, c; HTC 2013;Apple 2013a, b, 2014), but the need for brevity prevents further details being given. (...)						
The end of life disposal of mobile phones does not often follow the recycling route assumed in manufacturers' declarations, due to variations in human behaviour and is therefore a rich area for further studies. These	[30]			X		Lure obsoletes to gateways.
In contrast*, Recycling* of phones is shown not to be economically viable as a stand-alone business, the reverse logistics eating away at the profit margin: the collection of mobile phones for recycling is almost entirely subsidised by the col- lection for reuse and their being a by-product of this industry (Geyer and Blass 2010). Planning of the remanufacturing pro- cess is necessary to extract the best benefit (Franke et al. 2006). Improved mechanisms for return of mobile phones within a short period of time after their use phase will lead to improved rates of reuse and remanufacture.						
9.4	[30]				X	Understand the value of obsolete resources.
Recycling is a third option, especially if phones have been subject to a lengthy hibernation.	[30]				X	Understand the value of obsolete resources.
Most often, the disposal of a phone is presented in terms of recycling, rather than disposal through other methods such as reuse, remanufacture or land- fill. This is likely to be due to the lack of control that the manufacturer has over the disposal route and the fact that recycling offers the most quantifiable data of all of the best practice disposal methods.	[30]				X	
The moment of disposal was no exception as parting from the garments, which had to be returned as a complete package at a designated time, was connected with emotional difficulty for some users	[31]			X		Lure obsoletes to gateways.
Ease of identification, verification, access, handling, separation, securing, alignment, stacking, wear resistance [improve disassembly of products]	[31]				X	Optimise the value of obsolete resources
For example, it could be interesting to explore which product data could be collected during use in order to improve the products� different life stages.	[32]		X			
To summarize the suggestions for improvements, many of them deal with the accessibility of parts and components that need to be accessed during maintenance and remanufacturing operations. Although there are no economic calculations made, most of these suggestions seem affordable and fairly easy to perform. Many of the suggested (and implemented) design changes are fairly easy to conduct, and many of the adaptations concern disassembly and/or reassembly of product components.	[32]				X	Optimise the value of obsolete resources
Concluding this paper, product/service systems place new requirements on products in comparison to traditionally sold products. Although the PSS approach may be profitable with or without remanufacturing with existing product design they can be improved. With a more optimized product design, obstacles can be reduced and profits increased. The	[32]				X	

A lease system that shortens the lifetime increases the level of material use; a lease system that extends the lifetime decreases the level of material use. (...) Whether the system extends life or shortens life is more important than whether it was a possession or a lease system	[33]	X		
The transfer of ownership from the user to the manufacturer in a PSS context implies that lifing decisions and maintenance strategies become even more important in the early product design and development phases. in the aviation industry, for example, the focus shifts from life expectancy to availability of the equipment. e.g. manufacturer may choose a shorter life in combination with advanced monitoring and maintenance	[34]	X		Communicate and agree on moments of interaction.
The major driver toward lower TRS lifespans is the saving of fuel costs due to weight savings. There is a trade-off between weight and durability, with the balance producing the optimal lifing strategy. (…) Knowing the probability of TRS failure as a function of lifespan				
can also aid in the development of lifing strategies that include recertification of TRSs after their designed lifespan. As demonstrated by the example shown in Fig. 11, a lifing strategy involving recertification would reduce the number of new TRSs that need to be manufactured, and has the potential to reduce overall lifecycle costs.	[34]	X		Align changes to the obsolete state with moments of interaction
The manufacturer can choose alternative maintenance				
(repair and/or replace) strategies to satisfy the availability requirements, considering, e.g., a shorter life in combination with advanced monitoring and maintenance services.				
	[34]	X		Monitor resources in use.
The consequence of weight optimization is thus an increased risk of reducing LCF life. This result is not visible to traditional design analysis methods (such as local strain approach or S–N curves); more elaborate methods are required. Moreover, these procedures will require much more input regarding the manufacturing process than is usually avail- able (NDT/NDE information, geometry variations, etc.). In consequence, modern design and manufacturing concepts need to be assessed differently than traditional ones. Different design options as they pertain to business cases can be summarized as follows:				
? Design to full life including manufacturing defects. This requires the reduction of stress levels.				
? Design to inspection intervals and replace parts? This requires inexpensive manufacturing methods and design materials.				
? Design to inspection intervals and repairs? This requires the development of efficient repair methods which will reset the structure to initial conditions.				
For	[34]	X		
Whilst recognising the validity of this claim, it is argued here that, in the context of an evaluation of PSS initiatives, a consideration of changes in the device concept should also be accompanied by a broader assessment of the effect on the management of an artefact at other life cycle stages. In particular, it is important that such an assessment accounts for the impact of a PSS on the management of products at the post-consumer stage.	[35]		X	Understand the value of obsolete resources.
The Directive, based on the principles of extended producer responsibility (EPR), imposes financial responsibility on manufacturers for the take-back of vehicles at the post-consumer stage, seeks to improve the environmental performance of all actors involved in vehicle life-cycle, and encourages manufacturers to implement design changes to facilitate the easier recovery of materials from waste vehicles. Although such legislation improves sectoral environmental performance and increases recycling rates at the macro level, there is no evidence of manufacturers offering product or component take-back services as part of a PSS contract with individual users	[35]		X	Optimise the value of obsolete resources
Moreover, the development of Mass customisation ‘‘requires modular product designs for cross compatibility of components’’ [30].	[35]		X	Optimise the value of obsolete resources
The changed incentive structure in relation to the management of products at the post-consumer stage may also have a number of implications for the way in which companies approach the design of products and services. To begin with, they will benefit financially by designing products that are easier, and therefore, generally cheaper, to disassemble, refurbish or recycle after the initial use phase. In addition, manufacturers may be motivated to improve the durability of products in or- der to realise the maximum amount of revenue through use of the minimum amount of resources.	[35]		X	Optimise the value of obsolete resources
the definition of ‘hibernation’ we use here is that as				

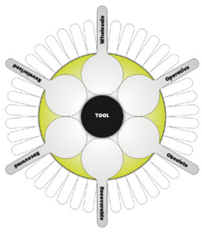
defined by the work of Murakami et al. (2010); where the 'possession span' is the combination of the 'duration of use' (during which the consumer is using the goods) and 'dead storage period' (when the goods are no longer in use). It is the dead storage period which we define as hibernation here. Others	[36]	X			
When presented with the question 'If you have kept any old mobile phones, for what reasons did you keep them?' (…) over three quarters of the participants that have kept one or more phones responded with 'I keep it as a spare' (…) A new phone must be protected, even from themselves and their own actions, whereas an older phone is more acceptable to be lost or destroyed, even if it still has a relatively high economic value and is fully functional, as it is mentally perceived as already being replaced and therefore replaceable (thus also suggesting that one can only have a single 'primary' phone at a time). (...) participants to have kept several mobile phones, beyond what one would assume to be useful (...) the difficulty for the participant was determining what to do with the redundant spare, not the secondary phone	[36]	X			
given that by the point of which the secondary phone has truly become redundant (i.e. no longer a primary or secondary phone), one can assume that its economic value would have dropped (...) kept for longer than they were ever actually used as a primary phone, pointing to a significant opportunity for shortening the period between end of use and return in order to maximise value return.	[36]			X	Understand the value of obsolete resources.
The unanswered question here is whether emotional attachment to the data and its life narrative qualities are permanently associated with the hardware creating and containing it, or whether it can be separated to allow the mobile phone to be recycled? Indicating a functional limitation towards this disembodiment at end-of-life, one participant stated that they "Hadn't transferred all of my stuff over to the new phone".	[36]		X		Lure obsoletes to gateways.
Mobile phones have a perceived residual value (economic, environmental or functional) to the user, irrespective of actual end-of-life value, which has inhibited the return of many of these hibernated devices (Hanks et al., 2008; Jang and Mincheol, 2010; Rathore et al., 2011). This perceived value is also weighed against the users knowledge (or lack thereof) with regards to how and where to return end-of-life devices (Yin et al., 2013; Yla-Mella et al., 2015; Wilhelm et al., 2011), a common issue with many small electronic products	[36]		X		Lure obsoletes to gateways.
The importance of upgrading services aiming at closing the product material cycle by taking products back, secondary utilization of usable parts in new products and recycling of materials if					
reuse is not feasible. [they borrowed from Mont] (…) The end-of-life service can be achieved as a finalizing operation while playing a key role in closing the material cycles.	[37]		X		
The traditional sensor data transfer mainly concerned the product state information assigned to attributes, e.g., temperature or state, or maintenance data, whereas now, the IoT data can even include the object properties (i.e., semantic relations) between IoT or even rule contents. Some such examples include: the battery "was detached from the car", an owner "purchased a car", and so on. All information can be exchanged using the same message envelope. It turned out that the semantic framework gives a chance to enlarge the knowledge content available for enhanced PLM [product lifecycle management]	[37]	X			Monitor resources in use.
For the purpose of responding to a holistic CL2M, which includes the notions of services, service					
lifecycle and actors, the Product-Service Lifecycle Ontology (PSLO) was modelled. (…) concerns the physical products' lifecycle, readers are referred to [2,3].	[37]	X			Monitor resources in use.

