THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DESIGNING OUT WASTE
Exploring barriers for material recirculation

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Abstract

This doctoral thesis has investigated what hinders material recirculation in society, to later suggest possible ways to support material recirculation in the future. Since material recirculation is proposed as a way to use waste materials for new production, it was deemed relevant to investigate two separate case studies that enabled recirculation from production systems and waste management. These two case studies addressed the topics of designing with waste and sorting waste, presented in Topics 1 and 2, respectively. Additionally, a third topic was developed as a way of providing a broader context for the case studies. Given that it has been argued that waste is a design flaw and that there are many design strategies aimed at waste minimization, Topic 3 investigated specifically how design currently relates to material recirculation.

Designing with waste proved to be a difficult endeavour, mainly due to the lack of a clear design brief and reliable information about secondary materials. Topic 1 resulted in a process diagram for how to design with waste, based on generic design process models. This process diagram is complemented with two earlier steps needed to design with waste: 1) Collect and sort the discarded material in an adequate manner, 2) Investigate and test secondary material's properties.

Waste sorting is therefore a precondition to designing with waste. Improving the way waste materials are sorted and collected is a challenging task that has been broadly researched from several disciplines. It is a topic that couples behavioural and societal aspects that are difficult to explain, to complex technical solutions, resulting in a challenging complex socio-technical system. Topic 2 concludes that it is crucial to understand what service users deem as convenient infrastructure when designing waste collection systems. To better understand service users, user requirement elicitation methods that are commonly used in the design discipline might be useful to develop and improve waste sorting systems.

Topic 3 concludes that design currently does not sufficiently support material recirculation. Although designers see and describe the effect their profession has on resource use and waste generation, in practice only a third of the consulted designers had actively used EoL considerations in their latest project. In order to aid designers in recirculating materials, Topic 3 presents two models: 1) A resource recovery route model, based on recirculation to different life-cycle stages, and 2) A model of ways in which designers can address resource conservation.

The factors hindering material recirculation found in the three topics could be grouped into six main barriers. Material recirculation is complicated, it is a task with many steps, a variety of materials and several actors are involved. Since so many people are involved, acting by themselves, there is a lack of control over how materials flow through society. There is also a lack of communication among the different actors. As a result, the actions and responsibilities of the different actors are unclear. To know how to best use the discards, reliable information about the material properties is needed, but such information is often unavailable. Recirculating materials requires more time and effort than simply discarding them. These barriers seem to point to a lack of guidance and common vision around what material recirculation should mean for the different actors in society. To generate a common vision among the main stakeholders (i.e. producers, users and waste managers) policy regulations and collaborations that foster better understanding among the actors are suggested as possible ways forward.

Keywords: resource recovery, designing with waste, waste management, waste sorting

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Appended articles and author contribution

Article A

Ordóñez, Isabel and Rexfelt, Oskar. In press. Designing from the dumpster : experiences of developing products using discards. International Journal of Sustainable Design, pp.1–18.

Ordóñez planned the study, performed the interviews, analysed the data and wrote the article together with Rexfelt.

Article B

Ordóñez, Isabel, Khan, Amaltas, Tandon, Puneet and Rexfelt, Oskar. 2016. Designing with waste: Comparison of two practice-based education cases. In 18th International Conference on Engineering and Product Design Education. pp. 1–7.

Ordóñez and Khan planned the comparative analysis. Ordóñez and Rexfelt wrote the parts regarding the Swedish case study while Khan and Tandon wrote about the Indian study.

Article C

Rousta, Kamran, Ordóñez, Isabel, Bolton, Kim and Dahlén, Lisa. Submitted. Support for the Design of Waste Sorting Systems: A mini-review. Waste Management & Research.

Ordóñez conceived, designed and performed the literature review together with Rousta. Dahlén and Bolton reviewed the manuscript drafts providing constructive critical comments.

Article D

Ordóñez, Isabel, Harder, Robin, Nikitas, Alexandros and Rahe, Ulrike. 2015. Waste sorting in apartments: Integrating the perspective of the user. Journal of Cleaner Production, 106 (433), pp.669–679.

Ordóñez planned and implemented the study with support from Harder. The article was mainly written by Ordóñez, with the help of Harder and Nikitas and feedback from Rahe.

Article E

Ordónez, Isabel and Rahe, Ulrike. 2013. Collaboration between design and waste management : Can it help close the material loop ? Resources, Conservation and Recycling, 72, pp.108–117.

Ordóñez planned the study, performed the interviews, analysed the data and wrote the article with feedback from Rahe.

Article F

Singh, Jagdeep and Ordóñez, Isabel. 2015. Resource Recovery from Post-Consumer Waste: Important Lessons for the Upcoming Circular Economy. Journal of Cleaner Production, 134, Part A, pp. 342–353.

Ordóñez planned and executed the interviews and practical example categorisation, while Singh contributed the review of recovery routes. Both authors planned and wrote the article together.

Article G

Ordóñez, Isabel and Rexfelt, Oskar. Submitted. Product End-of-Life : Are we designing away waste? International Journal of Sustainable Design.

Ordóñez planned the survey, analysed the data and wrote the article with feedback from Rexfelt.

Other publications

Ordóñez, I. & Rahe, U., 2012. How Design relates to Waste : A Categorization of Concrete Examples. In *17th International Conference Sustainable Innovation 2012, 29 – 30 October, Alanus University, Bonn*.

Ordóñez, I., Rexfelt, O. & Rahe, U., 2012. From Industrial Waste to Product Design. In T. Jachna, Y. Y. Lam, & S. Tzveetanova Yung, eds. *Incorporating Disciplinary Dynamics Into Design Education, 4-5 December 2012*. Hong Kong: DesignEd Asia Conference Secretariat, pp. 65–77.

Ordóñez, I., Harder, R. & Rahe, U., 2013. Sorting waste in apartment buildings : facts and possibilities. *Proceedings of the ERSCP-EMSU 2013 conference, 16th Conference of the European Roundtable on Sustainable Consumption and Production (ERSCP) & 7th Conference of the Environmental Management for Sustainable Universities (EMSU), 4–7 June 2013, Istanbul.*

Rexfelt, O., Kääpä, J., Li, L. and Ordóñez, I., 2013. Take Waste and Make: Guidelines for workshops to find new applications for industrial waste material. In *IASDR Conference 2013, Consilience and Innovation in Design, 24-30 August 2013, Tokyo.* Tokyo, pp. 4151–4162.

Ordóñez, I., Rexfelt, O. & Rahe, U., 2014. Waste as a starting point: educating industrial design engineering students to be active agents in closing material loops. In *International Conference on Engineering and Product Design Education, 4 & 5 September 2014, University of Twente, the Netherlands.* pp. 1–6.

Table of Contents

1 Introduction

This chapter introduces the problem addressed in this thesis, providing a short background intended to help the reader understand how the problem has been framed and addressed during the doctoral studies.

1.1 The challenge of closing material loops in society

Global material resource use is still mostly linear, i.e. resources are taken from nature to use for the production of goods that are later transformed into waste, with 44% of the extracted resources being used for energy supply while the rest is destined for construction and manufacturing (Haas et al. 2015). For the past 40 years, global resource consumption has been above our planet's capacity to provide these resources (WWF 2014). Population growth and increasing consumption trends are the main drivers behind the demand for resources, and are expected to continue to rise (Matthews & Hammond 1999; United Nations 2014; World Bank 2016). Once material resources are used to manufacture goods, the goods are then used or consumed by the population. After fulfilling a use period most of these goods are discarded as waste. Inadequately handled waste generation is a risk to human health and pollutes the environment, causing biodiversity loss and reducing even further the production capacities our ecosystems have (Basel Convention 2012). Higher incomes and urbanization rates imply more solid waste generation world wide, which is expected to double by 2025 (Hoornweg & Bhada-Tata 2012). To use current solid waste as a source of material resources for future production has been proposed as an alternative, more sustainable way of using material resources that would keep material resources in loops in society (European Commission 2015; Foundation 2012; McDonough & Braungart 2002; Haggar 2010; Patala et al. 2014; Lindhqvist 2000). This may be achieved in several ways, e.g. by recycling, reusing or composting. This thesis uses the concept of material recirculation as an umbrella term for ways of bringing material from one use period to another, emphasising that the material is recirculated in society, regardless of how this is achieved.

Several examples of material recirculation exist: Ricoh offers and sells reused and re-manufactured multi-functional printers (Ricoh Group 2012), Caterpillar has developed rebuild programs that update customers products extending their use period (Caterpillar 2015), Terracycle is a company that collects and up-cycles hard to recycle waste internationally (TerraCycle 2016), and industrial waste has been used as input material in other industrial processes through industrial symbiotic systems (Jacobsen 2006). Despite this, much work still needs to be done to successfully transform our linear production to closed loop systems, where waste generation is reduced to a bare minimum. This thesis intends to contribute to this transformation by investigating what currently hinders material recirculation and to suggest how recirculation could be facilitated. A good starting point to identify barriers for recirculation is to learn what materials are discarded, how they are disposed of, why they are not recirculated and how they are handled today.

1.2 Waste, waste systems and waste management approaches

The idiom “One man's trash is another man's treasure”, highlights how subjective the definition of waste may be. The phrase “Waste is what is left behind when imagination fails” (Ekberg 2009) illustrates how it is desirable to constantly reconsider waste as resources if given another context or application. Waste is a human concept that means that a given material has no use or value, or that its potential use or value has not been defined yet. Therefore, it can be said that waste is a design flaw. The processes and systems that generate waste do so unintentionally, as the result of poor design (Anastas & Zimmerman 2006).

For practical reasons this research will use a concrete definition. Waste in this thesis will be considered as “Substances or objects which are disposed of, are intended to be disposed of, or are required to be disposed of by the provisions of national laws” (UNEP 1989). This definition of waste will also be referred to as “discards” or “refuse”. Ecosystem waste refers to dispersed resources that accumulate in land, air or water ecosystems and cannot be reintegrated to the environment's biochemical cycles (Greyson 2009). Also referred to as pollution, ecosystem waste is the undesirable side effect to nature from human activity and has been suggested as a key indicator for sustainability (Azar et al. 1996; Gaines 2002).

Waste is usually categorised according to the following four criteria: Origin, Composition, Toxicity or Management. Using origin as a criterion to categorize waste, one would describe waste depending on where it is generated, e.g. mining, agricultural, medical or household waste. Composition refers to what the waste is made of, e.g. lead, metal, paper or textile. Toxicity categorizes waste according to how dangerous it is for human health or the environment, e.g. radioactive, toxic, infectious or corrosive. Finally, management describes waste according to how it is treated, e.g. collected, sorted, recycled, landfilled or incinerated (Baker et al. 2004). These waste categorizations are useful to identify the different aspects that help better describe waste material. Since waste can be classified in so many ways, it is common in waste management to refer to different waste fractions: i.e. a part of the total waste that shares some specific characteristic. This is commonly used to distinguish material that has different management solutions but shares the same origin, e.g. the biodegradable or recyclable fraction of municipal solid waste.

1.2.1 Waste systems

Waste management (WM) is normally regarded as a system; it is composed of several elements that relate to each other in order to fulfil a goal, which in the case of WM is to handle discarded material. System theory is commonly used in the waste branch because it allows a combination of interrelated elements to be addressed as a whole that transforms input to outputs and that presents emerging characteristics that are not found in the elements that make up the system (Skyttner 2001). This perspective is used to describe and design the act of managing waste, since it can simplify the complexity of WM practice by providing relevant concepts and tools (Chang & Pires 2015).

WM systems are socio-technical systems. This means that people interact with technology within an organization to achieve the system's purpose of handling waste. Socio-technical theory understands that the interactions between people and the technology they use are deep and can only be partly explained, often having unpredictable effects on each other. This implies that changing one aspect alone will result in unexpected and often undesired consequences for the system as a whole (Cooper & Foster 1971).

WM systems are also complex systems. Complex systems are defined as systems that are open, i.e. they interact with their environment, constantly evolve over time and contain several elements and numerous interactions between these elements (Rotmans & Loorbach 2009). Complex systems have feedback-loops and non-linear interactions between their elements, where a small stimulus may cause a large effect or a large stimulus may generate no effect at all (ibid.). Complex systems are also nested and have several organizational levels (ibid.).

Having a nested system means that WM systems can also be considered a “system of systems”. This means that WM integrates many independent, self-contained, systems to satisfy common goals in a multi-functional larger system (Chang & Pires 2015, p222). This means that one could consider a particular portion of the WM system as a sub-system, which in combination with other portions make up the whole of the WM system. For example, the elements that handle specific fractions can be sub-systems, e.g. the system for handling hospital waste, or the different functions needed in

WM can be considered to be sub-systems in their own right, e.g. the waste collection system. Also, one can effectively handle waste in a single household. Waste would be generated when cleaning or cooking, then separated to be handled later. Depending on what sort of waste it is it might be suitable to be composted in the garden, burned in the chimney or put aside to be given away to others or used later for other purposes. This could work independently or be connected to several other households, or even other actors, who would enable other ways of handling waste. This means that the entire WM system will depend on the actions of individual households, which are later aggregated with other households, to provide a common way of handling waste.

WM systems engage several stakeholders in performing the different functions needed to handle waste. A sustainable municipal solid WM system is proposed to have six main functional activities: (1) Waste generation, (2) Waste handling and separation at source, (3) Collection, (4) Transfer and transport, (5) Processing and transformation of waste in material recovery facilities and (6) Disposal (Tchobanoglous et al. 1993). Given that these functional activities deliver discarded materials from generation to final disposal, they can also be referred to as stages of the material flow within waste management. These stages are executed by different system elements that exchange discards, but also information, energy and remuneration for the different services provided (all stages or functions are illustrated in Figure 1, where the names for each stage have been simplified).

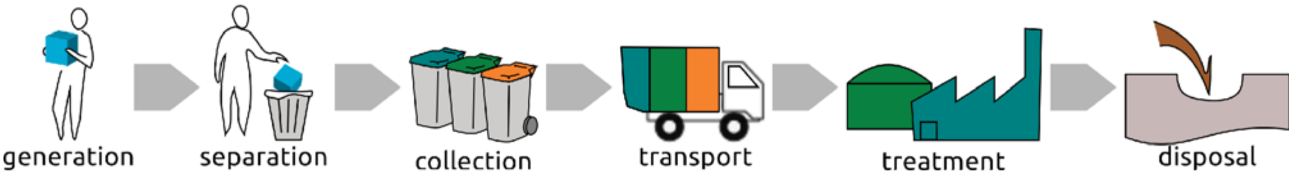

Figure 1: Functions of a WM system.

Waste **generation** corresponds to when something is considered waste and therefore discarded by the person who has used it. Characteristics about waste generation relevant to know to be able to adequately handle it include the volumes produced and the composition. This can be partially explained by where the waste is produced (e.g. restaurant waste has a different composition to office waste) but may also be specified as more detailed information from weight based billing systems or waste characterization studies.

Separation corresponds to the action of segregating different types of discards from each other. This can be done by the user (i.e. before or when discarding waste), or later in the WM system. The purpose of separating waste is to be able to treat the sorted fractions in different ways. What is separated by the user depends on what fractions are collected by the waste system or other systems that collect discards (e.g. pawn systems for PET bottles or aluminium cans). This is why separation and collection are often treated as a common stage.

Collection is when the material is passed from the user to the WM system, so that the user who generated the waste no longer owns the material. This is commonly done by leaving the materials in bins that are emptied on a regular basis.

Transport corresponds to the action of moving the discards from where they are generated to where they will be treated. **Treatment** is the core of what WM does. Here discards are processed in order to recover some of their intrinsic value (e.g. biodegradable waste is used to make biogas and fertilizers, discarded paper is used for recycled paper) or so that can be discarded in a non harmful way (e.g. controlled waste incineration to reduce volume and avoid uncontrolled off-gassing). To increase the value of waste, common procedures are applied to separate valuable materials, clean them and later compress the sorted fractions for transport to further processing facilities.

The last stage of WM is **disposal**. This stage corresponds to when the waste system deposits the final discards somewhere in the biosphere. It can be done in an uncontrolled manner (i.e. open dumping) or through sanitary landfills. Controlled landfills could be considered still to be within the WM system, since efforts are made to minimize gas emissions or leakage of fluids (a.k.a. leachate) from landfills. However, when landfills are decommissioned, i.e. they are closed down and no more waste can be placed there, they are no longer part of the WM system, just part of the environment.

Given that different functions of the WM system are carried out by different actors, it is each of these actors that define to some extent how that function of the system will be fulfilled. Local authorities and governmental regulations issue guidelines on how each function may be done. From a systems engineering perspective, WM actors and local authorities represent the two starting points possible in designing WM systems; bottom up or top-down, respectively. A bottom-up design would start by specifying the requirements and capacities of the different actors and would establish how they should interact with each other, to later have the total system behaviour emerge. A top-down approach would start by specifying the overall aim of the system and then later define each system component to contribute to that aim by following centralized management (Chang & Pires 2015). Usually local and national authorities provide a top-down planning perspective, but in practice most WM systems are a hybrid combination of both the top-down and bottom up approaches.