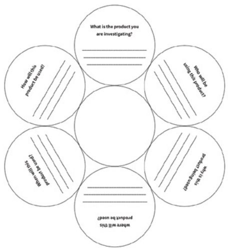
Appendix C. Study 4 Flow Mapper Development

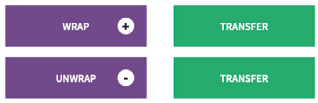
Pilot

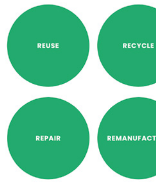
Flow Mapper 0.0

V1

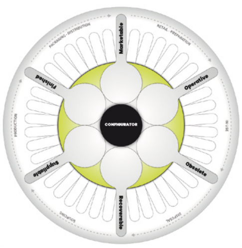


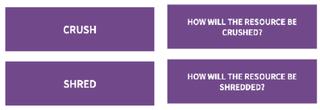


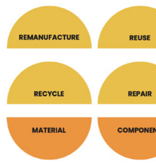




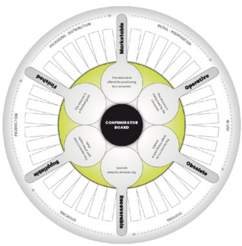
V2

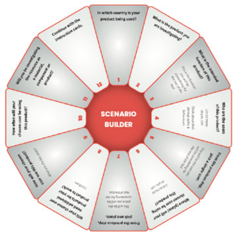


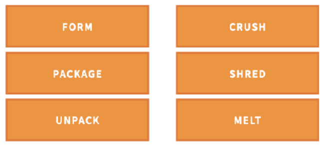




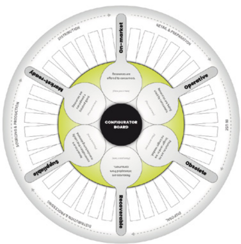
V3

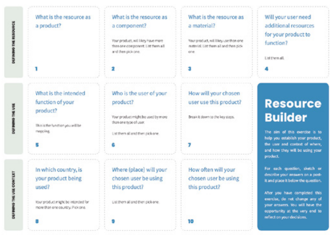


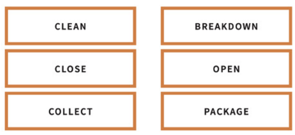




V4



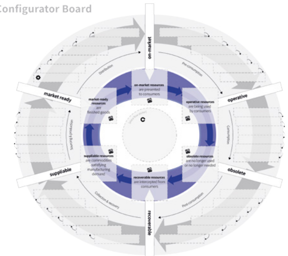




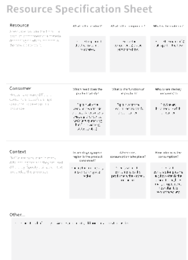
Flow Mapper 1.0

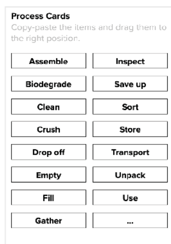
V1

Configurator Board



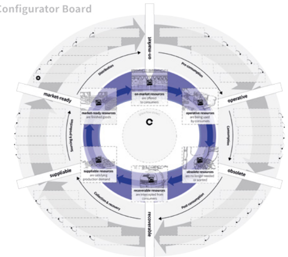
Resource Specification Sheet



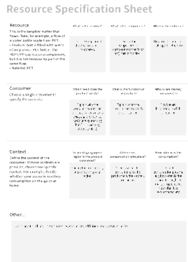


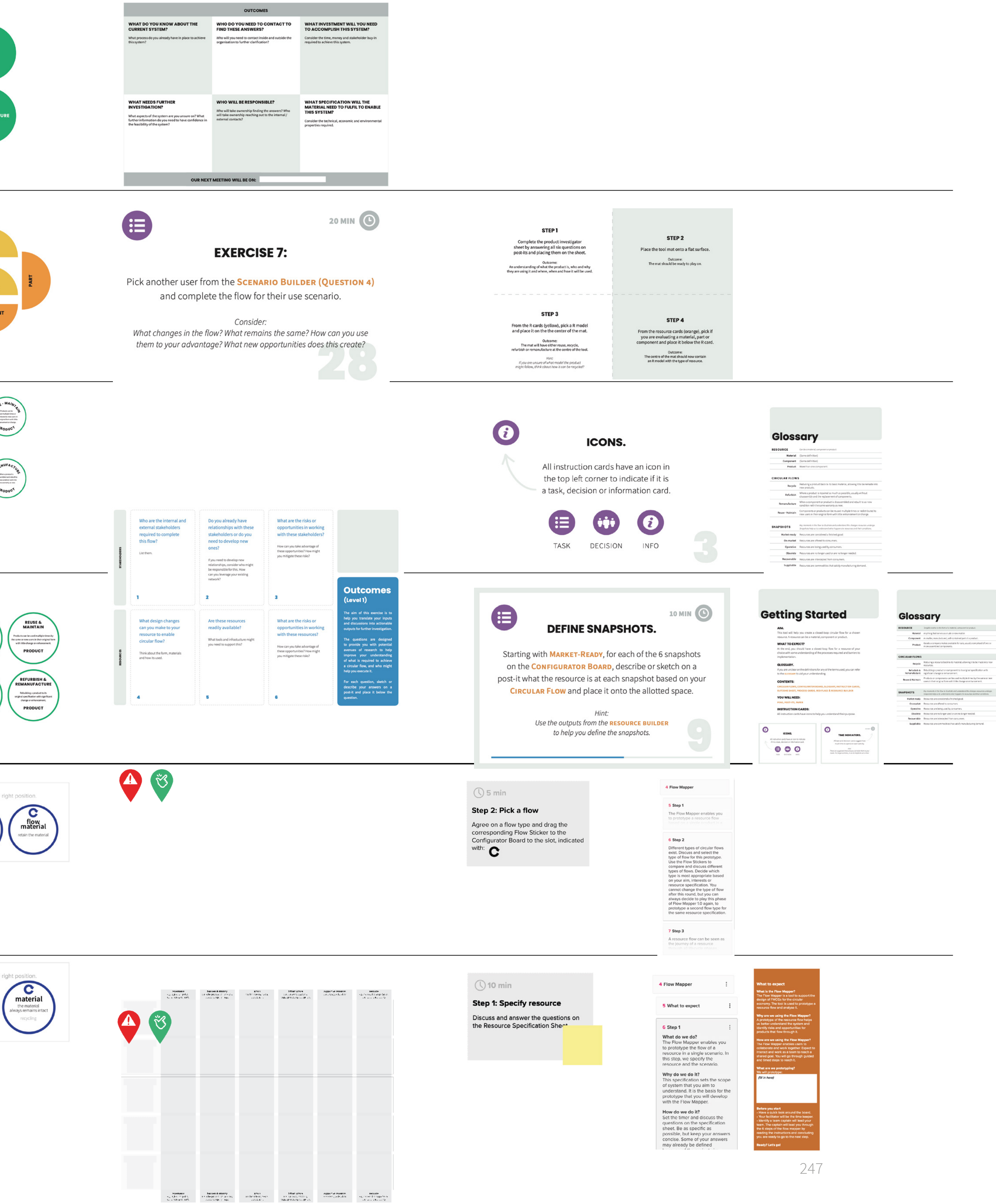
V2

Configurator Board



Resource Specification Sheet




OUTCOMES
WHAT DO YOU KNOW ABOUT THE CURRENT SYSTEM?
WHO DO YOU NEED TO CONTACT TO FIND THESE ANSWERS?
WHAT INVESTMENT WILL YOU NEED TO ACCOMPLISH THIS SYSTEM?
WHAT NEEDS FURTHER INVESTIGATION?
WHO WILL BE RESPONSIBLE?
WHAT SPECIFICATION WILL THE MATERIAL NEED TO FULFIL TO ENABLE THIS SYSTEM?
OUR NEXT MEETING WILL BE ON:
20 MIN
EXERCISE 7:
Pick another user from the SCENARIO BUILDER (QUESTION 4) and complete the flow for their use scenario.
Consider:
What changes in the flow? What remains the same? How can you use them to your advantage? What new opportunities does this create?
28
STEP 1
STEP 2
Place the tool mat onto a flat surface.
STEP 3
STEP 4
ICONS.
All instruction cards have an icon in the top left corner to indicate if it is a task, decision or information card.
TASK
DECISION
INFO
3
Glossary
Who are the internal and external stakeholders required to complete this flow?
Do you already have relationships with these stakeholders or do you need to develop new ones?
What are the risks or opportunities in working with these stakeholders?
What design changes can you make to your resource to enable circular flow?
Are these resources readily available?
What are the risks or opportunities in working with these resources?
Outcomes (Level 1)
REUSE & MAINTAIN
REFURBISH & REMANUFACTURE
PRODUCT
10 MIN
DEFINE SNAPSHOTS.
Starting with MARKET-READY, for each of the 6 snapshots on the CONFIGURATOR BOARD, describe or sketch on a post-it what the resource is at each snapshot based on your CIRCULAR FLOW and place it onto the allotted space.
Hint:
Use the outputs from the RESOURCE BUILDER to help you define the snapshots.
9
Getting Started
Glossary
flow material
5 min
Step 2: Pick a flow
Agree on a flow type and drag the corresponding Flow Sticker to the Configurator Board to the slot, indicated with: C
4 Flow Mapper
5 Step 1
6 Step 2
7 Step 3
material
10 min
Step 1: Specify resource
Discuss and answer the questions on the Resource Specification Sheet
4 Flow Mapper
5 What to expect
6 Step 1
What do we do?
Why do we do it?
How do we do it?
What to expect

Appendix D. Study 4 Example of a session report

Workshop 5 – Session report

Workshop date	24 April 2020
Flow Mapper version	1.0-V1

Setup

Case description
The Flow Mapper was used in an illustrative workshop using an existing product (aluminium soda can) in an existing recycling infrastructure (aluminium recycling).

Aim of the workshop
The aim of the workshop was to test version 1.0 with users. We aimed to recruit participants who could relate and contribute to the topic but did not expect or aim to produce a specifically useful outcome.

Participants
We recruited participants within our department i.e. Design Engineering at Imperial College London. The participants brought in different expertise on resource flow. The majority of them had knowledge on the Circular Economy. Six participants were invited and five of them agreed to participate. Two of the participants (•) had experience with the tool and the theoretical backgrounds.