Although it is broadly accepted that WM can be described in terms of a socio-technical system, local authorities and even researchers often have a technology-centred approach to WM, commonly using system analysis tools and models to help optimize their operations (Juul et al. 2013). These models and tools focus on optimizing system performance according to specific criteria (e.g. minimizing costs or environmental impact) by changing some of the controllable system variables such as collection frequency, distance to treatment facility or type of waste treatment. However, less controllable aspects affecting the waste system, for example waste composition or sorting participation, are less commonly addressed. Thus, even though waste is generated and treated by people, a technology-centred approach to WM only addresses the “hardware” of the system and therefore normally fails to fully address the challenges of WM (Scheinberg et al. 2001).

The Integrated Sustainable Waste Management (ISWM) framework was developed to counterbalance this technology-centred view. ISWM describes waste management as a complex socio-technical system, but highlights that it is interconnected with the context in which it is located. It consists of three dimensions; waste system elements, stakeholders and relevant aspects (Figure 2). The waste system elements correspond to the functions normally optimized by the technology-centred approach to WM, i.e. collection, transfer, disposal and treatment, but expands them to include also waste minimization elements, i.e. reduction, reuse, recycling and recovery (Scheinberg et al. 2001). The stakeholders are all the actors that execute the functions defined by the waste system elements. They have an interest in, and interact with, the WM system. Stakeholders and waste system elements constitute the socio-technical system of the ISWM framework. The context in which the socio-technical system operates is described by Scheinberg using different aspects. The aspects in ISWM are considered as different lenses for assessing the WM system. There are six defined aspects (Figure 2) that range from environmental impact and financing schemes (traditionally included in WM work), to socio-cultural and institutional elements that affect WM, which are most commonly neglected (Scheinberg et al. 2001).

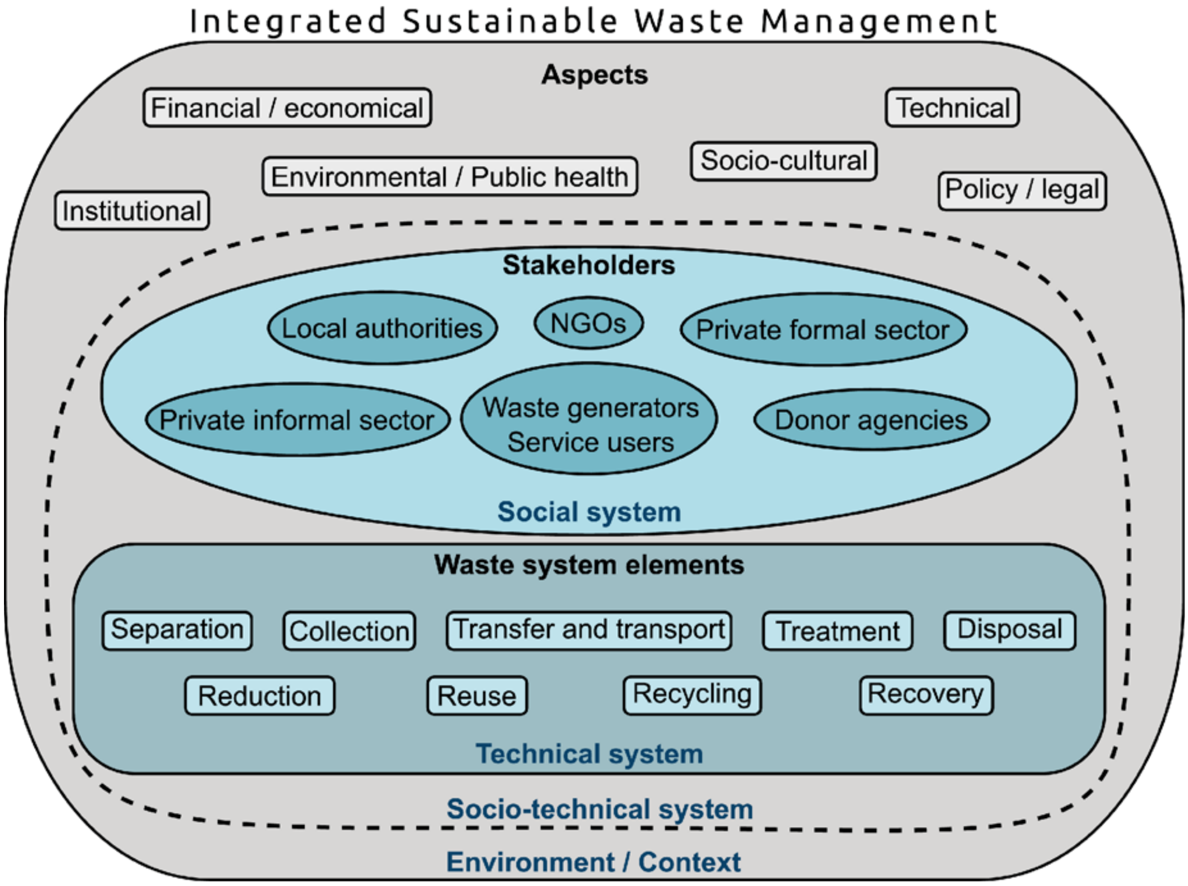

Figure 2: Components of the ISWM framework. Adapted by the author from (UN Habitat 2010).

When WM is mentioned in this thesis it refers to this complex, nested, socio-technical system, that has been briefly described in this section. Such systems vary depending on location and their performance is affected by the actions of several stakeholders. Although the research done for this doctoral thesis has not actively used complex system theory tools or methodologies, it has been the underlying model used for understanding and describing the world.

1.2.2 Waste management approaches

Waste management systems were not always this complex. This section provides an overview of the different waste management approaches society has had over the years (as shown in Figure 3), obtained from several sources that explain a historic development of WM (UN Habitat 2010; Baker et al. 2004; Weinberg et al. 2000; Melosi 2004; Bournay et al. 2006). Although human society has always discarded materials, the need to systematically handle municipal solid waste appeared with urbanization (Ludwig et al. 2003; Melosi 2004). Before large cities, waste was managed with a "**dilute and disperse**" approach, where the residual material was expected to be absorbed by the environment (Baker et al., 2004). This was even the practice in large cities of ancient civilizations, like Troy and Rome, where discards were thrown out into the streets with no further treatment. In contrast, excavations of ancient Babylon, Greece and Mesopotamia show evidence of well-constructed sewers and drainage systems intended to facilitate the collection of waste waters, a practice that was to become more widespread later on (Melosi 2004). From these ancient civilizations up to the industrial revolution, material resources were scarce. Therefore, household goods were repaired and reused, generating little to no waste (Strasser 2000; Weinberg et al. 2000).

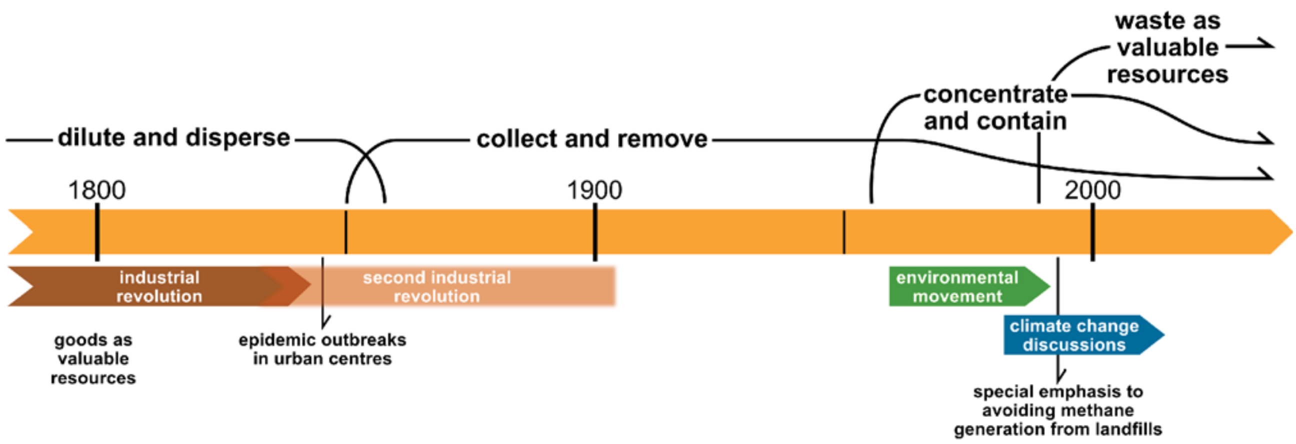

Figure 3: Historical overview of WM approaches.

Later, cities started congregating people to smaller areas. Epidemic outbreaks in urban centres during the mid-19th century shifted the WM approach to "**collect and remove**" in order to protect the population from unhygienic living conditions (Melosi 2004; Weinberg et al. 2000). Consequently waste started to be collected from urban centres to be discarded elsewhere with no sort of treatment. Most low and medium income countries still rely to some extent on this WM approach (e.g. Cambodia, Latvia, Mexico, Morocco, Surinam, Turkey) (Hoornweg & Bhada-Tata 2012).

The environmental movement of the 1960s and 70s promoted the importance of disposing of waste in a way that would minimize pollution, bringing forward the "**concentrate and contain**" approach. This meant an increased focus on minimizing gas and water leakages from landfills, as well as gas emissions from the incineration of waste (UN Habitat 2010; Melosi 2004).

Concerns about global warming shifted WM attention to the avoidance of methane generation from biodegradable waste (referred to in this thesis as bio-waste) (UNEP & ISWA 2015). Methane is a powerful greenhouse gas, which is naturally generated when bio-waste, such as food waste or garden clippings, decompose in the absence of air. These conditions are normally present when bio-waste is disposed in landfills, so it has become more common, since the early 1990s, to avoid discarding untreated bio-waste (UN Habitat 2010) or to collect the methane gas generated at controlled landfills.

The most recent WM approach is linked to a growing perception of material scarcity. Global demand on resources is increasing due to population and consumption growth, while the capacity of the planet to deliver the needed resources is decreasing (Baker et al. 2004; Holmberg 1998). The risk of resource depletion has changed the WM approach once again to consider "**waste as valuable resources**", rather than just undesirable discards. This means that strategies such as Reducing, Reusing and Recycling waste (a.k.a. the three Rs) are now more commonly used in WM efforts. Figure 4 shows what WM functions are present in the different WM approaches.

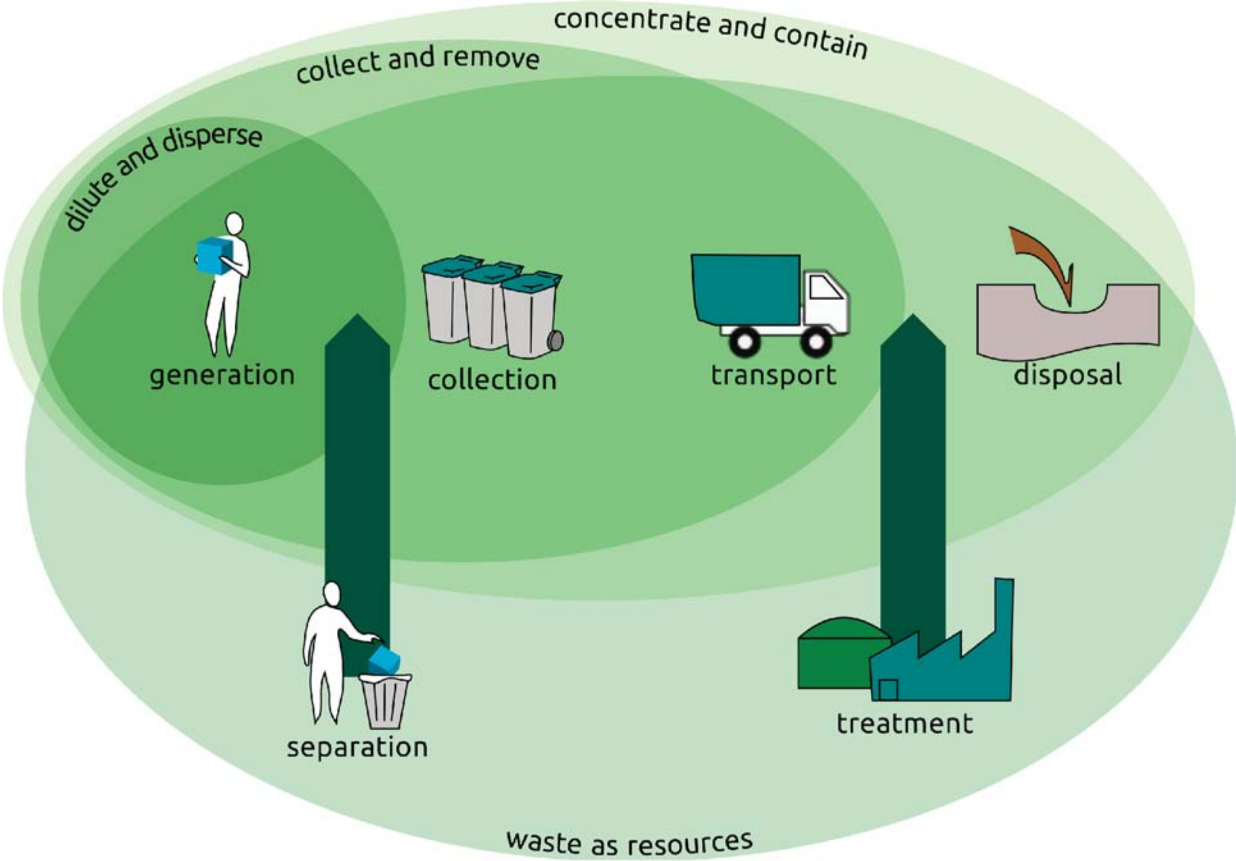

Figure 4: Waste management functions present in the different historical WM approaches.

Several authors argue that it is necessary to go beyond WM, proposing a zero waste approach (Haggar 2010; Ludwig et al. 2003; Curran & Williams 2012). Zero waste is defined as a holistic approach that aims to eliminate waste, rather than to manage it. Zero waste proposers intend to eliminate waste by conserving and recovering material resources as well as reducing the volume and toxicity of waste, acting at the waste generating source (Williams & Curran 2010). Zero waste, as well as Cradle to Cradle or Circular Economy suggest adopting completely closed-loop resource systems by changing fundamental manufacturing strategies (McDonough & Braungart 2002; Foundation 2012). These production-centred material recirculation approaches are presented in more detail in the next section.

1.3 Production-centred material recirculation efforts

Material recycling is not new. It has been a common strategy to tackle resource scarcity in human societies for centuries (Karageorghis & Kassianidou 1999; Bradley 1988). Both World Wars marked a rise in the collection of discards due to patriotic attempts to support the war efforts by collecting useful but scarce resources (Cooper 2008; Witkowski 2003). However, recycling materials to reduce the environmental impact of manufacturing, consumption or waste generation appeared with the environmental movement in the 1960s (Ackerman 2013). Despite the wide-spread recognition that material recycling has to contribute in order to tackle resource scarcity, the largest environmental gains from recycling are the reduction of energy and transport needed in the production of goods from secondary material in comparison to virgin material (Grosse 2010). Secondary materials are discarded materials that have been identified for their potential for recirculation (European Commission 2016).

1.3.1 Production systems

The production of goods can be described also as a complex socio-technical system which, like waste systems, exchanges materials, information, energy and remuneration between its functional elements or components. Production starts with resource extraction, which takes resources to makes raw materials, consuming energy and generating waste. Manufacturing takes the raw materials and makes finished goods to be delivered to users, also using energy and generating waste. Production normally consists of several more stages, integrating numerous actors to go from raw materials to a final product. Commonly referred to as supply chain or value chain, the interaction between the different suppliers within manufacturing is beyond the scope of the present research. For the purposes of this thesis it is sufficient to describe the production system as consisting of two main stages: resource extraction and manufacturing (as shown in Figure 5). The terms production and manufacturing are used practically interchangeably, and when referring to industries in this thesis it may refer to manufacturing or extracting industries, always within the production system.