	Position	Relevant expertise
P1 •	Research Associate	Circular Economy, behaviour, FMCGs
P2 •	PhD Candidate	Circular Economy, behaviour, FMCGs
P3	Senior Teaching Fellow	Circular Economy, manufacturing, sustainability
P4	PhD Candidate	Circular Economy, sustainability
P5	PhD Candidate	UX, design for emotions

Facilitation
The workshop was facilitated by AZ and MA. The facilitators aimed to observe without intervening as much as they could, but intervened in case there was confusion.

Session planning

FM – Step 1 Specify Resource	10 min	
FM – Step 2 Pick a Flow	5 min	
FM – Step 3 Take Snapshots	10 min	
FM – Step 4 Map that flow	10 min	
FM – Step 5 Analyse th prototype	5 min	

Data

Data was collected during this workshop in the following ways:

- Observations of workshop. Both AZ and MA kept notes during and after the workshop and discussed their observations afterwards.
- Feedback from participants. There was a discussion with the participants on their experiences at the end of the workshop. In addition, AZ reached out to P5 who had no circular economy knowledge and no previous engagement with the research.
- Survey. A survey was shared with the participants shortly after the workshop. All participants completed the survey.
- Audio recordings. The discussion of the participants was recorded during the session (with consent of the participants) allowing the researchers to review specific decisions made during the workshop. We had aimed to record the process of using the Flow Mapper in Mural, but unfortunately this recording failed.
- Workshop material. PDF exports from the workshop results in Mural.

Survey results

		Response 01	Response 02	Response 03	Response 04	Response 05	Average Workshop 5
Prior experience with the flow mapper							
	None	x		x	x	x	
	Engaged in one or more Flow Mapper workshops		x				
Usability							
	The Flow Mapper can be used to prototype a resource flow	5	5	5	4	5	4.8
	It was easy to prototype a resource flow using the Flow Mapper	5	4	4	4	4	4.2
	The process of prototyping with the Flow Mapper was logic	5	5	5	5	4	4.8
	The instructions for the 5 steps in the Flow Mapper were sufficient to guide us through the process	4	5	4	4	3	4.0
	The instructions for the 5 steps in the Flow Mapper were clear	4	4	5	5	2	4.0
	The time suggested to complete each of the 5 steps in the Flow Mapper was sufficient	5	3	2	1	2	2.6
Interactions							
	The Flow Mapper encouraged the team to collaborate	3	5	3	5	4	4.0
	There was sufficient knowledge in the team for a discussion	5	5	5	4	4	4.6
	Using the Flow Mapper is similar to playing a game	3	4	4	5	4	4.0
	The Flow Mapper provoked discussion	4	5	5	5	4	4.6
	I was able to contribute to the discussion	4	5	5	2	5	4.2
	My contributions were picked up by others	5	5	5	5	4	4.8
	Other made contributions to the discussion	5	5	5	5	5	5.0
	I gained insights from others	5	4	5	5	5	4.8
Usefulness							
	The project aim was clear	4	5	5	5	3	4.4
	It was clear why we needed a prototype of the resource flow	5	4	5	5	3	4.4
	The prototype developed with the Flow Mapper is useful to achieve our project aim	5	5	5	5	5	5.0
	I develop new insights on the system that we reviewed	5	4	2	5	5	4.2
	I developed new insights on the product that we reviewed	4	4	4	5	5	4.4
	The result of the workshop is actionable	4	4		5	5	4.5

Further feedback left on usability

- The step in which the mapping took place, step 4 I believe, would benefit from having slightly more time (15+ minutes?) to give the players opportunity to cover and discuss all possible steps
- The usefulness of the tool was clear and also evident at the end of the activity. It was not clear how many people can participate simultaneously in filling out the gaps and when the time was running short, the activity was done somewhat carelessly. Having said that, the time allowed at the end to review the map was beneficial.

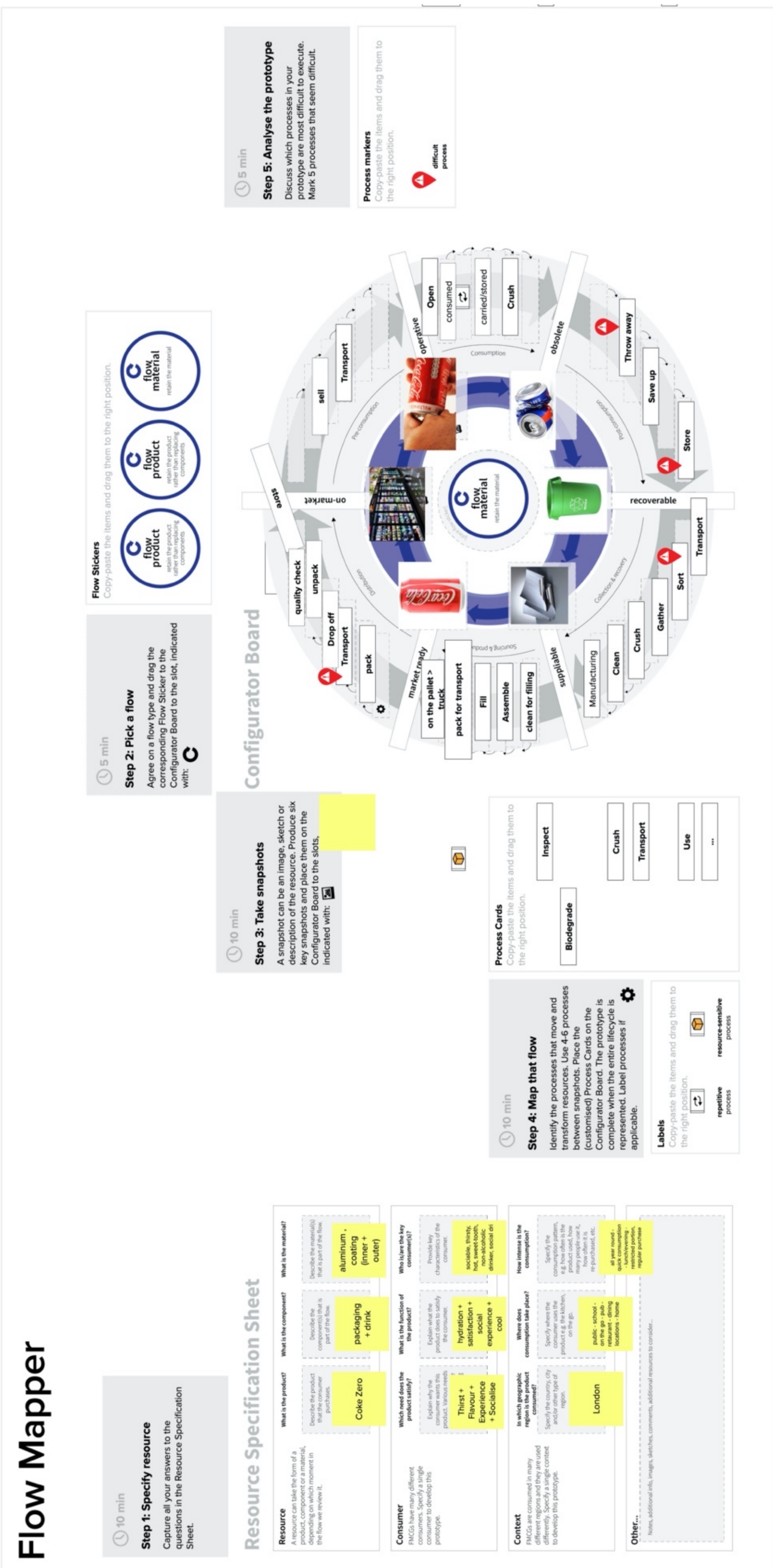
Further feedback left on interactions

- Making it a group activity made it easier to grasp how the activity is meant to play out and it was rather fun.
- *I am thinking whether the game could have a winner*
- I think a warm-up talk at the beginning to inspire the participants or have them engaged carefully can be beneficial. *Also, the activity should not re-create an examination environment when the activities are timed. The accuracy of the input provided by the participants can be compromised if they do so under pressure.*

Further feedback left on usefulness

- It was a great experience, *I would suggest to add a step to identify the leakage before step 5, were we need to identify possible leakage from the system which can help to understand the system better and identify the important points in the flow that need a special attention*
- The aim was not clear at the beginning, but it became more explicit as the activity was proceeding.

Workshop material



Detailed review

Preparation (pre activity and introduction)

Users were asked to complete activities to prepare for the session. The main goals of the pre activity were to provide users with key skills to use Mural; get consent from all users for recording the workshop; extract knowledge from the users; introduce users to the Flow Mapper.

Mural tips & tricks	The users mentioned that this was a little 'dry' but *that the Personal Profiles were a good chance to put skills into practice* The users mentioned that the tips were useful. *Few times things appeared to the background and the function 'move to front' could have been useful.* Once accidentally removed an item. The facilitator was able to recover it. Some users explore Mural beyond what was suggested. Using Mural was enjoyable and encouraged users to play with it. None of the users had used Mural prior. One user pointed out that making the personal profile was most useful practice.
Sign the consent form	No issues reported. Observed struggles using the sketch function to sign, although not mentioned by the users
Personal profile	This exercise was fun and a good way to practice Mural skills. There was *no guidance as to how much knowledge to share*, as a result some users had richer profiles than others. Some users had more relevant knowledge than others. The activity encouraged users to research the topic All users provided different viewpoints. *Only one user had used the brain marker*. *The lifecycle diagram in here did not associate with the lifecycle in the Configurator Board.* *The diagram did provoke thinking.* Ask me anything – was not used All users prepared this activity at the last minute (although most of them had already logged on to the Mural prior to this) It seemed clear to everyone what was expected The exercise helped to prepare as it forced to think about the process. Works well to get people to research the topic and gather their insights
(prior Q&A session)	Although none of the users dialled in immediately, everyone prepared their personal profile in this slot Few technical questions emerged.
Welcome	Tech check was a bit dry. People were a bit quiet at first but made sounds when asked to. The facilitator needs to set the scene here. A quick overview of the Mural seemed useful. Opportunity to solve final tech / setup questions. Summon to follow function worked
Team introduction	Who goes first with introductions? 30 seconds was very short