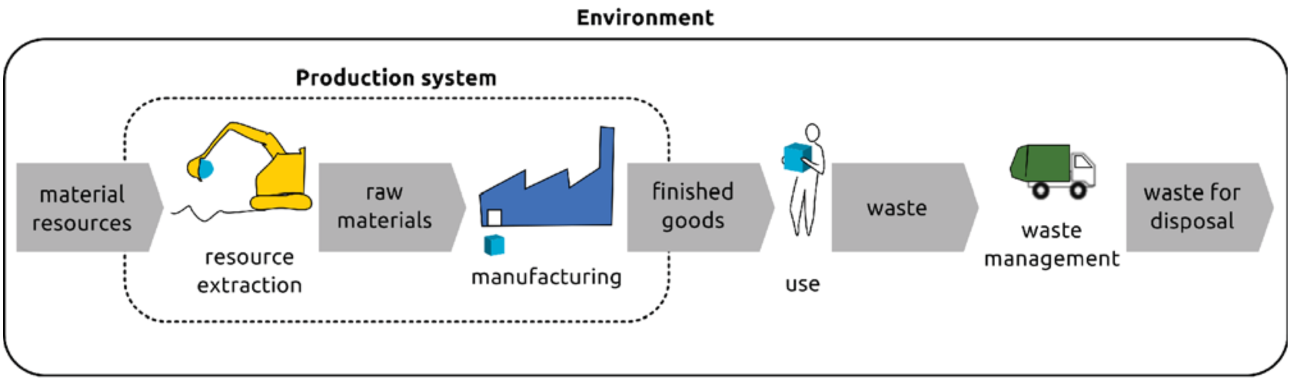

Figure 5: Production system and how it fits in a linear material flow though society.

The production system plays an important role in making materials flow through society. Zero waste proponents describe material resource flow through society as a closed system, where we do not consume materials, we only use them to later return them in a different state to the environment (Ludwig et al. 2003). The flow of the material stream comes from our environment, goes through the production systems, and is used and later discarded into the WM system (Figure 5). WM handles the end of the material stream, returning materials to the environment, in one way or another. Figure 5 only shows the material flow between the different elements, but each of the elements require energy to work and most often generate waste. The large amount of waste and energy needed for resource extraction is avoided if manufacturing is done with recirculated resources from the waste system.

1.3.2 Production systems that recirculate materials in society

Industrial ecology appeared in the 1990s as an emerging field that aimed to minimize the environmental impact of production by optimizing the consumption of materials and energy in "industrial ecosystems", while at the same time minimizing waste generation (Garner & Keoleian 1995). Industrial ecosystems are suggested as a group of industries that together could imitate natural ecosystems by making use of all the materials flowing in the different industrial processes. The excess materials or energy from one industry could for instance serve as raw material for another process, hereby avoiding waste generation completely (Frosch & Gallopoulos 1989). With its roots in engineering and management, industrial ecology has been based on tracking material and energy flows through industrial systems with the aim of supporting decision-making for industrial managers and governmental agencies (Duchin & Hertwich 2003). Eco-industrial parks have been developed to facilitate these types of collaborations and have shown great advantages in reduced resource consumption and waste generation (Chertow 2000; Jacobsen 2006). However, given that industrial ecology is a relatively new field, much remains to be done for global production to be fundamentally transformed by it.

Cradle to Cradle (C2C) follows the industrial ecology line of thinking, but focuses on the product design level. Using the premise that "waste equals food", C2C highlights the importance of designing products by also considering what happens to the product after its useful life is over (McDonough & Braungart 2002). C2C proposes that the End-of-Life stage of products (i.e. when a product is no longer useful) should be transformed into a new "cradle" stage for the next product. This means that C2C expands the space for action from manufacturing, to include also the use and eventual reuse of products.

Circular Economy (CE) is a generic term for an industrial economy that recirculates materials by using resource recovery routes, to minimize waste and pollution. Resource recovery routes are the paths that resources can take in order to be circulated back into the production system, CE is rooted in several schools of thought, including industrial ecology, C2C, Biomimicry, Regenerative Design and the Blue Economy, among others (Foundation 2012). All these sources draw upon the idea that manufacturing and consumption should imitate natural ecosystems, where resource and energy flows are useful and regenerative to the environment that sustains them. Although C2C and CE have a broader scope than industrial ecology, they are still very much rooted in industrial production. CE has been promoted as a strategy for production, where it is expected that producers establish close relations with the users of their products, enabling them to provide maintenance and later refurbish the products sold (i.e. recondition the products for new use by the manufacturer). This has the intention that the manufacturing company retains the value in the products they make. The basic idea is to shift the economic drive from planned obsolescence to maintaining value through several life-cycles of products. This business model works successfully with high-end technology products consumed by industry or institutions (e.g. Caterpillar industrial equipment and Ricoh printers, both mentioned earlier Caterpillar 2015; Ricoh Group 2012). The question remains whether or not this business model can be easily applied to fast moving consumer products as well, since the collection of common consumer products is more of a challenge. Even though a CE has initially been presented as a strategy for the production industry, the recent EU action plan for a CE states clearly that WM has to develop to be able to recirculate materials to the producing industries (European Commission 2015), so connecting manufacturing to resource recovery from WM.

Figure 6 shows how the different production-centred recirculation efforts discussed relate to each other, locating them at different stages of a generic material flow diagram. As discussed earlier, industrial ecology focuses on waste from the production stage, while C2C incorporates the use stage to be able to recirculate used products to new production cycles. CE considers further recirculation by recycling discarded material for new production.

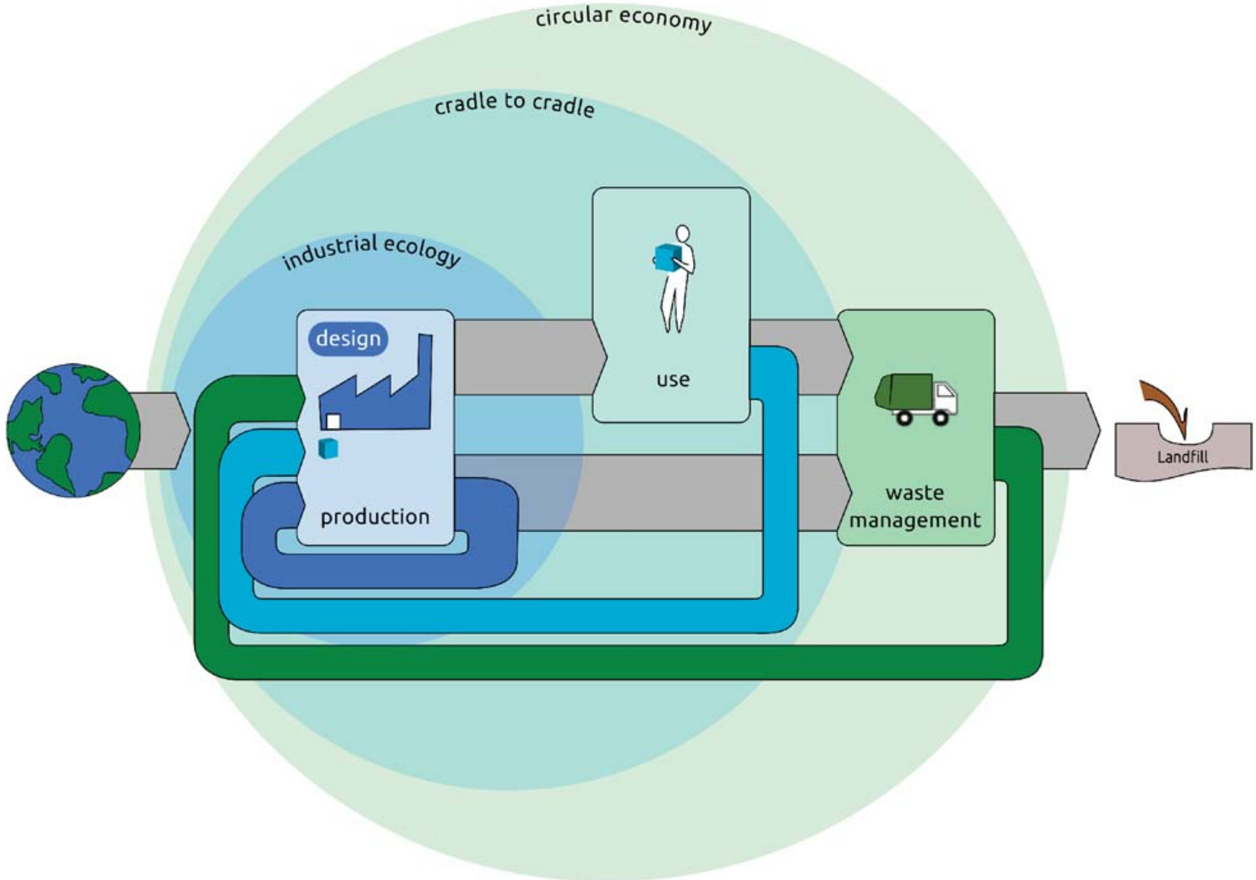

Figure 6: Production centred recirculation efforts.

1.4 From success stories to widely established recirculation

Sustainable waste management and the production centred recirculation efforts described earlier are frameworks that support material recirculation. They present a set of ideas and provide examples that illustrate how those ideas can be successfully implemented. These success stories suggest that if these frameworks were to be applied on a large scale we could witness a reduction in the amount of materials that go to waste. However, waste reduction is not the case. Not only has waste generation not reduced over recent years, it is expected to double by 2025 (Hoornweg & Bhada-Tata 2012). Despite the difficulties in collecting reliable data for waste generation and treatment on a global scale, rough estimations still set landfilling as the most common waste disposal strategy used globally (i.e. landfill corresponds to 44% of the waste disposed, with 18% recycled, 15% incinerated, 9% dumped, 8% composted and 6% have other disposal strategies) (ibid.). The EU performs better than the global trends, having reduced landfilling to 31% of the total waste treated in the region in 2013. However, with 26% of the waste being incinerated, this means that still most waste treated in the EU is not being recirculated (i.e. 57% of the total waste treated) (Bourgeais et al. 2015). This means that despite all the recirculation efforts cited earlier, our global material use is still predominantly linear.

So why aren't more material quantities recirculated? One explanation could be that these frameworks are not disseminated widely enough for us to see any effects in global waste generation. But is the solution to merely to up-scale their use, or are there barriers that make these frameworks inapplicable? Regardless of what framework is used, what hinders the recirculation of materials in practice needs to be better understood. The term practice is used in this thesis to describe what actually happens when taking ideas to action, as opposed to what one thinks may happen (Cambridge English Dictionary 2016)[1]. This step of "bringing recirculation into action" needs to grow from isolated success stories to a widely established use of secondary material, where most materials handled by WM are returned to production. The research presented in this thesis is therefore dedicated to describing the difficulties encountered when trying to recirculate materials, in order to propose suggestions to accomplish preconditions to increase material recovery.

1 Practice is a term that is colloquially used with this definition, as putting into action. This is how it has been used throughout the thesis. However it is also well defined in scientific research, with practice theory being a broad and growing field. How this research relates to practice theory will be addressed in the discussion chapter in section 7.1, when positioning this research among other relevant research fields.


Design for Sustainable Change
Anne Chick/Paul Micklethwaite
Required Reading Range
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WM&R 29/9
waste management & research
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September 2011
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SUSTAINABLE WASTE MANAGEMENT IN HOUSHOLDS –
FROM INTERNATIONAL POLICY TO EVERYDAY PRACTICE
ICONS
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2 Approaches, aim and study overview

This section is dedicated to presenting the research approach, professional perspective and epistemological viewpoint on which this thesis is based. Later the overall aim of the research, research questions and an overview of the studies are presented.

2.1 Research approach

There is much written about how closed-loop production and consumption systems could work (as presented in section 1.3), but how such closed-loop systems work for the materials that are currently discarded still needs to be seen in practice. Therefore, it seemed natural to choose a practice close action research. This means that the research projects presented in this thesis were done in close collaboration with several stakeholders and practitioners in different case studies. It is expected that such collaborations generate knowledge that is relevant to practitioners and hereby find direct implementation (Hellström 2015). Here the term practitioner is used to refer to people who execute a practice or activity, rather than theorize about it. So the knowledge that this thesis aims to generate is pragmatic; it hopes to be useful in practical implementation, helping to predict situations, solve problems and execute actions.

As a researcher I had no intention of merely observing and documenting a situation in order to explain and rationalize it. The intention was to alter the existing situation to a desired one by different actions, carried out in collaboration with the stakeholders. Later, reflecting on the effects produced by the actions taken, the lessons learned are used for theoretical generalization in trying to provide an explanation for the phenomena observed, contributing to the creation of knowledge. This is similar to how McNiff & Whitehead 2002 describe knowledge creation in action research.

Multidisciplinary (i.e. collaboration across academic disciplines) and later transdisciplinary (i.e. collaboration between several sectors focused on practical rather than academic problems) research are based on the assumption that some problems are so complex and manifold that they can only be addressed by combining and transcending disciplines and sectors (Hellström 2015). The problems framing this thesis, i.e. resource scarcity and waste handling, are of this kind and are also commonly mentioned as typical examples of “wicked” sustainability problems. Wicked problems can only be solved by using holistic approaches that go beyond the analysis and optimization of technical systems (Lönngren 2014). Therefore, the research presented in this doctoral thesis has been multidisciplinary (writing articles with colleagues from industrial ecology, civil and mechanical engineering) as well as transdisciplinary (collaborating with stakeholders from the WM branch, municipality and housing companies).

2.2 Disciplinary perspective

Subscribing to constructivist epistemology, I believe that the professional formation of any researcher will influence the way they approach and carry out their work. I am educated as an industrial designer, so the research presented in this thesis is done from that perspective.

The practice of design is strikingly close to action research, where “A designed artefact is a researched proposition for changing reality” (Press 1995, as referred to in Swann 2002). Both scientists and designers perform research. The main difference is that scientists are problem focused and problem-solve by analysis, whereas designers are solution focused and problem-solve by synthesis (Cross 1994). That is why, as a designer, the interest I have in the problems presented by material recirculation, lies in being able to propose possible solutions to these problems. This thesis describes the situations investigated based on the results of the studies made, to later take on a prescriptive role, suggesting possible improvements for the situations described. These suggestions are not as elaborated as a final designed artefact, but rather general recommendations or guidelines. That intention of pointing to a solution is grounded in my professional formation as a designer.

Additionally, industrial design is one of the disciplines needed at the manufacturing stage and is therefore relevant to the topic addressed by this thesis. Industrial design appeared after the industrial revolution, with the purpose of providing aesthetic and semantic guidelines to the new industrially produced goods, to increase their usability and user appeal (Heskett 2005). The design discipline has since then evolved to develop user interfaces and later user experiences, moving beyond the development of physical goods to intangible systems, still focusing largely on the user and use phase (Brown & Martin 2015). User-centred and later human-centred design argue strongly for optimizing a design around what users need and want, rather than forcing users to adapt to products that are not well fitted for them. The extent to which designers include users in the creative process varies widely; some may barely find inspiration from observing users, while others work actively together with users though all the stages of product development, iterating the results in several opportunities. Regardless of this variation, the term design in this thesis is considered as development activities that strive for incorporating user requirements to products, services or systems. The term product development will be used when referring specifically to the design of physical products.

2.3 Epistemological base and its methodological implications

The epistemological bases for transdisciplinary research, action research and design research are similar and can be supported by critical realism. Critical realism accepts that the world exists independently of our knowledge of it. Knowledge, as a social construct, is fallible, theory-based and will never grasp the totality of reality. There are people with needs in the world and the production of knowledge is done to address these needs, rather than to explain reality (Easton 2010). The socially constructed ideas about the world are useful, since we can imagine a desired state and build it. The world alters our view of reality, but we also alter the world to fit our purposes through our actions. That is why it is useful to engage in building knowledge, however limited it may be, to help us design the future we wish to have.

In this research the production of knowledge is done to address the need for change, not as a goal on its own. Therefore, the theories used to explain things become secondary (e.g. practice theory). Theories are used to facilitate communication among the actors engaged in generating change. So this thesis has aimed at generating understanding for action, rather than just understanding.

Transdisciplinary research, action research and design research all have a declared intention to change something in the world (Hellström 2015; McNiff & Whitehead 2002; Saikaly 2002). To generate change an intervention is defined and executed, and the results of the intervention are later monitored by gathering data and observations. Depending on the results, a new intervention may be devised and so the process is iterated. These research approaches accept that the knowledge generated does not provide an objective undeniable truth and is (at least initially) highly context dependent. Often, practice close action research is done through case studies. Case studies provide a real object of study, with multiple aspects and characteristics that would be impossible to replicate under controlled circumstances (Woodside 2010). By investigating real cases, the observations obtained can be directly put to the test to help build understanding for complex real-life situations. The research presented in this thesis consists of three topics, explained in more detail at the end of this chapter. Of these three topics, Topics 1 and 2 are composed of studies that correspond with transdisciplinary action research. The work done under Topic 3 does not have any intervention nor a detailed analysis of a case study, but rather explores current practice using a more traditional researcher-observer perspective.

Given that this research focuses on complex socio-technical systems, a mixed methods approach was considered relevant. Different aspects of the cases studied can be best captured with specific measurements, using several methods to collect data that can complement each other to provide a broader understanding. The subjective experiences of the relevant actors have been collected through interviews and surveys, while different types of empirical measurements provided factual data to describe the situations studied (e.g. field observations, product studies). However, time and resource limitation often resulted in the possibility to use only a few observation methods at a time. Each study in this thesis has different set-ups and constraints, therefore a more detailed description of the methodology used will be presented for each study in the following chapters.

2.4 Aim, research questions and study overview

This thesis aims to better understand the barriers for recirculation for the materials used in the production of consumer goods, in order to propose ways to facilitate circular material use in society. The object of study is how material recovery is achieved, so case studies were done to observe this activity in real situations. Since the material flow between WM and production systems needs to be increased (as argued in the introduction), two case studies were chosen; one to inform of production-centred recirculation efforts (Topic 1), and the other focused on material recirculation through WM (Topic 2). These case studies where then complemented by a third study that investigated how recirculation is currently addressed by designers working in manufacturing (Topic 3). Figure 7 illustrates how the topics relate to each other in a simplified recirculating system.

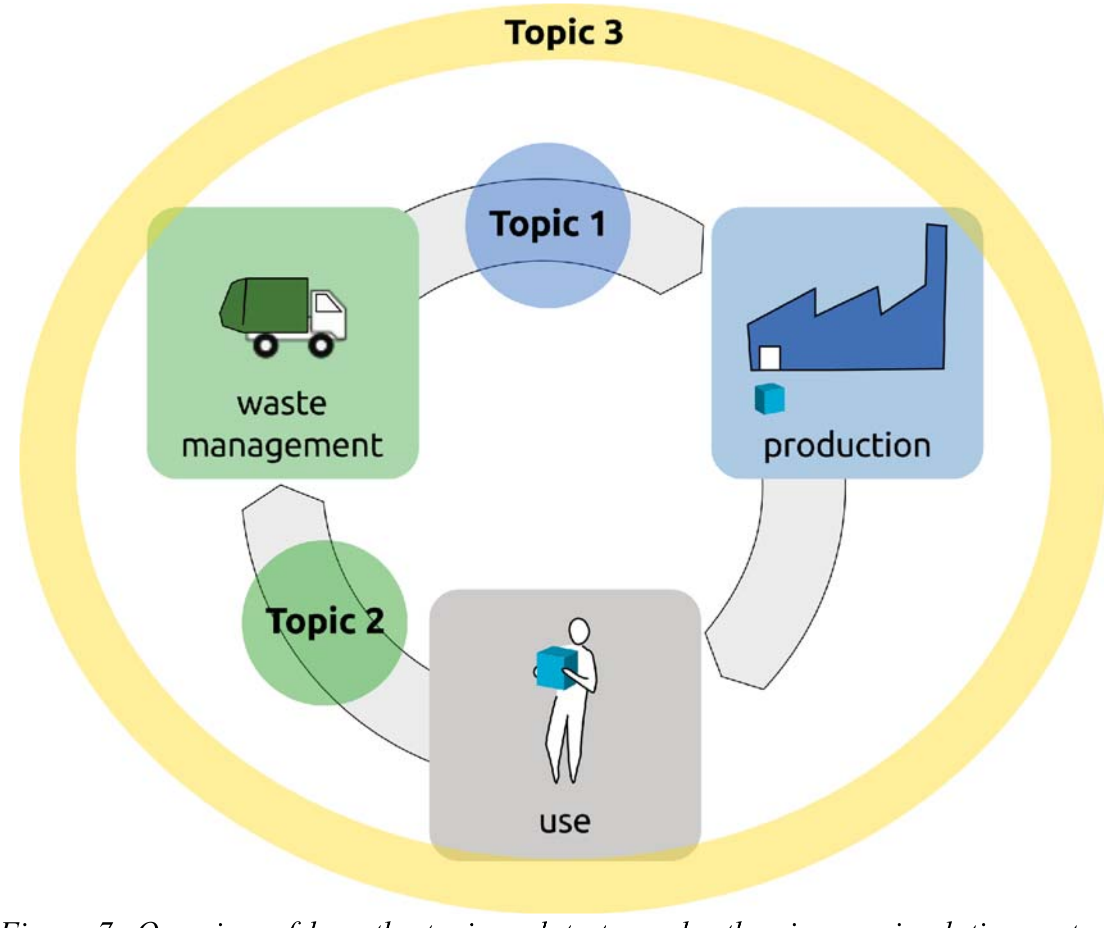

Figure 7: Overview of how the topics relate to each other in a recirculating system. Topic 3 addresses all stages of recirculation, but it does so from designers' perspective.

The case study targeting recirculation through production, is presented in Topic 1. This case study aims at recirculating materials that are currently discarded back to production by using them in new product development. By focusing on materials currently discarded as waste this study targets the problematic flows that still do not have a working solution for recirculation, thus helping to highlight the existing barriers. This topic explores the first research question "**What hinders product development from discarded materials?"** (RQ1). To do this, Topic 1 presents the results of observing and analysing controlled cases of product development using waste material done by design students. These student projects constituted the Waste to Design (W2D) project, which was part of the MISTRA Closing the Loop initiative[2] and resulted in several conference articles (Rexfelt et al. 2013; Ordoñez et al. 2014; Ordoñez et al. 2012) as well as in Article A. Later a comparative study was done to triangulate these projects with similar ones done in India, presented in Article B.

Topic 2 addresses material recirculation through WM. In order for WM to be able to return resources to production, it has to be able to adequately sort the discarded materials into useful fractions. This is already implemented in WM to some degree, but it has to improve drastically in order to recirculate most discards. Therefore, this study investigates the second research question "**What are the barriers to improving waste sorting?"** (RQ2). To tackle such a broad question, Topic 2 makes use of a literature review (presented in Article C), followed by three case studies (i.e. cases A, B and C). The case studies were decided in collaboration with a local housing company in Gothenburg to investigate A) What hinders waste sorting in apartment buildings that use material sorting rooms, B) What effects do small variations in such infrastructure have on sorting behaviour, and C) What effects do vacuum sorting infrastructures have on sorting behaviour. These cases were chosen to help inform in what ways does sorting infrastructure affect behaviour and how could infrastructure be altered to increase sorting. Case study A is described in detail in Article D, while case studies B and C are still being analysed and only partial results are presented in this thesis.

Topics 1 and 2 investigated barriers for material recirculation in specific cases, which led to suggestions for improving recirculation in those cases. These cases occur within a larger context that needs to be understood if we are to understand what our suggestions may imply for other cases. So a third topic was investigated to provide some understanding of the broader context for material recirculation, while still investigating it in practice. Given that it has been argued that waste is a design flaw (Anastas & Zimmerman 2006) and there are several sustainable design strategies that directly address waste minimization, it seemed relevant to explore the broader context for material recirculation from the design practice. This is personally motivating for me, being a designer myself, since it would allow me to better understand how my profession could contribute to using resources more sustainably. Therefore, Topic 3 investigated **"How does design currently relate to material recirculation?"** (RQ3). To investigate this it was deemed relevant to know what types of collaborations exist between designers and WM. A direct approach was taken in an exploratory interview study targeting designers that had worked with waste and WM professionals (presented in Article E). The interviewees also provided a list of products that they saw as good examples of recirculation. These examples were further investigated and compared to the recovery routes presented in the literature, resulting in Article F. To complement the view of the designers that had worked with waste, a web survey was done and shared with a wider group of designers through social media. The web survey, summarized in Article G, investigated how designers used End-of-Life considerations in their work.

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2 MISTRA Closing the Loop is an initiative by the Swedish Foundation for Strategic Environmental Research which financed seven independent research projects in its first stage, with six projects ongoing in its second stage. The initiative's aim is to enable material recirculation of Swedish industrial waste.

In summary, the work presented in this thesis consists of three topics, each of which focused on answering one of the three research questions presented earlier. Topic 1, Designing with Waste, observed and documented six student thesis projects aimed at designing with discards, later comparing them to similar projects done in India. Topic 2, Waste Sorting, explored the challenges of waste sorting through a literature review and three case studies. Topic 3, Design and Waste, investigated the current relation between design and material recovery using an exploratory interview study, complemented with a product study and web survey. Figure 8 shows an overview of what type of studies and materials were used to inform each topic and what articles they resulted in. Each topic consists of at least two partial studies addressing more specific questions. The topics and the studies that form them are described in greater detail in chapters 3, 4 and 5, respectively. Later, chapter 6 combines the results obtained from the topics to provide an integrated overview of the conclusions from this doctoral thesis.

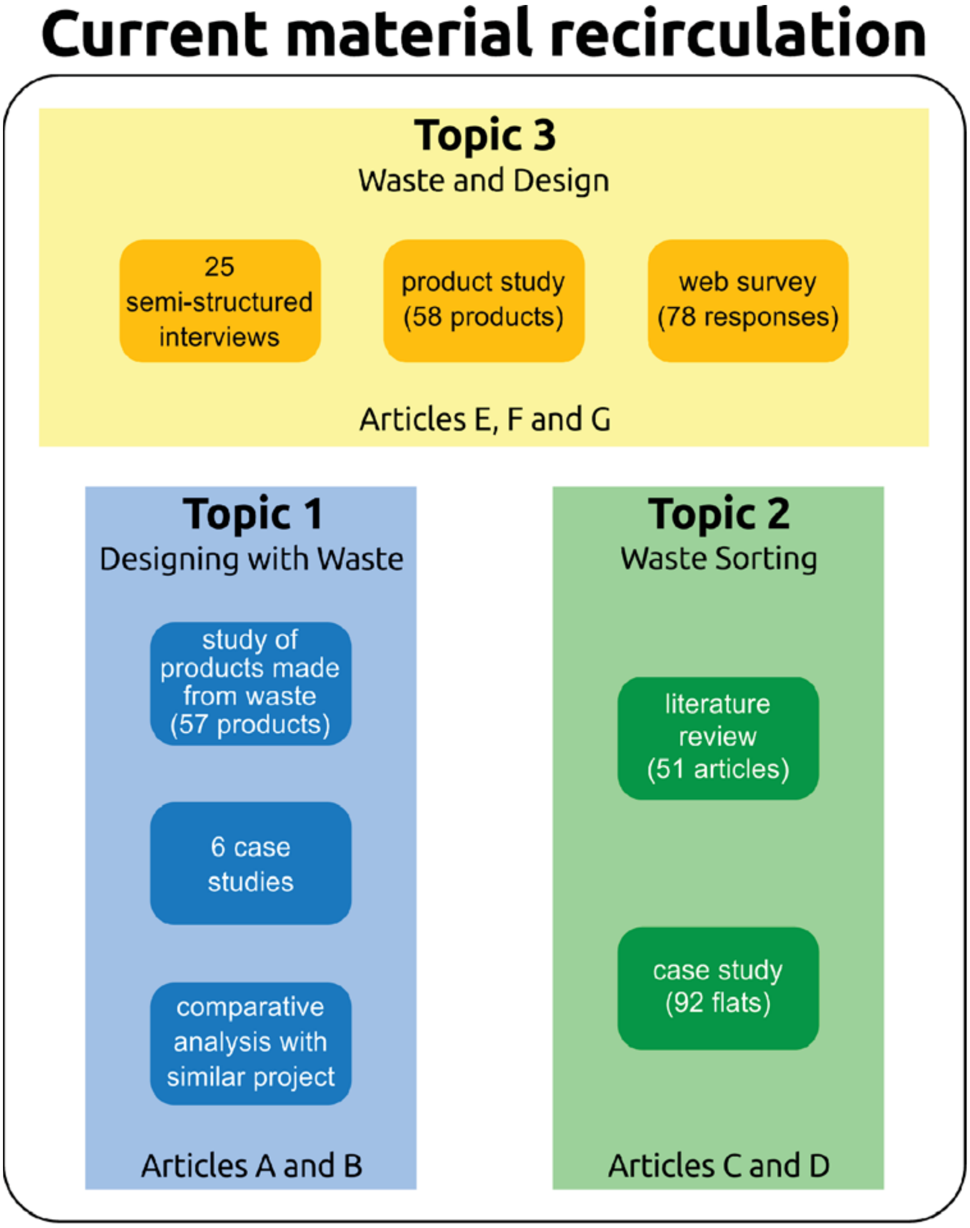
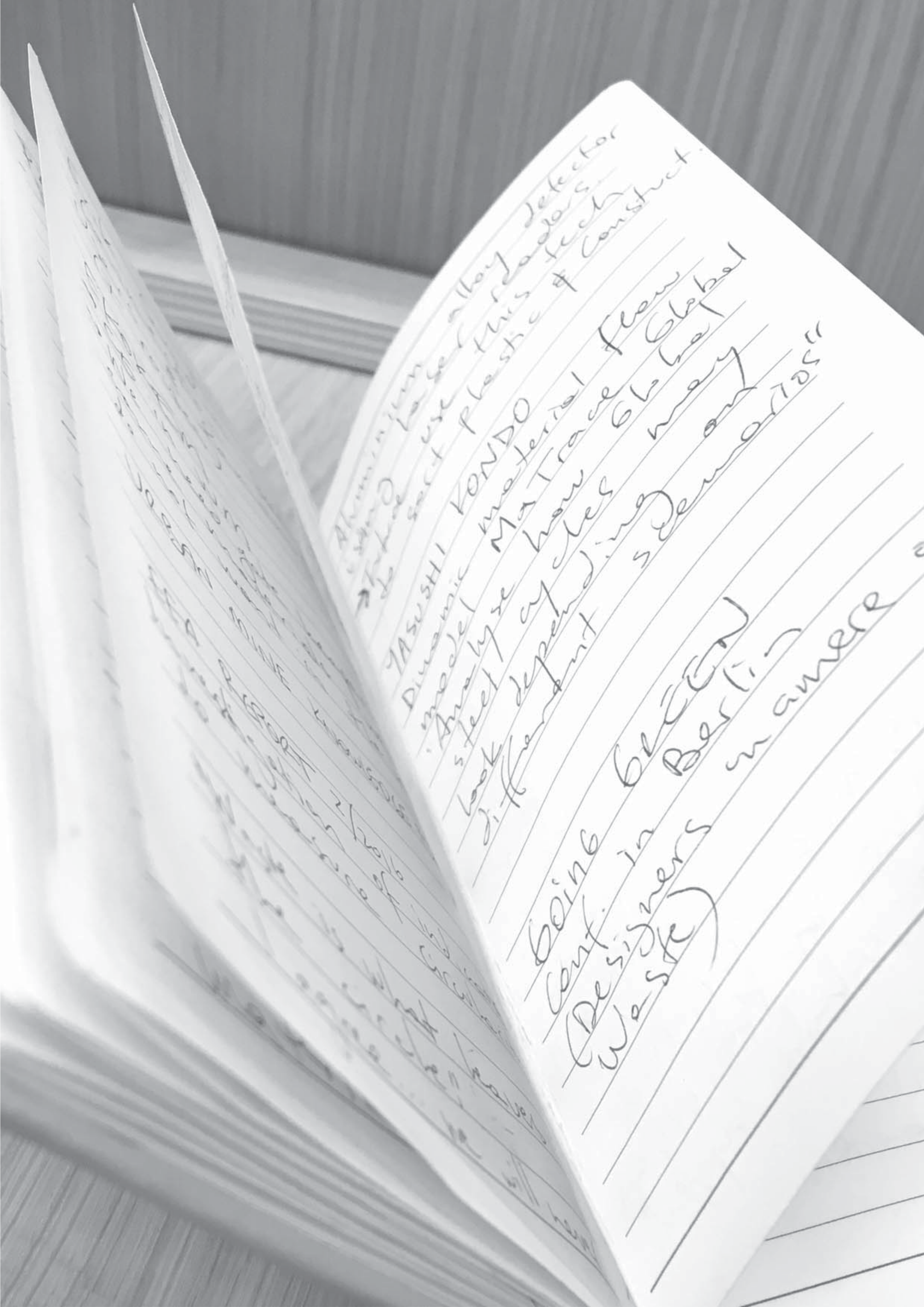


Figure 8: Topic overview, with topics 1 and 2 zooming in on specific cases of material recirculation and topic 3 providing a broader context for recirculation.


YASUSHI KONDO
GOING GREEN
Conf. in Berlin

The topics

The following three chapters describe the topics that form this thesis. Each topic chapter presents a short introduction, its delimitations, a methodological description that introduces more detailed research questions and the main results obtained from the studies that inform that topic. Then the results are used to respond to the research questions for each topic. Finally, each topic chapter ends with suggestions for overcoming the barriers described by the studies.