	Timer was useful *Questions to personal profiles did not really happen.* It is logic to start with the personal introductions (rather than the project aim) Despite being a simulation, the users had a lot to share on the topic. Seemed a lot of valuable knowledge is here, but it is not discussed into detail. *It was less useful in the 30 seconds to share knowledge* – *maybe be more specific about how to build the process so people can relay and engage with it in the workshop*. *Present self and present one interesting fact about "the system" (already indicated) in 60 seconds* *Ask users to write down questions on post its during the presentations. We will answer them at the end.*
<u>Project Aim</u>	The facilitator struggled to reach the view. It was not in the outline. *"Performance of the soda can" is not very well understood as terminology.* Open loop and closed loop recycling are not very precise terminology. Is the can both? *"How well it flows back in the system" it is not the same as flowing through the whole system as this will also include the consumption etc.* Not clear to users what the intent was of doing this activity of reviewing on the aim.
<u>Themes</u> The aim of this activity is to provoke thought and discussion on "the system" Also to gather expectations.	This was not a very smooth and intuitive activity. *Instructions are needed to tell exactly what people need to do. Make clear that they are discussing knowledge and insights on "the system". We can link the activity better to personal profiles.* Only after a while the users picked up that the intend was to provoke thought and ask questions. The facilitator had to guide/lead the discussion and engage users to share their knowledge. It worked well e.g. "What does this statement mean?" "What does it mean for you?". *Users could own this discussion. Facilitator leads the activity. It seems enough to ask questions to provoke discussion and introduce certain themes.* Users desire to know exactly what is expected from them (in any activity) The themes were not all statements which was confusing. Some themes were distracting the users, but it seemed to work provocative Quotation marks seemed to confuse but also provoke thought e.g. "This statement makes me think that…" There was not a lot of connection between personal profiles and the themes, which seemed a loss of the previous effort. The users were not very connected to the themes, which made it harder to discuss it, but also provoked thinking. *Suggested structure in the next workshop.* *1) Users position all their questions on a shared lifecycle diagram (for the system). New questions can be added.* *2) Users discuss the questions.* *3) Users to identify and define themes.* Themes are… risk areas?

	Post-its were not used in this exercise – the facilitator also did not ask. Not all statements received equal time. Users are able to bring in facts in this discussion Users are able to draw on previous experiences and knowledge User suggestions: unstructured was good because 'random' thoughts emerged. But a little structure would have been helpful to get you going.
What to expect	Asking for volunteers to read out the detailed instructions worked well. *The facilitator did not explain what the Flow Mapper is and why they are using it* The facilitator explained where the instructions to the Flow Mapper are. One of the users still asked where to find detailed instructions. *We could better explain what the Flow Mapper is and why we use it; and also explain that they can expect to collaborate as a group, going through guided steps and with a time pressure. All instructions are provided and used in x way. It would also be good to emphasise the role of the facilitators.* *To bring back the game element, we could have a (democratic) leadership (or a dictatorship). The leader(s) could read the instructions, conclude the step, and hand over to the next leader.*

The Flow Mapper

FM Step 1 – Specify resource Participants complete the resource spec sheets by discussing and answering the questions on the sheet. (timed)	Gives an intro of why to use the tool. It was not clear that the facilitator was not facilitating, the users did not know what to do. The users did not see they had to do this as a group. The user pointing this out had been involved in earlier test rounds. Users were finding out for the first time that everyone can see their answers here. *It was not obvious that they were doing this for the aluminium soda can. The instructions can be simplified and clarified. How specific is 'as specific as possible'?* How specific to go was different for the three points on the spec sheet. The resource was very detailed, the user somewhat generic, the context was however very generic. *The current process allows to have variation in the system e.g. the loose ends, differences between recycling systems. Although not realised by the participants, some choices were already made by the definition / aim of the case.* One user was able to speed up the decision-making process. One user stepped us as a natural leader. One user was not engaging in the discussion. Not clear if users got bored in this activity. The facilitator had to encourage the users. Aluminium vs component – what is it. This raised questions with some. It was more natural for users who are familiar with the research framework. *We could give more context to what the meaning of a resource is (as a Product, component, material). Perhaps we can use examples to explain it*

	better. It needs to become obvious what is the difference between material, component and resource for users in this step to help them also in step 2. Interesting debate emerged i.e. Is the consumable part of what is flowing. Consumable does influence the transport and the flow. The questions on the spec sheet influenced the discussion, was this too much? The instructions speak of universal/generic. The instructions say you cannot change it *which was confused with during the step.* The *users were conscious of the time because of the timer*. *The facilitator intervened to encourage to make the context specific*. "pick one specific context" Use intensity question worked well. The facilitator indicated the ending of the steps and asked for volunteers. On user pointed out that the post it notes are limiting the detail of the answer Additional user feedback: it is difficult to understand product, components, material (and how they differ) and to decide what they are, *because you don't know why you have to make these decisions.* E.g. "Does it matter if we choose a Coke can or a beer can?"
FM Step 2 – Pick a flow Participants choose between three types of resource flow. (timed)	Users need to digest the instructions – ask for verification of what is expected, and the facilitator has informed. Users see the Configurator Board for the first time and are checking it out. *Add to the instructions an intro to the Configurator Board and what to focus on, guiding the participants through this.* Not clear how to use the flow stickers and where to put them. They think they can use any of them. *There is a discussion on what the difference is between the flows.* The participants *struggle to understand their constraints* i.e. what is already defined in the aim / spec sheet. *There is no link made to the spec sheet,* where they have also discussed component and material. What is the point of this step if everything is already defined in the aim or spec sheet? It is not clear to users if there is a difference between product and component. They do mention some components besides the can e.g. the lip to open but focus on the can as the component. *Make the Flow Stickers more informative / intuitive. For example with icons, descriptions or examples.* "What would happen if we choose flow x, would the board configure differently?" *The participants struggle to understand circularity trade-offs* e.g. what decision is worse or better than another. *How can we make provide insight on sustainability / circularity at this point?* The facilitators have actually pre-defined the flow to 'material' due to the project brief to focus on aluminium recycling. The users did not pick this up specifically, but they did feel a materials flow made most sense. Some users are familiar with the term resource as a product, component and material. *Timer helped to make decision*. The time was spent on understanding what to do and discussion the flows. The final decision was made quickly.

	They lost the flow sticker here – the facilitator brought it back through activity history The facilitator had to close the discussion and suggest going to the next step. Additional user feedback: *it is difficult to make these decisions if you don't know what the consequences (and constraints) are of a decision or how to make trade-offs*. E.g. "intuitively, a materials flow seems more sustainable to me". (noted this is partly because of being a beginner)
FM Step 3 – Take snapshots Participants collect images to represent the resource at different moments in the resource flow. (timed) The aim of the snapshots is to outline roughly the flow of resources i.e. find the narrative.	One user asked "What is a snapshot" then said "I see now it is an image or post it" The term 'resource' was not questioned again. The term 'snapshot' was questioned. Some users were familiar with the snapshots. *Some participants have used the term snapshots before, this seems to help the others to get the hang of it. What exactly is each moment is not the most significant thing here.* Rather, they represent different moments in time and help build that narrative. Inclined to start with 'Suppliable' It was clear to most users to place the snapshots in the box. The users did not discuss in depth what the snapshots were e.g. the descriptions were not discussed in detail. Only some users raised questions pointing out uncertainties on what the differences were between the snapshots. *We could provide more explanation, icons or even an illustration to what a snapshot is.* The users did not refer back to the spec sheet. The users took turns finding images, *sketches or post were not used.* The timer was useful, but *there was time left*. Not all users were engaged in this step. Facilitator asked to reflect on the flow. *The snapshots were not very rich in context, rather they were 'clean' images of products and materials.* The context is important for the narrative and to align with previous decisions. *This could be emphasised by the instructions or the facilitator.* Users confirmed there is a narrative, but not the in-between processes. Facilitator asked for quiet users for feedback. *Facilitator had to wrap up*. Additional user feedback: it was easy to follow snapshotting because others seemed to know what to do. *It was sort of clear what the 6 snapshots were, but not their boundaries which seemed to spark the discussion.* *Images or detailed examples could be really helpful to better understand what is meant.* Acknowledge that some users need more help than others, *how can you help the beginners?*
FM Step 4 – Map that flow Participants use process cards with	The labels were confusing – two sets of labelling e.g. process cards *and labels did not seem different*. *We can simplify the labels of processes, and only include the 'repeat' label.* Starting as a group at 'market-ready'.