3 Topic 1: Designing with waste

This section presents the results of Topic 1, which zoomed in on a specific case of production-centred recirculation by investigating: “**What hinders product development from discarded materials?”** This was explored in the Waste to Design (W2D) project, which collaborated with a local recycling company and an engineering consultancy firm. The W2D project was one of seven projects financed by the Mistra Closing the Loop initiative, aimed at supporting research that could contribute to the recirculation of industrial waste in Sweden (Smuk 2015). The W2D project provided a set up for design students to dedicate their thesis work to developing products using discarded materials provided by the recycling company, with supporting supervision from the engineering consultancy firm. The results from the W2D project were later compared with a similar initiative from an Indian university to see if the results were to some extent generalizable.

3.1 Introduction

The doctoral work in this thesis starts by accepting the premise that material recirculation is more sustainable than a linear use of material resources for the production of goods. The problem is that material recirculation has not been possible with all materials used in society. The waste currently not recirculated needs to be somehow redirected for its use in production. Initiatives like up-cycling and industrial symbiosis, which make use of waste in new production, have successfully created new recirculation paths, at the small, hand-crafted scale as well as at large industrial volumes. Although there are several examples of serialized up-cycled products, little has been written about how the process of designing with discards can be achieved. Therefore it is difficult to know how to facilitate this process in order to increase the amount of materials that get recirculated this way. In order to shed light on the process of designing with waste, a case study was carried out to observe how design students used discarded materials to design new products.

3.2 Methodology

Given that Topic 1 explores what hinders product development from discards, it was first necessary to describe how this could be done. So, Topic 1 started with a product study focused on products developed with discards to see if it was possible to describe **the process of designing with waste, including the methods and competences needed** (RQ1.1). Several examples of products made from waste were found, but no explanation of the process of making these products, nor what methods and competences were used (Ordoñez et al. 2012). Designers tend to present a final product, but rarely describe how they have come to these results. Since product development, like any creative process, is carried out by externalizing cognitive operations iteratively (Babapour 2015), qualitative methods are needed to make the subjective understanding of the designer's own process explicit. The W2D project gave the opportunity to follow design students in their process of designing with waste from the very beginning. In this project design students were presented with the challenge of designing with some material collected by the recycling company and that currently was not recycled. To facilitate their process they had access to supervisions from professionals in the recycling company, as well as the engineering consultancy that collaborated in the project. This set up provided a controlled situation, where the design process could be observed in real time, not only retrospectively.

The W2D project investigated six cases of design students developing products from waste material by observing their work process through regular supervision, weekly work diaries kept by the students, their final thesis report, final product proposals and a semi-structured interview after their work was completed. The supervision sessions and work diaries were used to follow the students work process in real time, while the thesis report and final product proposals provided the resulting outcome. The interviews were used to get the students to reflect on their process and final results, describing the difficulties they encountered in retrospective. From this material it was possible to identify the **main barriers experienced by designers when designing with waste** (RQ1.2).

After the W2D project was completed, information about a similar project performed at a university in India became available. Together with the researchers from the Indian project, a comparative analysis was made to better understand the challenges of designing with waste and to see how context dependent these challenges are. The comparative analysis served as a multiple triangulation (Thurmond 2001), where different investigators, using different data sources and methodological approaches but having a similar theoretical perspective investigated the process of designing with waste.

Figure 9 shows the three studies that inform Topic 1, the share of qualitative and quantitative material obtained in each and how these studies inform the research questions of Topic 1.

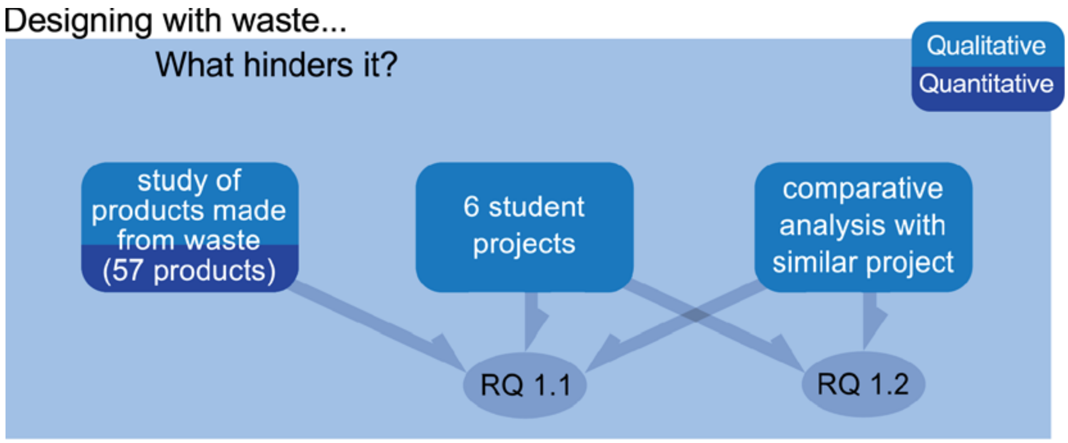


Figure 9: Overview of the studies that form the basis for Topic 1.

3.3 Delimitations

Product development from discarded materials could be done in several ways, for example this could be executed by varying stakeholders (manufacturers, users, recyclers, designers, constructors, etc.) using different types of materials. The case studies used to inform this topic focus on product development done by design students, using materials provided by a local recycling industry or collected at a local landfill. The materials they could choose from were materials that currently have no recirculation path implemented, and could be either post-consumer or pre-consumer industrial waste.

3.4 Summary of results

In short, designing with waste is a challenging task with multiple considerations, requiring more steps than a regular design process. The results presented here refer to the W2D project if not stated otherwise, with a comment about how the results compare to the Indian project, at the end of each section. The results of the W2D project are described in Article A, while the comparative analysis between W2D and the Indian project is presented in Article B.
The process of designing with waste requires a pre-process, before the students could engage in

more traditional design work. The main goal of the pre-process was to decide what type of product could be made from the waste material to be used. All student projects varied slightly in their pre-processes, but they all included three central activities (Figure 10):

1. Analysis: Familiarization with the discarded material through material analysis and research.
2. Ideation: Develop product applications ideas, based on the material information gathered.
3. Selection: A screening process for the ideas generated to identify the most promising ones.

All students struggled to execute the pre-process, taking a longer time than originally expected. The analysis and selection phase proved to be the most challenging ones, with ideation being easiest to do for the design students.

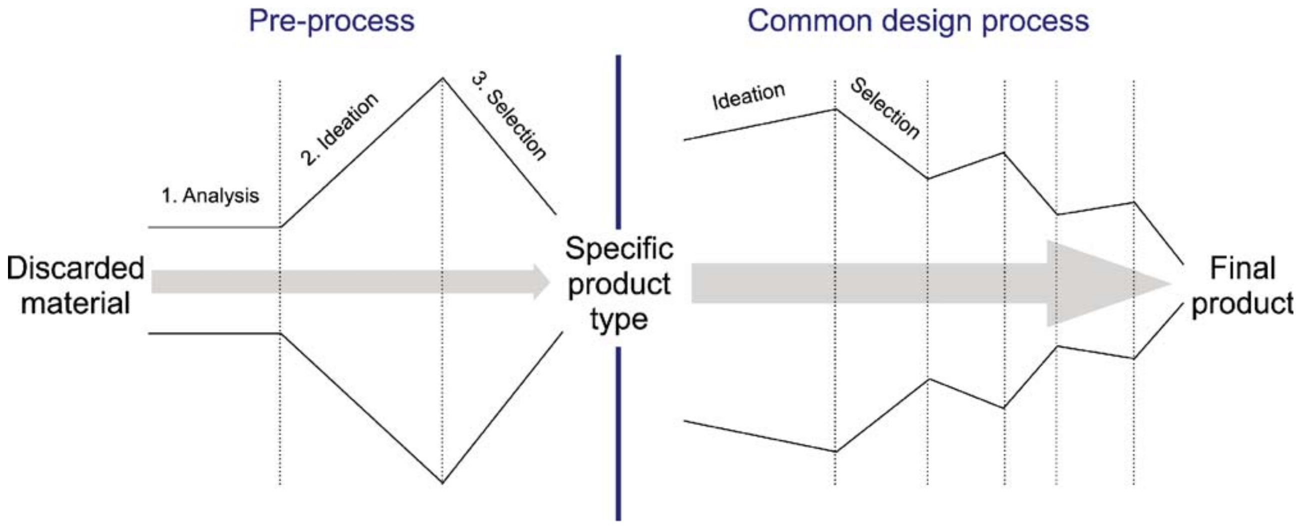


Figure 10: Designing with waste process diagram.

The process diagram for designing with waste material (seen in Figure 10) was developed based the empirical experience from the W2D project, as well as on existing generic design process models. Such models define the process of designing as sequential stages of idea generation and selection to narrow down and specify a finished product starting from design objectives (Pugh 1991; Cooper 1986) or an understanding of a use situation or user needs to be fulfilled (Ulrich & Eppinger 2004; Andreasen & Hein 1987). The process diagram for designing with waste presented in Figure 10 is an application of such models to the specific case of designing with waste, in order to provide a process description for this endeavour, which was lacking. Just like the generic design processes it consists of idea generation and selection, but starts from the waste material properties. Although some authors argue that "the ability to use the imagination and embrace preformed waste items should in essence be no different from the utilization of any material" (Bramston & Maycroft 2014), it can be argued that this did not hold true in the W2D project. Common material selection (i.e. selecting materials based on the properties required) is a challenging task since there may be many requirements that the design demands of a material, which are met by several materials in different ways. There is much research to support this type of material selection (e.g. Ashby et al. 1993; Deng & Edwards 2007). However, the task of starting to design based uniquely on a material inverts the way material selection is commonly done, i.e. the material given provides the properties it has that are then to be matched to a suitable application area. There is little to no research available to support "application selection" based on a material. If quality standards for secondary materials are developed this "inverted material selection" process might be unnecessary.

3.4.1 What methods and competences are needed to design with waste?

Since the pre-process stages are unique for designing with waste, only the methods used by the students during the pre-process are reviewed here. Different methods were used at each of the three stages of the pre-process.

The **analysis stage** of the pre-process collected data about the waste material to be used by consulting with different sources (i.e. available scientific literature, the virgin material producers, manufacturers that used that specific material, material databases and material researchers), inspecting samples of the material and even conducting experiments and tests to evaluate basic properties. This stage required an analytical evaluation of the material and the material properties. Some of the projects worked with a material that had more uncertainty about its origin and composition. This meant that more effort was needed to collect sufficient information to be used in the following ideation and selection phases.

The creative work to identify possible application areas for the material turned out to be less challenging than expected, with the students generating easily hundreds of ideas for using the material. Methods used in the **ideation stage** included:

1. A variety of creativity focused methods (i.e. brainstorming).
2. Using material information and samples as stimulus for the ideation sessions.
3. Inviting people with varied competences to an ideation workshop.

Students commented that the creative idea generation methods used seemed to work as in any product development process. Inviting people with different competences proved to have little effect on the results of the ideation sessions, but in retrospective, the variety of competences was considered to be more useful later, when screening the ideas. Having adequate material information and physical samples of the product were considered by the students to be crucial to help generate viable product ideas. The fact that some students lacked reliable material information forced them to make assumptions, which made it difficult to know what ideas were feasible during the screening stage.

The **screening stage** was experienced by the students as the most difficult stage in the pre-process. They used several evaluation criteria to be able to determine if the ideas generated were worthy of pursuing. The type of criteria used varied, with all projects considering aspects related to the functionality, manufacturability and aesthetics of the product. Some projects also considered aspects such as: market potential, waste volumes used, risks related to safety and health, possibility to recover material at the end-of-life of the product and compatibility with laws and regulations. All criteria used to evaluate the product ideas required relevant material knowledge. Consequently, the projects that had insufficient material information got stuck with several ideas and needed to gather more material information before proceeding. After reducing the number of ideas to an amount that could be compared more thoroughly, more traditional evaluation methods were used: i.e. Pugh matrices, consultation with experts, market benchmarking, digital and physical prototyping.

When comparing these results to the Indian student project, it was observed that they also had the three stages of analysing the material, generating ideas and later selecting one product concept to develop further. However, there were also two earlier steps described; collecting the sorted material and investigating the material properties needed. These steps were also relevant in the Swedish cases, but they had been addressed to some extent by the framework of the W2D project, given that the students got the sorted material from the recycling company. Observing the differences between both projects, it can be said that designing with waste depends on the WM context where it is carried out, but three general steps can be described:

1 Collect and sort the discarded material in an adequate manner.
2 Investigate and test the material properties.
3 Identify a suitable application for the material by correlating the identified material properties with the application characteristics.
    3.1 Analysis.
    3.2 Ideation.
    3.3 Screening.

The first two steps described, are crucial since they provide access to the material and knowledge about the secondary material's properties. They are to some extent prerequisites to be able to design with waste. The third step corresponds to the process of designing with waste itself, described here as the pre-process needed to identify a specific product type with which "traditional" design process carried out. It requires creativity to propose applications for the material, followed by analytical work to decide whether the creative ideas are feasible. Here, knowledge in design fundamentals, material science and manufacturing technologies are essential. Access to the material and reliable material information are vital to facilitate the generation of relevant proposals and the selection of feasible product ideas.

The W2D project made use of industrial waste, which is to some extent homogeneous and sorted by the providing industry. This made the conditions for the W2D students much easier than those for their Indian counterparts. The Indian students sorted and collected the discarded materials themselves, directly from local landfills or generating sources. This meant that they had to cover all three steps mentioned earlier, whereas Swedish students only had to engage in steps 2 and 3. Given that the Indian students were restricted to suggesting products that could be manufactured by hand by marginalized communities, they had less freedom when suggesting product concepts, facilitating to some extent their screening process. Some of the students in the Indian project had working experience as designers and as such had better knowledge of production techniques, resulting in physical prototypes much closer to production than the products proposed in the W2D project. However, the Indian project had a smaller time frame for product development (i.e. seven weeks as opposed to 20 weeks used in the W2D project) resulting in a quicker pre-process with less emphasis on generating several ideas to compare and choose from. The process observed in the Indian project was quicker to come to product concepts to develop, spending more time in the actual product development and prototyping stages.

In summary, access to the material, good knowledge of the material properties and the possible production techniques that can be applied to the material are crucial to select feasible product ideas at the pre-process stage of designing with waste. Both creative and analytical methods are required in this pre-process in order to suggest novel application areas for the material that are still feasible and realistic.

3.4.2 What are the main barriers experienced by designers when designing with waste?

The main barriers experienced by the design students in the W2D project were: irregularity in the provided material, little reliable information about the discarded material's properties and the lack of a traditional design brief.

Irregularities in secondary materials translates to irregularity in the quality of these materials. Quality is a tricky concept, which has been defined by many scholars with no clear consensus. It is accepted that quality is defined by consumer satisfaction, or by the object being fit for purpose, whichever that purpose may be. However, besides being a subjective evaluation, there has been a strong need in industry to measure quality, expressing quality in quantitatively measurable product characteristics (Shewhart as expressed in Hoyer & Hoyer Brooke 2001). The consistency of the physical properties of materials is one of these measurable characteristics that can be identified with product quality. Therefore the irregularity of secondary materials will always find them lacking when compared to more stable virgin materials. This is an issue that several of the projects financed by the Mistra Closing the Loop initiative, shared (Smuk 2015). Irregularity leads to uncertainty and poor knowledge of material properties, reducing the possibilities of using secondary material for new production. However, irregularity is an intrinsic characteristic of waste materials, which was also observed as a main challenge in the Indian project. Therefore, in order to provide more consistent material, discards should undergo some sort of treatment or selection. In the W2D project, this was done to some extent by the industrial recycling company. They could separate waste streams coming from pre-consumer or post-consumer sources and with this assure in some cases a certain regularity in the material. This is why some student projects limited their proposals to use pre-consumer waste, or defined a certain date of the original material production, to be able to assure that certain chemical components were not present in the material. In the case of the Indian project, the students were the ones collecting and identifying the materials. This meant that they also had to collect, clean and process the discarded materials in some way to be able to develop products with it. Such extra tasks delay the design process and designers would benefit from these tasks being done by other actors, such as municipal enterprises or informal waste pickers.

The irregularity in the discards leads to unreliable information about the material. If the materials are collected and processed in some way there should be some possibility to analyse and characterize the secondary materials to be offered for new production. The secondary material market currently does not include the materials targeted by the student projects (e.g. polyurethane foam from vehicle seats or PVC from cable sleeving), so separate collection and characterization are not available for these materials. It would be best if collection and analysis of the material are done by other actors to reduce the work load designers have when designing with waste. Also, material experts would be better suited to analyse material in order to provide the relevant material characteristics needed later for production.

The lack of a traditional design brief also generated uncertainty in the task of designing with waste. The brief given to the students was uncommon, i.e. to use a specific material for product development. Not defining what product to do was intended to provide the students with the freedom to choose an adequate application area for the material they worked with, but too much freedom resulted in the students having difficulty of not knowing how or when to start to design. Normal product development starts with a use situation to be addressed, some requirement to be fulfilled or a product to be improved. Rarely is the material to be used the starting point for product development. In contrast, in the W2D project the use situation also had to be identified and suggested by the students, delaying the start of the traditional product development process. Students in the Indian project also lacked a design brief, but were encouraged to identify user requirements to develop product concepts, and the sort of product was also free for them to define.

In summary, of the three barriers experienced by the students, the first two, i.e. material irregularity and unreliable material information, refer exclusively to the material to be used. The third barrier, lack of a design brief, is a problem that arises when only focusing on using a specific material for product development. This is not a normal starting point for a product development process, so that is why it generated uncertainty among the students.

3.5 How can product development from discarded materials be facilitated?

It can be claimed that product development from discarded materials is not more widespread than it is because it is difficult to do. Both the W2D and the Indian project concluded that it is difficult to design with waste, but a relevant and beneficial endeavour if finally achieved. Both projects are initial explorations of the process of designing with waste, identifying what steps and methods are needed in this process, as well as what hinders it.

It is recommended that secondary materials should be processed to guarantee certain material quality and provide designers with reliable material information for end-of-life recovery purposes. Currently the sorting and collection of discarded materials are done to some extent by WM actors around the globe (UN Habitat 2010). How many materials are sorted, and their quality vary considerably between different locations (Wilson et al. 2012a), covering normally only materials that have existing recycling markets. In order to design with materials not suitable for recycling, such materials should also be sorted and collected, but this is not yet a reality within existing WM systems. In order to support designing with waste there is a need to improve the quality and quantity of the materials sorted from waste fractions (this is further addressed in Topic 2).

Determining the properties of the discarded materials is an even bigger challenge. Today the total responsibility of defining the discarded material properties lies with the designer who wishes to design with waste, making it significantly more time consuming than regular product development. Ideally more actors should be engaged in analysing secondary material, thus simplifying the designer's task. When using virgin materials the material quality and its properties are defined and ensured by a material provider. Therefore, secondary material providers might be the right actors to address these issues in the future.

Designing with waste could potentially be more easily massified among designers if material regularity and reliable material information can be provided for secondary materials. This would allow designers to choose secondary materials in regular product development activities, much in the same way as they select materials today. This raises the question, “Are designers aware that their material choice affects waste generation and could support resource recovery?” This aspect is further studied in Topic 3.

In summary, designing with waste could be facilitated by processing secondary materials to ensure quality, expanding the sorting and collection activities to currently not recycled materials, and having material providers determine secondary material properties. These suggestions correspond to changes in the broader system that provides access to secondary materials and therefore, the research presented here has not been able to test any of these suggestions. Based on the observations from the W2D project, specific suggestions for facilitating the ideation and screening stages of the designing with waste process can be made, as shown in Figure 11. Also, if the material properties have not been confirmed, they will need to be tested for the application selected.

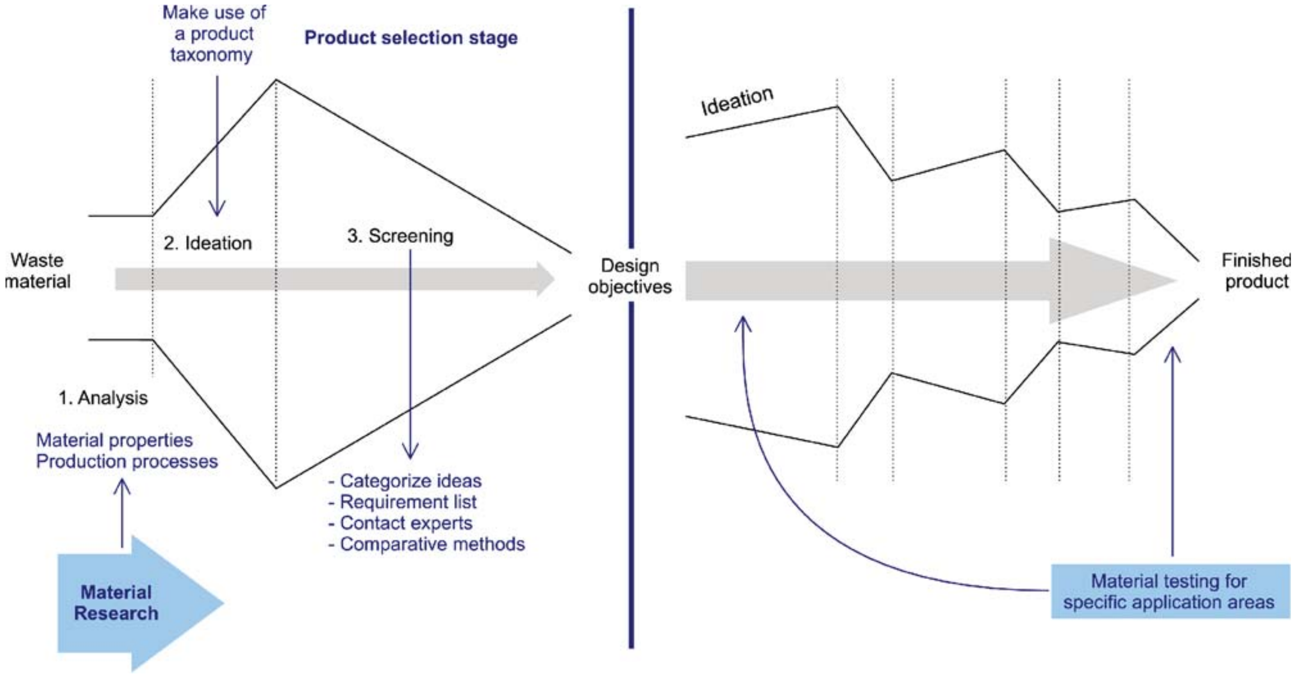


Figure 11: Process diagram for designing with waste, with suggestions to facilitate the ideation and screening stages.

Future work on this topic should test:

- Working with experienced designers, since experience in production could facilitate the task.
- Collaborating with material experts, to help provide the missing material information.
- Contacting relevant manufacturers, to gain information about the targeted markets and products.


Fisk och skaldjur
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4 Topic 2: Waste sorting

This section presents the results of Topic 2, which zoomed in on recirculating materials from the WM system by investigating "**What are the barriers to improving waste sorting?"** This was explored through a collaborative project with a local housing company that was interested in improving waste sorting in their buildings. Initially the collaboration consisted of observing the current waste sorting situation in specific buildings belonging to the housing company, to later provide suggestions for improving the waste sorting performance observed. This work was complemented by a literature review that provided a broader understanding of the difficulties common to waste sorting systems.

4.1 Introduction

To increase resource recovery from solid waste, waste has to be sorted into usable fractions. This is particularly difficult in the case of household waste, since this varies in composition, it comes from several generating sources and tends to mix several types of materials and products. Although municipal solid waste (including household waste) only accounts for 10% of the total waste generated, it is commonly the centre of political and research interests, given its complex nature and its links to consumption patterns (Blumenthal 2011). In practice, the sorting of household waste involves passing sorted material between several actors and is strongly affected by households' waste generation and sorting behaviour. Since the sorting of municipal solid waste involves several actors it is far more challenging to achieve than the sorting of industrial waste, where large volumes of homogeneous material are generated by single actors. This makes designing a system that accommodates all the actors involved in municipal waste sorting a more challenging task. The work in Topic 2 is based on the assumption that the infrastructure available for sorting waste will affect how waste is sorted. Therefore, the aim of Topic 2 has been to try to describe and understand this influence, in search of ways of improving the system to increase correctly sorted waste volumes and the quality of the collected fractions.

4.2 Methodology

Topic 2 is based on the assumption that infrastructure affects behaviour (as described in Thaler et al. 2010). This topic consists of a literature review and three case studies. The review investigated **how does sorting infrastructure affect waste sorting behaviour?** (RQ2.1). The review therefore targeted two main subjects; waste sorting systems and sorting behaviour. The articles reviewed were categorized according to the methods they used and the results they obtained.

The practical implementation of waste sorting systems is a challenge, given that many aspects affect their implementation and influence user acceptance. This is why research through case studies was deemed most relevant for Topic 2. To identify a feasible case study, the municipal waste office of Gothenburg was contacted to explore the possibility of collaborating with them and to learn how waste sorting interfaces are designed in the city. After initial investigations the space that proved most adequate for evaluation and a possible intervention was waste sorting infrastructures in apartment buildings. These systems are medium sized, defined by the housing companies and affect several waste system users at a time. Having a small dedicated group of people in charge of the design, maintenance and evaluation of the waste sorting infrastructure made it possible to understand the development and implementation process. Also, these systems cover several thousand households giving the researcher access to a broad group of service users. Collaborating with a housing company provided synergies with an engaged stakeholder that was not directly the user, but affected how users could interact with the system, resulting in direct implementation of research results. Three case studies (referred to here as studies A, B and C) were defined together with a housing company in Gothenburg, to investigate **"What are the main problems with material sorting in apartment buildings?"** (RQ2.2).

Study A observed the current state of waste sorting in two buildings without introducing any alterations to the infrastructure (presented in Article D). Study B tested seal-able bags and removing the lid of the containers for bio-waste in apartment buildings that used waste sorting rooms. Study C tested the same seal-able bags for bio-waste used in study B, in buildings that used waste vacuum systems as their sorting infrastructure. All studies inform RQ2.2, with studies B and C having further research questions related to the infrastructure variations they observed. However, the results of studies B and C have not been published, since data analysis and reporting is still ongoing for these cases. Therefore only preliminary results from these studies inform Topic 2 and their specific research questions are not formulated in this thesis. Nonetheless it was deemed relevant to include these preliminary results since it would be impossible to respond to RQ2.2 without acknowledging the influence of the information collected for studies B and C.

Figure 12 shows how the partial studies inform the research questions and make use of qualitative and quantitative material, while Table 1 provides an overview of the methods used and the resources that informed case studies A, B and C.

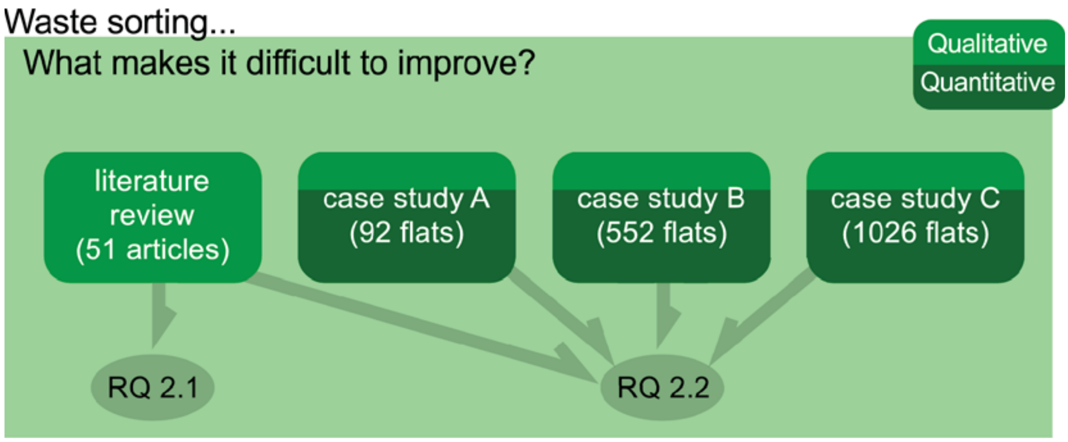

Figure 12: Overview of the studies that form the basis for Topic 2.

A mixed methods approach was considered relevant for the case studies, since different aspects of waste sorting can be best captured with specific methods (the methods used in each case study are shown in Table 1). Waste volumes, waste characterization and sorting errors were considered the most adequate tools to describe actual sorting behaviour. Field observations were used to understand the contextual circumstances of the different sorting systems and provide an impression of what service users do when sorting, while registering weekly variations and sorting errors in the system. Service users were surveyed to gather their opinions and preferences. In case study B the survey was followed up by a more in-depth focus group. Interviews with system managers, maintenance staff and waste collectors helped to understand and describe the administration of the sorting and collecting infrastructure, as well as to inform about the frequent issues that these infrastructures have in daily use.

Table 1: Overview of the methods and resources used to inform case studies A, B and C.

	A: Current state	B: Open/closed tests	C: Seal-able bag
Sorting infrastructure	Sorting rooms	Sorting rooms	Vacuum system
Number of flats	92 in 1 location	552 in 2 locations	1026 in 2 locations
Groups of flats	No	4 groups per location	2 groups per location
Changes introduced	No changes	Seal-able bags and removed bio-waste lid	Seal-able bags
Information campaign	No	Yes	Yes
Waste weight data	Bi-weekly	Bi-weekly	Weekly
Composition study	Mixed & bio-waste	No	Bio-waste
Interview with staff	2 administrators 2 maintenance staff	4 waste collectors 2 maintenance staff	1 waste collector 1 maintenance staff
Field observations	12 weeks	4-8 weeks	2 weeks
Postal survey	19 responses	87 responses	138 responses
Focus group	No	5 participants	No
Reported	Article D	-	-

4.3 Delimitations

Although Topic 2 starts with a broad interest in waste sorting, it only addresses the sorting of municipal solid waste, excluding industrial waste. Institutional waste, which is sometimes included in the definition of municipal solid waste, has also been excluded. This was done in order to exclusively investigate the sorting of common consumer products and packaging purchased by private people through a business-to-consumer model. These type of products have been identified in the introduction (section 1.3.2) as being more challenging to recirculate since they are used in small volumes in a heterogeneous mix by individual users or households, rather than in larger, more homogeneous amounts by industries or institutions (as would be the case for products sold business-to-business). Within household municipal solid waste the case studies in Topic 2 addressed sorting in apartment buildings in Gothenburg, at a building level, not going into each household. The aggregated building level was considered easier to access and redefine, while still being influential for household sorting behaviour. WM in cities in Sweden has a strong emphasis on having waste sorted at the generating source, so the case studies reflect that. This means that other WM approaches, where waste is sorted centrally or by entrepreneurs, are not addressed in this topic.

4.4 Summary of results

The results found in the **review of the literature** are discussed and presented in Article C. Figure 13 shows the result categories and the number of articles that provided input to each category. In summary, the main consensus found in the literature is that convenient physical infrastructure supports sorting behaviour. Another recurrent conclusion is that no single solution is suitable for all contexts. The articles reviewed still seem to present a divide between technology-centric research and research focused on understanding the behavioural aspects of waste sorting. It is crucial to understand how users perceive and interact with the sorting systems. This can only be done by using both empirical data that can describe sorting behaviour and qualitative data that may explain the observed behaviour. Such a combination of methods is only observed in a couple of articles in the review. The literature review also reported that engaging in waste sorting is harder for households living in apartment buildings than it is for those living in detached houses. Therefore, by carrying out the case studies in apartment buildings the households that have more difficulties to engage in waste sorting were targeted .

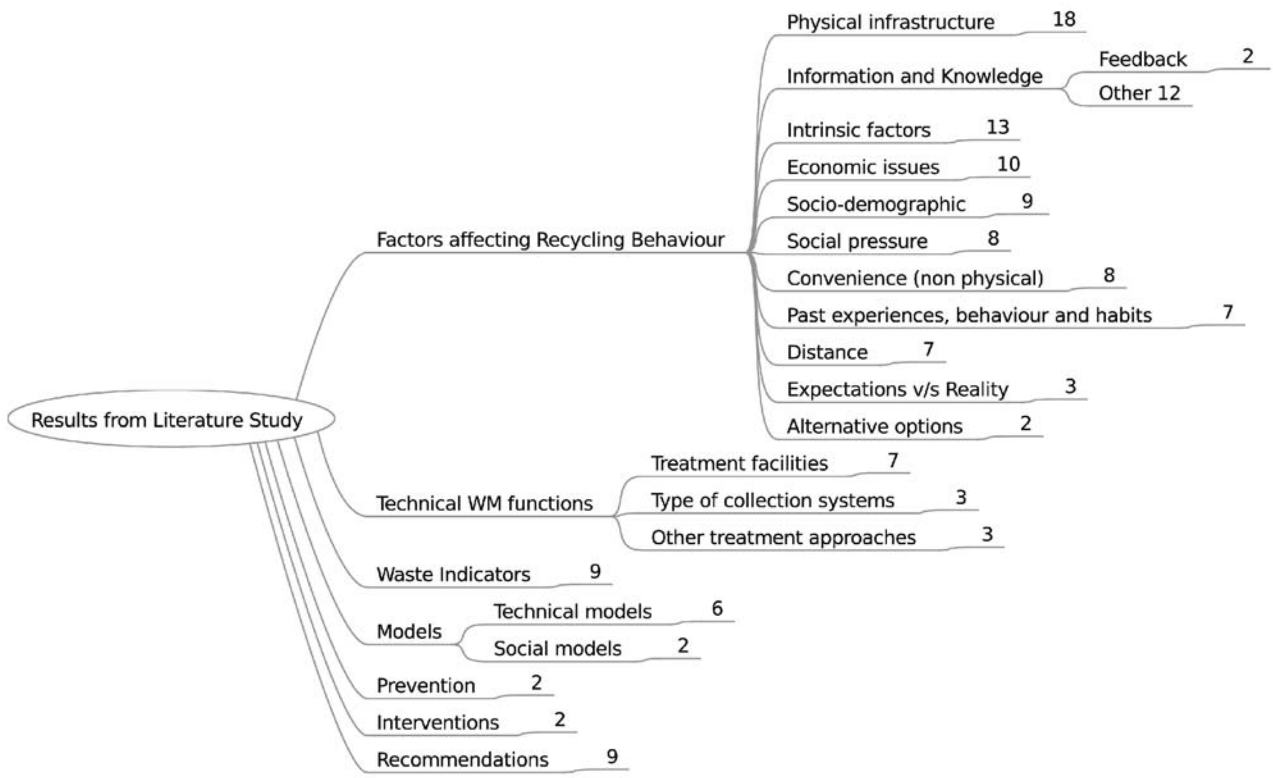

Figure 13: Categories that group the results of the articles reviewed in Article C, organizing the literature results between factors that affect recycling behaviour and other aspects relevant in the development of waste sorting and collection systems.