function to detail the flow of resources and explain what happens between snapshots. (timed)	Process cards have different meanings at different parts of the board. The users discussed these meanings e.g. 'storing' on the market or 'storing' in use. *The meaning or scope of a process is not and cannot be captured on the configurator board currently. Do we want users to define unique processes?* The discussion was difficult sometimes as the participants had no reference to indicate which part of the board they were referring to. *We could add numbers to the process slots to ease the discussion. Or the phases could be made more visible on the Configurator Board.* Facilitator emphasised that you can customise the cards. It seemed difficult to get started. *Consider doing training to give people an example.* "Do we need to fill out all the processes?" Users identified gaps and decided to focus the discussion on there. A card got lost underneath the board There is some further discussion on the snapshots. Desire for efficiency from the users. Time pressure e.g. users fear they cannot find 6 processes within the given time. *We could instead spend 2 minutes quietly to individually add as many processes as possible and spend the rest of the time going through the processes as a group to refine and re-iterate all the sections.* Users did refer back to the spec sheet, but not sure if they actually looked at it. *Mural gets confused if two people are moving the same item.* Users did not discuss in depth the difficulties of the flow. Although some discussion e.g. it has to happen all the time. *Not sure if participants found the logic that we intended them to find.* Not all participants engaged equally Facilitator has to cut off. *Can we keep this in 15 minutes or do we need more time?*
FM Step 5 – Analyse the prototype Participants identified processes to which resources performed particularly well or particularly poor.	The word 'difficult' is confusing. *Change back to pivotal, not difficult. Pivotal keeps it open if it is good or bad, but it emphasises importance.* Facilitator emphasised it is a quick exercise and said it can be up to 5 selected. The users picked 4 processes, five as a maximum seems a good number. A maximum of 5 seems ok, but how do we make sure no pivotal processes are missed? Time was not a constraint, although the users did change the selected processes later on, which seems to imply that they did not pick the most difficult processes. *A short time to identify these processes is ok, as long as we allow to change the processes later on.* One user has referred to the difficult processes as the 'pain point'. Seem to naturally focus on failures rather than successes. Users need context to base these decisions on i.e. what makes the process pivotal. Some talk about contexts e.g. volumes of materials emerged as important, energy intensity, impact of transportation etc. *This context is not very obvious or apparent. How can the participants decide on pivotal processes and what do they have to base their decisions on?*

	The marker was accidentally locked and had to be unlocked by the facilitator. It was confusing for the discussion that some processes existed twice on the board. Some participants related back to the can, but this did not emerge naturally.
<u>How, why, when</u> Reviewing the pivotal processes to understand how they work / what makes them a success or failure.	Not a lot of introduction provided as to what was going to happen now and why; not asked to relate back to the can. Not explained risks or really used it in this step Facilitator copied the most important processes and asked to discuss in depth Facilitator gave an example that was already mentioned by the users. Why the processes are difficult. *This step could be turned into a Step 6 for the Flow Mapper as it finally focuses on the system.* Elements did emerge in the discussion. E.g. "whether it happens depends also on if there is a bin". *It was difficult to capture the elements* e.g. pick them out of the discussion during the discussion. *We could have a process such as 'why are they pivotal' to structure the discussion*. Users writing their own post its helps to formulate their view/point. It is not clear how many elements (why's) do we expect. We could provide more structure e.g. "5-why" or a mind map? The discussion was unstructured and jumped between processes and between elements. The meaning of processes was unclear in the discussion sometimes, partly because they were undefined, partly because they occurred more than once in the flow. The users challenged here whether the processes were really difficult. How do we make sure we don't miss risks? *The participants could first refine the processes to make sure they are discussing the same process and have the same scope in mind. This is where they may decide to choose different ones (or make sets?)* Variants in the flow emerge now in the discussion – i.e. variants that have not been defined in the spec sheet yet nor have they been mapped in the flow. *This seems to be a good reflection on the flow and processes in the flow. It could help to understand and discuss the complexity of the system.* Facilitator were able to provoke discussion by asking questions. Two users engaged less. Not all the processes were given equal time. There was no time / opportunity to reflect back on the system. *How much time to spend on each process and this exercise? 20-30 minutes?*
Wrap up	Do we feel like the can will flow? – *Did this question make sense?* Not sure if participants understand this question or if they had the tools to answer it. *The elements are our performance indicators for the resource. We don't use them yet, but we will take them into the final discussion.* Users are now *inclined to think about solutions* e.g. how can we incentivise, using smart bins, stickers, planning, examples of Zurich recycling systems. Take away of participants e.g. engage the consumers, the human factor is a critical risk, where there is less control, costs of transport, locations of sites. The take-aways are not captured or made actionable in this version.

	Users enjoyed discussion.

Main takeaways

Format

Templates

- The lifecycle diagram used for the personal profiles was aligned with the Configurator Board, but this was not obvious to the participants.

Language

- **Terminology used to describe the use of the tool and the objective were not always clear and easy to understand**. For example, the 'performance of the resource in system'; 'how well a resource flows' or "do we feel the resource will flow"; "as specific as possible".
- Definitions of resource i.e. material, component product were not obvious to the participants (in the Spec Sheet). Some of the participants had worked with earlier versions of the tool or were familiar with the research and thus this terminology was more intuitive for them. Other participants could lift of this.
- There was some inconsistency between the definitions and use of terms such as lifecycle and 'the system', which may be confusing.

Instructions & facilitation

- Participants indicated in the survey that the instructions were sufficient, but that there was not enough time to complete all the steps.
- The participants did not immediately realise that the process was self-guided. The facilitator still took a high-level role to stop and start the different steps. It did not seem clear from the instructions when the step was completed and when to move to the next step.
- **The instructions provide a training / induction to the tool.** As the thinking process is new to most of the participants, the instructions are essential. Participants needed time to digest instructions.
- There was inconsistency in the way the instructions had been written and between the short instructions in the Mural, and the detailed ones in the outline. The structure of the instructions could be aligned throughout the tool and perhaps examples would help with understanding and interpreting the process.
- The Configurator Board could do with an introduction as it contains a lot of information. The participants seemed to get a bit lost in particular on where to place movable parts e.g. getting lost with the Flow Stickers, not sure where to place snapshots (despite icons).
- **Preparation to the Flow Mapper is important to a good result and good interactions during the model**. For example, sharing knowledge/introducing team members; align on the boundaries of the case; understand the purpose of using the Flow Mapper.

Mural

- Training in the virtual environment is essential for a smooth workshop but could be made less dry by preventing a lot of reading. Hands-on training (e.g. creating the personal profile) seemed most effective and enjoyable. Having this training 30 min prior to the workshop was effective. When the simultaneous group work started, there was some excitement on seeing each other's posts.
- Few technical issues i.e. some moveable parts were in the back and items got locked. There was a time lag in Mural sometimes.

- The sketch function was not useful, but image import was.
- The outline was very useful for instructions and navigation. The facilitator explained where to find them at the start, although later one participant still struggled to find them.

Time

- **The timed steps of the processes helped to obtain a result quickly through fast decision-making.** Nevertheless, there was not enough time for the steps, in particular step 4 could have done with more time. The time-pressure created some idea of delivering a result, bringing back the idea of playing a game or solving a puzzle.
- **The pressure of time may compromise the quality of the model.** In some of the steps there was little discussion, which may have been due to the limited time that was allocated. One of the participants commented in the survey "timing can feel like a test and can compromise the quality of the outcome".

Interaction

- A virtual and remote setting challenges natural interaction between participants. For example, it was not clear immediately to the participants that they were even working as a group. The facilitator had to get the conversation going and made an effort to engage the quieter participants.
- The facilitator asked for a volunteer for each step to read the instructions. **Sharing leadership seemed to engage the participants to the workshop.** Perhaps a single leader of the team would create a more competitive atmosphere. In a truly self-guided process this role would also have to be carried by the participants. What is expected of participants and what the role of facilitators is could be explained better at the start. A 'game' environment could be achieved by using these dynamics.
- **The participants were able to share knowledge and collaborate.** Participants indicated in the survey that they felt they made contributions and that those were picked up by others. They also indicated that the tool encouraged them to collaborate. Working as a team was described by participants as fun and easy to grasp the objectives of the workshop.
- Users said they enjoyed the workshop.

Expertise

- There was a lot of relevant expertise on CE and FMCGs. Some participants had worked with earlier versions of the tool or were familiar with the research background. This seemed to have improved their understanding in the tool. **Having few more knowledgeable / experienced participants helped the less experienced**.

Process

Getting started

- The facilitator did not explain what the Flow Mapper is and why they are using it. The aim of the workshop and how the Flow Mapper did not seem clear to everyone. Not clear if the participants understood that the Flow Mapper helps to build a model. Providing an overview of the entire Mural could help prepare what is ahead of the participants.
- **There is no official step that is part of the Flow Mapper to share expectations and the purpose of using the workshop.** Nevertheless, they are always proving to be needed. It may be useful to include them or consider guidelines to prepare for using the Flow Mapper.
- In retrospect, the case had already defined a number of the steps of the Flow Mapper. To avoid confusion, some of these steps could have been pre-filled and excluded from the

process, which would also save time. The links between case definitions and the tool were not easily made by the participants.

Team building / knowledge sharing

- As this was a group that had not worked together, the team building was useful to introduce the participants to each other. The personal profile exercise encouraged participants to dig into the topic although they did not have a clear idea of how much knowledge to gather/share. All participants had found relevant knowledge to share and presented different views.
- Presenting the personal profiles was exciting, but the presentations could be structured better to organise/extract relevant knowledge rather than general introductions / or both. May have to do with digital environment also.

Defining the case

- **The case was defined by the facilitators (in writing) but the language used to describe it was not very clear**. This could be an opportunity to explain what system, flow and resource are.
- The themes exercise was used to familiarise and align on the case, to provoke thought and trigger discussion. The pre-defined themes were not very obvious to the participants, perhaps because they did not align directly with the knowledge shared by the participants. There might be more ownership if participants defined their own themes. After the themes were contextualised a bit, they did provoke though and trigger discussion/brainstorm.
- The purpose of this activity and how it related to the rest of the workshop was not really clear to the participants. It could be aligned better to the resource spec sheet.

Resource Spec Sheet

- **The Resource Spec Sheet does not sufficiently push participants to define a single case.** The participants struggled to achieve a single use scenario, rather they tried to summarise the universal use of the resource. The consumer and context were not very specific. We need to review how much ambiguity is acceptable and manageable in the process.
- One participant mentioned that filling out the Spec Sheet was difficult as the consequences of their decisions are not clear. It seemed that the participants also not really used the boundaries provided on the case to fill out the Spec Sheet.

Picking a flow

- There was a discussion on the differences between flows. Participants have difficulties choosing which flow is the right one or best choice as **they do not understand the constraints to and consequences of their decisions**. Only participants with good CE expertise would intuitively be able to say what are the circularity trade-offs i.e. which decision is better or worse? Even for them this was not easy.

Snapshots

- Some users were already familiar with this term Snapshot, which influenced the other participants. The other participants could follow the experienced participants although some wondered what a snapshot is i.e. is it an image a sketch etc.
- There was not much discussion on the definition of each snapshot, although what the exact scope was did trigger some discussion.
- The snapshots were easily and quickly retrieved using the image search, and the participants did not discuss much whether they were the right ones. The Spec Sheet was not referred to. The participants started with 'suppliable.' **The snapshots itself did not have much context** i.e.

they rather were quite ‘clean’ product images. The participants said that the snapshots helped to find the narrative of the flow.

Mapping flow

- The participants struggled to make a start with the process mapping but eventually started with ‘market-ready’. It seems familiar snapshots are an easier start. Nevertheless, **there was not much discussion of logic or the connectedness between processes.** This may have been due to time pressure and a focus on filling the slots.
- Participants were comfortable customising the cards. They observed that the same process could occur in different moments in the flow but would have a different meaning. This triggered discussion. The labels, however, were confusing and not used.
- The participants reflected and re-discussed snapshots during this exercise, further triggering discussion. They also used the Spec Sheet to make their decisions.
- Participants suggested that they could have identified leakage of flow, prior to the mapping. Perhaps transactions could have also been identified here, to avoid these to contaminate the mapping of movement and transformation.

Pivotal processes

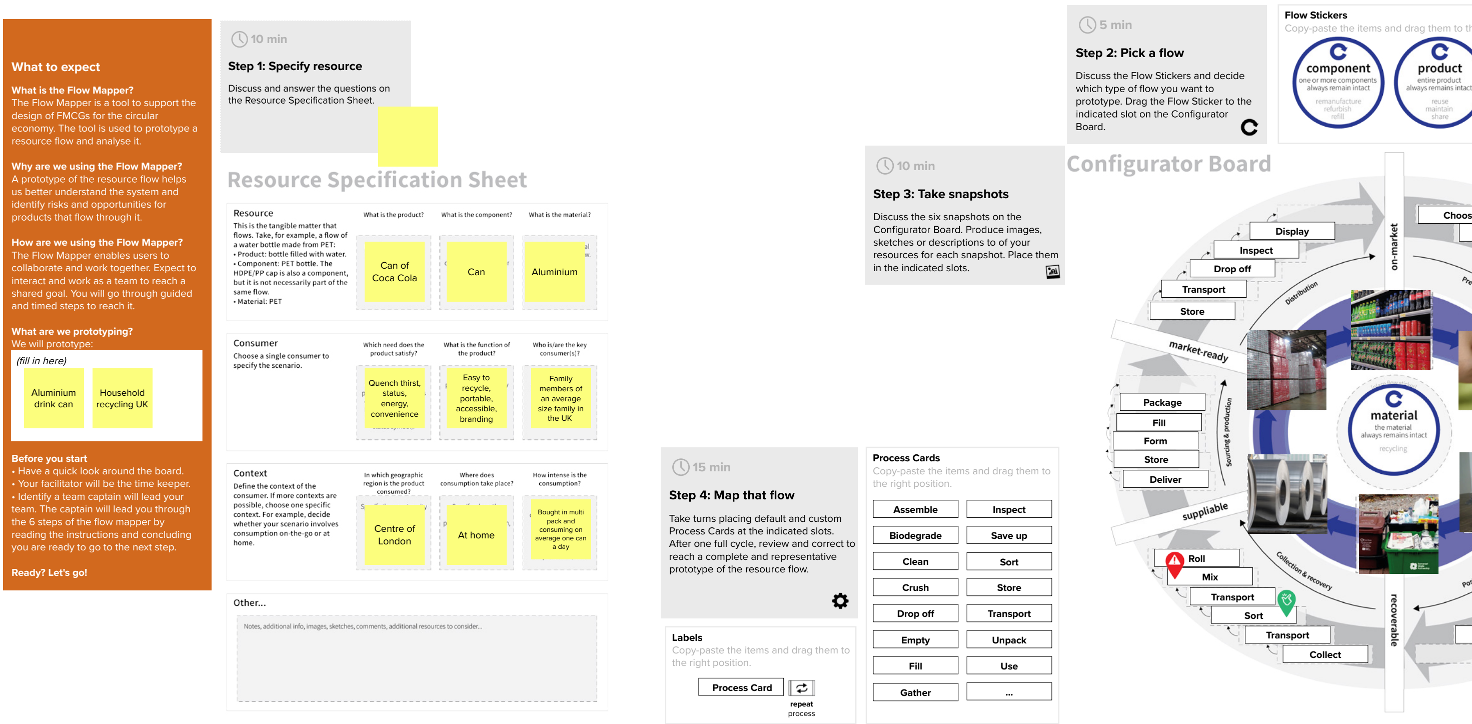
- **Participants struggled to select ‘difficult’ processes. Perhaps they do not have sufficient information to make a decision.** Participants did talk about context/elements when discussing whether the processes were difficult. It did not seem to be understood that difficult related to the resource against that function.
- The participants later changed their selection of difficult processes, which indicated that time pressure may have pushed them to make a decision.