Some of the methods used in the **case studies** were the same for all three studies. The waste weight data is automatically gathered when waste is collected and was made available for the period of the studies by the municipal office in charge of waste collection. All participating households in the three studies received a postal survey that they had up to two weeks to return. After having a low response rate in study A, study B collected surveys not only through the care takers office but also through a box placed in the waste sorting room that corresponded to the apartments participating in the study. Study C also provided the option to fill in the survey digitally. In the case of bio-waste, the sorting systems studied rely on the use of a disposable paper bag in which tenants collect and transport their bio-waste to the collection point. These bio-waste bags have been specifically addressed in studies B and C.

Study A targeted two suburban buildings in Gothenburg that housed 92 independent households. These buildings made use of waste sorting rooms for their tenants to sort waste; a type of infrastructure favoured by the housing company. The study was set up so that the field observations were made twice a week for six consecutive weeks. The field observations registered the number of sorting errors that could be observed from the top of the bins for recyclable material, photographed unusual elements in the waste bins, and performed the sampling and characterization study for the mixed and biodegradable fractions. The main goal was to identify how much of what was sorted into the mixed waste could have been sorted into the other fractions available is the sorting room. It turned out to be about 65%, with roughly 40% being bio-waste and 25% corresponding to packaging, both paper and plastic. The field observations made evident that electronic waste was regularly being discarded in the mixed waste containers. Also, two sorts of mistakes were identified when sorting into the recyclable fractions; material-related errors and unrelated errors. Material-related errors are those that correspond to the material but are not packaging, e.g. a metallic rod in the container for metal packaging. Unrelated errors are mistakes that seem to have no reasoning behind them, e.g. a pair of jeans in the paper packaging container. More details and results from study A are presented in Article D.

Figure 14: Material related sorting error observed during case study A. The tree is located in the paper and cardboard packaging container.

Study B targeted a total of eight buildings, four in a suburban area consisting of a total of 186 households and four in the city centre housing 366 households. Four buildings were selected in each area because study B wanted to test how using a sealable bag for bio-waste and removing the lid from the containers for bio-waste in the sorting rooms affected the sorting of this fraction. Therefore, in each area one building was used as a control group, while the other three tested the combinations of new bag with lid on the container, old bag with an open container and new bag with an open container. Field observations were made every week for the first month, then once after two weeks and finally once four months after the initial measurements. The idea was to see if these variations motivated tenants to sort more bio-waste, and if it contributed to keeping the containers clean, reduced the amount of flies, or helped diminish smells. The final analysis of the data from study B is still ongoing, but it can be said that the variations did not help keep the containers clean. The effect on the smell and flies in the rooms was not possible to measure accurately, given that many additional factors seemed to affect these aspects. It was observed that several households that had the sealable bag did not close it as intended, while others merely continued using the normal open paper bag. Removing the lid from the containers for bio-waste in the sorting room significantly reduced the amount of sorting errors observed in this fraction. However it was a bit of a controversial issue among the tenants, where about two thirds considered that removing the lid was good, while the remaining third considered this to be undesirable.

Figure 15: Waste sorting room located in the city centre that participated in case study B. This room tested the sealable bags maintaining the lid on the bio-waste containers (brown containers seen at the right side of the picture).

Study C targeted 32 buildings, twelve in a suburban area with 616 flats and eleven in the centre of the city with 410 flats. The buildings were chosen because in each area they share a waste vacuum system, so the same collection point gathers the waste generated in these buildings. The waste vacuums system studied had a intake for mixed waste on each floor and one common intake for bio-waste at the first floor of each building. In each area, the buildings were divided into those which would test the sealable bag and those that did not. In the city centre six buildings tested the new bag and five did not, while in the suburban area eight buildings tested the new bags and four did not. Such an uneven division was necessary because groups of four buildings shared the laundry room where the bags where distributed. Field observations were done on two occasions, where the content of the storage tank for bio-waste was photographed. Given the characteristics of the sorting infrastructure, tenants interact only with the intakes of the system and that experience remained unchanged during the test period. Also because of the infrastructure the characterization study required that the buildings in the study were collected by the vacuum generating waste collector on a special occasion, which was only possible to do once. There it was impossible to differentiate between the material coming from any specific building group, so the entire generated bio-waste volume for that week in the targeted buildings was reviewed. It was found that more sealable bags remained whole after being transported, i.e. 51 whole sealable bags and 12 whole normal bags. Several sorting errors were found, that constituted approximately 20% of the volume of material collected, consisting mostly of plastic, paper and cardboard.

The infrastructure observed in all case studies provided no information about the sorting behaviour of the tenants, e.g. sorted volumes, sorting errors, and the desired behaviour was not communicated beyond providing access to the waste sorting rooms or chutes. When moving in tenants are informed about their available sorting infrastructure and brochures are available through the housing company. The housing company engages in door-to-door information campaigns regularly, but one area will probably not have more than one information campaign every five to ten years. This results in the housing company feeling that they work with informing their tenants all the time, while tenants often mention that they lack information.

Figure 16: Waste collection of the buildings in the city centre that had the vacuum system, studied in case C. In this case the air suction is generated by the collector truck.

4.4.1 How does sorting infrastructure affect waste sorting behaviour?

It became clear during the field observations that waste got sorted depending on how easy and accessible the sorting containers were, e.g. bulky and electronic waste in study A. This complies with the results from the literature review, which found that research mainly agrees on the fact that convenient sorting infrastructure supports waste sorting.

However, convenient infrastructure is not only about easy access to a collection bin. Despite the tenants of the targeted buildings having the same access to containers for mixed and bio-waste in studies A and B, a large fraction of bio-waste was not correctly sorted in study A. This implies that there are factors, other than the distance and ease of access to the collection bin, that negatively affect the ease of sorting bio-waste. Despite most survey respondents stating that they considered the sorting of bio-waste important or even very important, there were some respondents who stated never to sort bio-waste and considered it problematic due to e.g. flies and odours. It was common to hear users question the reliability of paper bags in containing wet bio-waste and plastic bags inside or around the paper bag were often observed in all three case studies.

It is important to note that the waste sorting system at each building is not only limited to the common infrastructure, such as collection bins or intakes, in which tenants discard their waste. It includes the bins used in each household as well as other, non-physical, factors such as information, economic incentives and social pressure, as mentioned in the literature. Information as mentioned earlier, is only based on what behaviour is expected and no consistent feed-back was provided in the observed case studies. Even though the targeted buildings have a collection system that charges them by kilo of mixed waste generated, the tenants in the studies have no economic incentive to sort, since the cost of waste handling is paid by the housing company and divided as a regular maintenance fee among all apartments. In the case of social pressure, it was observed that waste sorting rooms are spaces where tenants might run in to each other and can certainly see what other tenants before them have done. This has an effect on how tenants experience sorting, with literature suggesting that such interactions can be used to positively influence sorting. This social aspect is removed almost completely in the case of the vacuum systems studied in case C. In that case, tenants interact with a waste intake and never see the waste that has been discarded before since these are stored in tanks in the cellar. The fact that the intakes are located in common spaces of the building does allow for some interaction, but it is very reduced, specially in the case of mixed waste, where there are intakes on every floor. These examples make it evident that physical infrastructure is closely tied to the non physical aspects of the waste sorting system, e.g. information, economic incentives and social pressure. Therefore such aspects should also be taken into consideration when designing or improving the physical infrastructure.

In summary, convenient physical sorting infrastructure at a building level supports waste sorting, but other aspects also influence sorting behaviour. This is particularly evident in the case of bio-waste where other aspects, such as the paper bag, odours and flies, seem almost more influential than convenient infrastructure. The design of sorting infrastructure should also consider non-physical factors such as information, economic incentives and social pressure when developing or improving the systems available.

4.4.2 What are the main problems with material sorting in apartment buildings?

Sorting systems in apartment buildings aggregate the waste generated by each flat into one common volume of waste generated per building. This aggregation makes it impossible to determine the sorting behaviour of individual households, since only the behaviour for the entire building can be observed (unless some waste identification system is used). So, aggregated collection makes waste sorting and discarding more or less anonymous. This partial anonymity makes space for undesirable behaviour to pass unnoticed, or if noticed, impossible to associate to those responsible for such actions. As an example, large electronic waste discarded in the mixed waste of a single household living in a detached house would be noticed by the waste collectors. They might not collect it, inform the household that electronic waste should be discarded elsewhere, or even fine the household for wrong sorting. If the same object is discarded in a building, the collectors might not notice it in the larger volume of waste. If they notice it, they can only contact the housing company, so the household that discarded the large electronic device will not know of its error, nor suffer any consequences for its behaviour. In short, aggregated collection makes it difficult to provide feedback on sorting behaviour, thus hindering the possibility to inform users if they have not sorted correctly.

The common areas used for waste collection in buildings also suffer a “tragedy of the commons”. These spaces are not going to run out of resources, but since they are accessible to everybody in the building, individual tenants have a shared responsibility to keep these spaces clean. Given that waste is collected centrally, tenants see how others use the space and contribute or not to maintaining order and cleanliness. Tenants use the common infrastructure constantly and how they use it will have a direct effect on the amount of maintenance needed. The housing company has the responsibility of keeping the common areas and infrastructure in good conditions, but they can only react to how tenants use the spaces, they are not responsible for how they are used.

Households want to sort waste so that it is useful after, but often the categories which are available for tenants to sort do not necessarily match the materials they wish to discard. This mismatch is reflected by the material related sorted mistakes from study A, as well as the presence of specific types of materials in the mixed waste that could have been sorted, i.e. paper and plastic packaging. It is also evident that households discard items that they have no possibility of sorting but that could have been recirculated into reuse or recycling channels, e.g. textiles and items in usable conditions found in the mixed waste of study A.

In summary, the anonymity provided by central collection of waste makes it practically impossible to provide feedback on user behaviour. The infrastructure provided at a building level suffers a "tragedy of the commons" where no tenants feel responsible for the maintenance of the shared space. Even though tenants want to sort correctly, often the categories provided for sorting do not correspond to the items that they wish to discard. This results in tenants disposing of these items into wrong containers or the mixed waste fractions.

4.5 How can waste sorting be improved?

Since buildings gather several households through one infrastructure, the volumes of waste generated allow for some economy of scale, that could justify gathering specific type of discarded materials that are not normally collected, e.g. textiles or things in usable conditions. The collection of textiles was suggested in Article D, since it was the largest fractions found in the mixed waste that was not possible to sort. This was later tested by the housing company in 30 buildings around Gothenburg, collecting over 2 tons of textiles in the first month. The same housing company has a reuse room managed by some of their tenants in one of their districts. The idea of this reuse room is that tenants can leave things in good condition that they no longer wish to have, so that others may buy them for a symbolic price. It might not have a large effect on the waste volumes generated in that area, given that it is open once a week, but it is a way of motivating tenants to try to recirculate items that are in good conditions.

In more general terms, housing companies have the possibility to act as intermediaries between the WM system and the service users. Given that their infrastructures aggregate waste from several households they can reach some sort of economy of scale that might allow them to offer better sorting possibilities than the WM system currently requires of them. Also, since housing companies are in closer contact to their tenants, they could aim to incorporate tenants more actively in the development of their common infrastructure for sorting, making them more participants in defining their sorting possibilities.

In order to improve waste sorting the literature review makes a clear statement that convenient infrastructure supports waste sorting. However, this raises the question, "What is a convenient infrastructure?" Convenience is defined by individual users in a context, and therefore the meaning varies among service users and over time. This is aligned with another result obtained from the literature: there is no one solution that fits all. Both these results argue for a better understanding of user requirements for waste systems and context before defining the sorting infrastructure. However, the literature review showed little signs of integration of the social aspects of sorting behaviour into the development of the waste sorting infrastructure. Although the need to better integrate the social and technical aspects of WM systems has been acknowledged by several authors (e.g. Wilson et al. 2012a; Scheinberg et al. 2001; Troschinetz & Mihelcic 2009; Henriksson et al. 2010), the cases that take such integration to practice are a recent phenomenon, supported in broad terms by the ISWM framework. As explained previously in section 1.2.2, the Integrated Sustainable

Waste Management (ISWM) framework was introduced to help in developing sustainable WM options that make use of appropriate technology that is economically viable and can enable socially acceptable solutions for WM (Scheinberg et al. 2001). The ISWM framework describes WM stakeholders as all the actors that execute the functions defined by the waste system elements, including the service user but not focusing on them. Since it is a broad framework developed for the entire WM system and all stakeholders, it does not provide specific support for understanding the service users' requirements to engage in waste sorting activities.

Much research has been done to investigate the different factors that affect recycling behaviour, e.g. distance to collection bins, collection frequencies, socio-demographic factors, etc. (Tucker & Speirs 2003; Iyer & Kashyap 2007; Gellynck et al. 2011; Åberg et al. 1996; Timlett & Williams 2008; González-Torre & Adenso-Díaz 2005; Oke 2015; Martin et al. 2006; Nigbur et al. 2010; Schultz et al. 1996). Research that has compared the effects that different sorting systems have on behaviour or has introduced changes in a sorting system and measured the effects of such changes on the sorting behaviour are abundant (Bernstad 2014; Refsgaard & Magnussen 2009; Wilson et al. 2012b; Gallardo et al. 2010; Dahlén et al. 2007; Thøgersen 1997; Woodard et al. 2001; Schultz 1999). Less common, to my knowledge, are the studies that have explicitly used action research to support improvements within WM, such as one study focused on construction and demolition waste in the Stockholm region (Aid & Brandt 2010) and two studies focused on minimizing waste generation in households (Fahy & Davies 2007; Farrelly & Tucker 2014). Only a couple of recent studies can be found that improve the waste sorting infrastructure based on user input (Rousta et al. 2016; Blomér & Jansson 2015). This shows that incorporating user input to the development of sorting infrastructures is as yet a new approach. Even though this may be novel in the development of waste sorting infrastructures, it is based on more wide-spread action research routines (Rousta et al. 2016). Also, to understand user needs and requirements is generally considered to be a key factor in successful product development (Engelbrektsson 2004; Cooper 1999; Griffin & Hauser 1993). Different design approaches to product development vary widely on how much they involve users (Sinclair & Campbell 2014), but even the least user inclusive design practice, i.e. the “conventionally designed products” (ibid.), uses information on users to provide a starting point for the creative stage of product development. Therefore, it seems that to include designers, or their methods for understanding user requirements, in the improvement of waste systems could help incorporate user considerations into the system (how designers relate to resource recirculation, as well as how much they participate in developing waste systems is investigated in more detail in Study 3).

In summary, it seems that waste sorting can be improved by providing convenient infrastructure for the service user. Therefore, it is crucial to understand what service users deem as convenient infrastructure. To better understand service users, user requirement elicitation methods, commonly used in the design discipline, might be useful to develop and improve waste sorting systems. In some cases, WM actors are not in direct contact with their service users (e.g. when users live in apartment buildings), making the connection between WM system and service user dependant on another inter-mediating agent (e.g. housing companies). Such inter-mediators could proactively improve sorting system possibilities, before this is required from WM authorities.