Outcome

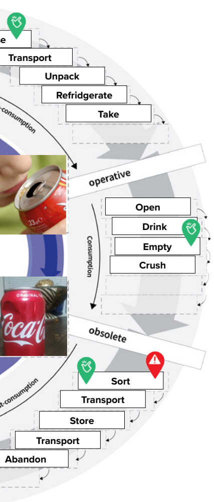
Analysis

- There was not much context provided as to the objective and process of the final step. There was a lack of structure in the discussion (jumping between processes).
- The participants are inclined to think in solutions first. The participants also challenged whether the processes were really the difficult ones. The participants suggested that there could be varieties in the flow.
- There are no takeaways discussed nor is the outcome of the analysis made actionable.
- **The participants gained new insights on the system and the resource.** In particular the less experienced participants emphasised the learning aspect. The participants indicated that the model could help then in designing packaging.
- **The tool and case could deliver different outcomes with other participants as the result is strongly dependent on the knowledge of the users.**
- Elements already emerged in the discussion, e.g. “whether it happens depends on whether there is a bin”. **Only elements related to the pivotal process were explicitly discussed**. It was difficult to capture the elements during this discussion. It is not clear how many elements can be expected.

Appendix E. Study 4 Flow Mapper Case Study



What to expect
What is the Flow Mapper?
The Flow Mapper is a tool to support the design of FMCGs for the circular economy. The tool is used to prototype a resource flow and analyse it.
Why are we using the Flow Mapper?
A prototype of the resource flow helps us better understand the system and identify risks and opportunities for products that flow through it.
How are we using the Flow Mapper?
The Flow Mapper enables users to collaborate and work together. Expect to interact and work as a team to reach a shared goal. You will go through guided and timed steps to reach it.
What are we prototyping?
We will prototype:
(fill in here)
Aluminium drink can
Household recycling UK
Before you start
• Have a quick look around the board.
• Your facilitator will be the time keeper.
• Identify a team captain will lead your team. The captain will lead you through the 6 steps of the flow mapper by reading the instructions and concluding you are ready to go to the next step.
Ready? Let's go!
10 min
Step 1: Specify resource
Discuss and answer the questions on the Resource Specification Sheet.
Resource Specification Sheet
Resource
This is the tangible matter that flows. Take, for example, a flow of a water bottle made from PET:
• Product: bottle filled with water.
• Component: PET bottle. The HDPE/PP cap is also a component, but it is not necessarily part of the same flow.
• Material: PET
What is the product?
What is the component?
What is the material?
Can of Coca Cola
Can
Aluminium
Consumer
Choose a single consumer to specify the scenario.
Which need does the product satisfy?
What is the function of the product?
Who is/are the key consumer(s)?
Quench thirst, status, energy, convenience
Easy to recycle, portable, accessible, branding
Family members of an average size family in the UK
Context
Define the context of the consumer. If more contexts are possible, choose one specific context. For example, decide whether your scenario involves consumption on-the-go or at home.
In which geographic region is the product consumed?
Where does consumption take place?
How intense is the consumption?
Centre of London
At home
Bought in multi pack and consuming on average one can a day
Other...
Notes, additional info, images, sketches, comments, additional resources to consider...
15 min
Step 4: Map that flow
Take turns placing default and custom Process Cards at the indicated slots. After one full cycle, review and correct to reach a complete and representative prototype of the resource flow.
Labels
Copy-paste the items and drag them to the right position.
Process Card
repeat process
Process Cards
Copy-paste the items and drag them to the right position.
Assemble
Inspect
Biodegrade
Save up
Clean
Sort
Crush
Store
Drop off
Transport
Empty
Unpack
Fill
Use
Gather
...
10 min
Step 3: Take snapshots
Discuss the six snapshots on the Configurator Board. Produce images, sketches or descriptions to of your resources for each snapshot. Place them in the indicated slots.
5 min
Step 2: Pick a flow
Discuss the Flow Stickers and decide which type of flow you want to prototype. Drag the Flow Sticker to the indicated slot on the Configurator Board.
Flow Stickers
component
product
Configurator Board
on-market
Display
Inspect
Drop off
Transport
Store
Distribution
market-ready
Package
Fill
Form
Store
Deliver
Sourcing & production
material
supplliable
Roll
Mix
Transport
Sort
Transport
Collect
Collection & recovery
recoverable



10 min

Step 5: Pivotal processes

Discuss in which processes your resource is most successful and in which it is likely to fail. Aim to select five such pivotal processes and mark them.

Pivotal Process Markers

Copy-paste the items and drag them to the right position.

not a great success

great success

30 min

Step 6: Risks & opportunities

Refine the meaning of the pivotal processes. Discuss what makes your resource succeed or fail in a process.

Process	Scope of process	Why is this process pivotal?	Relevant elements
Choose	Resource is chosen and purchased in the supermarket	Alternative purchases of drinks are likely to be in plastics which may be less easy to recycle	Coca Cola brand loyalty; Consumer prefers to drink from a can; Right amount for a drink; Consumers purchases the can; Visibility on supermarket shelves
Empty	Resource is no longer used by the consumer	The empty can is a clear indicator and motivator to dispose the resource shortly after it was in use	Right amount for a drink; Cue for recycling; Cans cannot be closed after they are opened
Sort	Resource is placed in the recycling bin by the consumer	Cans are known to be recyclable and have only few losses	Consumer is aware of recyclability; Recycling instructions are on the can; UK government campaigns on recycling; EU legislation mandates recycling instructions on packaging; Coke promotes recyclability; Consumer is motivated to recycle; Recycling bin is available
Sort	Resource is not placed in the recycling bin by the consumer	Not all cans are collected for recycling and therefore aluminium used for packaging can be lost	Recycling bin is in the kitchen; Consumption takes place in the living room; Kerbside recycling service provided by municipality; Information on recycling is on municipality website; A utility is used to store recyclables until collection day
Sort	Resource is automatically identified and separated	Aluminium cans are separated, baled and offered to recyclers at a higher price than other aluminium items	Eddy Current technology used to separate resources; Properties of aluminium are used for sorting; Aluminium can is easily crushed
Mix	Resource is mixed with virgin to become commercially viable	Mixing with virgin aluminium maintains the demand for virgin aluminium	Recycled aluminium is cheaper than virgin; Lack of legislation on the use of recycled aluminium; Lack information on the origins of recycled aluminium; Coke buys aluminium sheets on rolls