5 Topic 3: Waste and design

Topic 3 investigated current design practices and related them to waste generation and WM to describe **in what ways does design currently relate to waste**. The design-waste relation is a term used here to refer to how designers currently understand and act upon material recirculation, as well as how they describe the effect the design profession has waste generation and WM. This design-waste relation was explored through a semi-structured interview study intended to describe existing collaborations between designers and the WM branch. These interviews provided also a list of products considered to be good examples of material recirculation. These examples were then analysed in more detail in a product study. Since the interview study targeted only designers who had actively worked with waste, a web survey was later done to complement the interviews to catch the opinions of a wider group of designers.

5.1 Introduction

Material recirculation has been proposed as a sustainable way of using material resources by several production-centred initiatives (e.g. Industrial Ecology, Cradle to Cradle, Circular Economy). Within production, a discipline that takes an important role in the decision making process for product and business development is design. If production were to implement material recirculation, designers would be aware of it and it would in many ways change the way they do their job. Therefore, to learn how designers currently understand and eventually act to enable material recirculation would give a basis to infer how recirculation could be more widespread. How designers can act to enable recirculation is rooted in their understanding of their profession and how it affects waste generation and management. Thus, both the understanding that designers have for recirculation and waste has been investigated in Topic 3, which provides a broader context for the case studies of recirculation practices explored in the previous topics.

5.2 Methodology

Topic 3 investigated how design currently understands and acts upon material recirculation and waste. Since the aim was to describe a group's understanding of a topic, a qualitative approach was deemed most relevant. The three studies that inform Topic 3 collected qualitative information from different cases of design practices. Given that each study reviews several examples, some quantitative data has been gathered and mainly used to provide a summarized overview of the reviewed cases.

A semi-structured exploratory interview study was carried out with professionals from the WM branch and product designers who had actively worked with waste. The purpose of the interview study was to learn if there were any collaborations between designers and the WM branch and to explore if such collaboration could help contribute to resource recirculation. The interviewees were chosen based on their work, which increased the likelihood of them knowing about possible collaborations of interest or the recirculation of resources in itself. Recruiting interviewees was done by snowball sampling, starting with a diverse group of initial informants from four different geographical locations with both design and waste management backgrounds. This interview study provided material to answer two research questions, **“What resource recovery routes are currently used for recirculating discards?”** (RQ3.1) and **“What kind of collaborations exist between designers and WM?”** (RQ3.2). The material to answer RQ3.1 needed to be investigated further, and so was developed in more detail by a dedicated product study.

The product study, which was based on part of the interview material, responds to RQ3.1. A brief literature review of resource recovery routes was done to help categorize examples of material recirculation obtained from the interviews. The product study investigated those examples further by reviewing published material about the design and production of these examples, often consulting directly with the manufacturers or sales representatives. The gathered information allowed to categorize and compare the examples using criteria that would help better describe them, i.e. are the examples recovered as the same or different products, is value maintained or not, is it hand-made or serialized, does it use pre- or post- consumer waste, is there an existing recycling system for the material or not.

Since the interview study targeted designers who had openly worked with waste, it seemed natural therefore to complement their answers by asking designers who had not necessarily worked with waste, to see if they shared the same understanding for material recirculation and waste and if they saw similar opportunities for action. Therefore a web survey was done to ask a wide group of designers the main question of interest from the interview study, **"Do designers see a relation between design and waste?"** (RQ3.3). To provide a large, group of respondents, the survey was carried out digitally and spread through social media. It consisted of a mix of closed and open ended questions. To provide some context, the survey started by asking questions about the respondents' design practice. These questions investigated if they had used end-of-life (EoL) considerations in their last design project. In the survey EoL considerations where defined as strategies a designer can use to affect how a product will be handled by the user when he/she chooses to discard the product. If the respondents had use EoL considerations they were asked to explain how, and if they had not, they were asked to explain why not. Later in the survey more reflective questions were asked, where the respondents were to describe any connections they saw between design, waste generation and waste management. This was intended to make the respondents reflect about waste, even if they had not mentioned using any EoL considerations in their work.

Figure 17 shows how many cases were reviewed in each study, how much qualitative and quantitative material was used and how these studies inform the research questions of Topic 3.

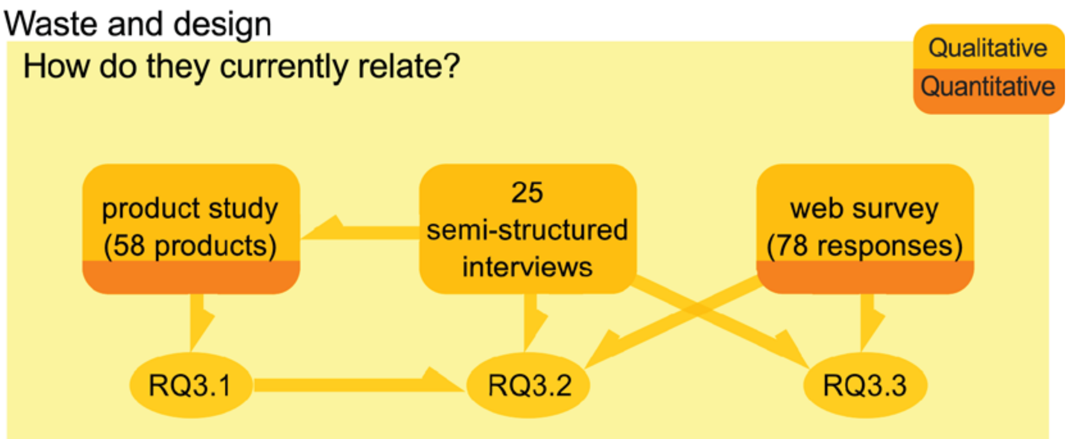

Figure 17: Overview of the studies that conform Topic 3.

5.3 Delimitations

Topic 3 focused only on current and recent design practices that could reflect the latest understandings about the design-waste relation. This means that the designers interviewed and surveyed were asked to reflect on their current views and actions and were not asked to project idealized scenarios in the future or recount how their profession has developed over the years.

Topic 3 was intended to explore the broader context for material recirculation, of which Topics 1 and 2 are specific cases. Therefore, the studies that inform Topic 3 avoided to specify fields in the design profession or waste fractions, in the hope that respondents would not limit themselves when describing their understanding of the design-waste relation.

5.4 Summary of results

All studies in Topic 3 helped illustrate how designers currently relate to material recirculation. The interview study provided four main results:

1. Examples of existing collaborations between designers and waste management;
2. A description of the difficulties faced in the collaborations mentioned;
3. Descriptions of four different WM systems;
4. A list of products that were considered good cases of material recirculation.

Figure 18 presents the first result in the list above: the areas for collaboration between designers and WM professionals. The collaboration areas are ordered here from the most design-centred (far left) to the most waste management-centred (far right). The first four areas can be classified into strategies that either avoid waste generation (i.e. design for durability and design for end-of-life), or recirculate discarded materials (i.e. waste as input material and packaging for improved recyclability). The last collaboration area does not fit into this classification because it does not address the material in use per se. Instead it considers the waste management system as the object to be designed.

Figure 18: Areas for collaboration between designers and waste management.

The second result in the list above were descriptions of the difficulties designers and waste managers had to collaborate. Some of the difficulties described are common to interdisciplinary work, e.g. the use of different concepts and approaches, while three types of difficulties where identified as being specific to the relation between waste and design: waste incineration, the lack of mutual understanding and differences of scale in both professions. **Waste incineration** allows for waste to be considered “environmentally friendly fuel”, which takes away the urgency of having to re-design products for recirculation, thus removing a mayor incentive for collaboration between designers and waste managers. The **lack of mutual understanding** reflected that both designers and WM professionals described the possibilities to collaborate with each other, focused around their needs only. Designers would want to work with WM as material provides, while the interviewed WM professionals did not see that possibility and rather wanted designers to develop better WM collection units. Both groups seemed to lack a broader understanding of how product design relates to waste, that would include the other group's ideas for collaboration. The last type of difficulties was that designers and waste managers work with **different time and volume scales**. Designers focus on one product or product type for several weeks at a time, while waste managers take in large volumes of mixed materials daily. This difference between “detailed” and “bulk” ways of managing materials is a professional gap that should be considered when planning for recirculating materials.

The third result in the list, the description of four WM systems, is presented and discussed in Article E, together with a more detailed description of the collaboration areas and barriers for collaborations presented earlier. The fourth result in the list, the examples of material recirculation, were used to inform the product study presented in Article F.

Table 2: Practical examples grouped by recovery route and described with the chosen criteria.

Recovery route (CE)	Total	Product		Value			Production		Waste type				Recycling system		
		=	≠	<	=	>	*Hand Made*	*Serial*	*Industrial*	*Post-consumer*	*Both mixed*	*Waste prevention*	*Yes*	*No*	*Varies*
Reuse	3	3	-	-	3	-	*	1	-	2	-	1	-	1	2
Maintenance	3	3	3	-	3	3	3	3	-	3	-	-	-	3	-
Remanufacture	22	1	21	2	2	18	12	10	6	15	-	1	5	14	3
Recycle	22	3	22	4	5	13	-	22	1	18	2	1	17	5	-
Biodegradable	3	-	-	-	-	-	-	3	-	3	-	-	1	2	-
Energy Recovery	2	-	2	2	-	-	-	2	-	2	-	-	1	1	-
Total cases summarised	**55**	**10**	**48**	**8**	**13**	**34**	**15**	**41**	**7**	**43**	**2**	**3**	**24**	**26**	**5**
	3	Examples did not fit any recovery routes													
Total Examples	**58**														

(Shaded cells:) Repeated examples that belonged to multiple categories

* Second-hand markets and charity organisations are not production processes to be considered as handmade or serial

The categorization and comparison of the examples made in the product study are summarized in Table 2. The categories used were based on the resource recovery routes described in CE for technological nutrients, adding a category for the biodegradable examples. It can be seen that recycling and re-manufacturing are the most common recovery routes among the examples, with the difference that all recycling is done at an industrial scale, i.e. processing several tons of materials regularly, whereas more than half of the re-manufacturing is hand made, i.e. generating fewer items that are one of a kind. Most examples reviewed increase the value of the material or product recirculated, are serialized and make use of post-consumer waste. This is positive if these examples are to help recirculate large amounts of post-consumer waste retaining the highest possible value. However, the fact that most of the examples reviewed have these characteristics does not mean that this sort of recirculation is most common. Instead, it reflects that these examples, that were considered by the interviewees as good cases for material recirculation, do in fact contribute to recirculation.

The results of the web survey (presented in Article G) show that little over one third of the respondents had used product EoL considerations in their last project (n=28 of a total of 78 respondents). The explanations of how they used EoL considerations where categorized into 14 groups, that were a mix of goals they wished to achieve with their EoL considerations (6 goals) and specific methods they used to achieve these goals (8 distinct methods). The goals described included (but were not limited to) material recovery routes. Survey respondents also described the goals of de-materialization, design for longevity and safe disposal. Such approaches do not aim to recirculate materials, rather they aim to reduce material use (i.e. de-materialization and design for longevity), or strive for minimizing environmental impact through safe disposal. Together, these three different types of goals for EoL considerations strive for resource conservation. Therefore, the ways in which survey respondents described their use of EoL considerations were grouped into six goals for resource conservation, and eight methods used to strive for these goals. Figure 19 shows how respondents described the different methods used to reach some of the goals for resource conservation, so it is not an exhaustive description of all possible methods to be used, showing only the ones mentioned in the survey.

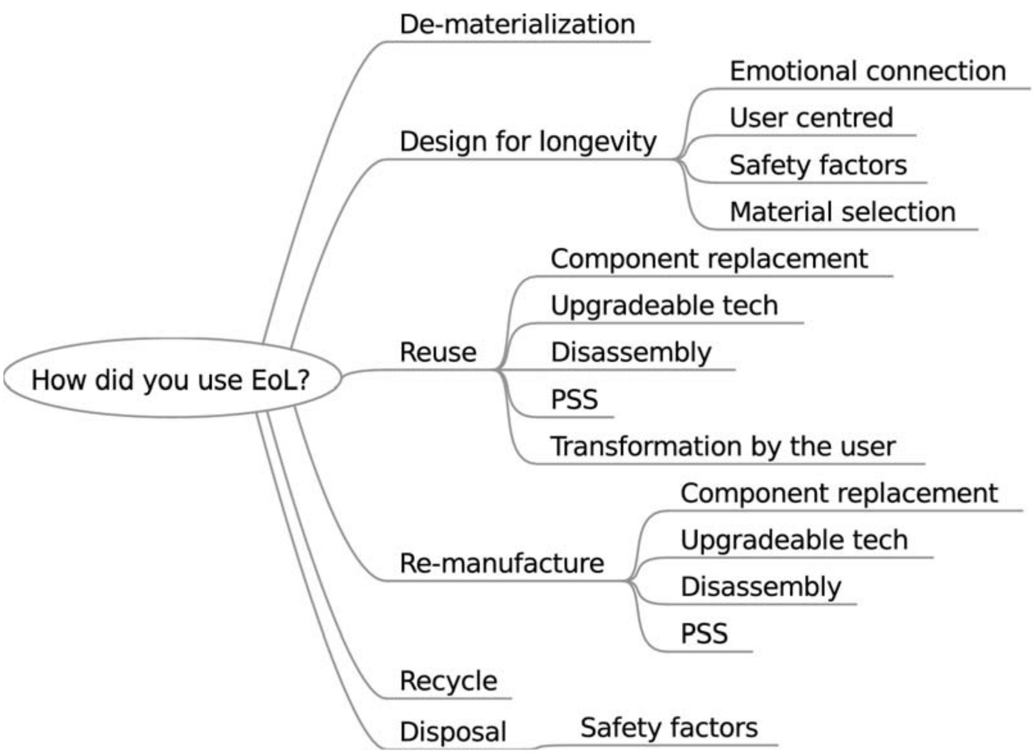

Figure 19: Goals and tools used as end-of-life considerations.

Of the fifty respondents who had not used EoL considerations in their last project, 19 said they would not have wanted to. This lack of interest was the most frequent barrier to applying EoL considerations among the survey results. The remaining 31 respondents explained why they had not been able to include EoL considerations in their last project. These explanations were categorized and complete the list of barriers for considering EoL aspects at the design stage:

- Designer lacks interest in EoL issues (n=19).
- Other aspects were prioritized in the given time frame (n=14).
- The project was an intangible product (n=8).

- EoL aspects were already considered at another stage of the industrial process (n=2).
- Respondents only did the initial design of the project (n=2).
- Respondents did not think about it at the time (n=2).

Most respondents saw a relation between design, waste and waste management. The responses that explained these connections in more detail repeated some of the EoL considerations mentioned earlier, but added also aspects such as: design's impact in defining the waste generated during production and use phase of a product, the need for clear labelling of materials, products used for WM (e.g. composting bins and collection vehicles), the design of WM systems, developing products using waste material and the need to be critical about what things should be produced in the first place.

5.4.1 What resource recovery routes are currently used for recirculating discards?

The product study aimed to describe the resource recovery routes used by the examples for material recirculation gathered in the interview study. However the recovery routes were also present to some extent in all studies of Topic 3. As mentioned in the introduction, resource recovery routes are paths that material resources can take to be circulated back into the production system or use stage. These routes were first mentioned when the European Union introduced its waste hierarchy, also known as the waste ladder in 1975 (Williams 2015). Therefore, they originally appear as strategies for WM to aspire to "move up to", opening the scope of WM goals from safe disposal to include energy recovery, recycling, preparing for reuse and finally waste prevention (EU 2008). Later the recovery routes have been at the centre of all the production centred recirculation efforts presented earlier in section 1.3.2. A brief overview of the literature around resource recovery routes (described in more detail in Article F), provided the following main conclusions: Despite ambitious recovery goals, globally only 30% of the waste collected gets recovered (11% to material recycling and 19% to energy recovery) (Chalmin & Gaillochet 2009);

1. The amount of materials or products recovered through reuse is largely unknown, unless the reuse is enabled by intermediaries;
2. Large volumes of post-consumer products are stocked in the use phase;
3. The re-manufacturing potential of many products is unknown, making this a not well-established practice, with the exception of some high value products (All-Party Parliamentary Sustainable Resource Group 2014).

Based on the questions raised when completing the product categorization and comparison in the product study (presented in Article F and Table 2) a revised view of resource recovery routes was developed (Figure 20). This revised model is based on the recovery routes presented in CE, but maintenance has been removed as a route. The model has three main recovery routes; recycling, re-manufacturing and reuse, based on what product life-cycle stage the resource is recovered into. If the recirculation results in the production of raw material it is recycling. If it results in finished goods after some physical alteration by a manufacturer it is considered re-manufacturing. If it results in goods with no need to modify them in an industry it is reused. Value conservation of the discarded resource is highest when reused, then re-manufactured and lowest when recycled.

Maintenance, repair and relocation are not considered routes per se, but rather strategies used to recirculate materials into any of the other routes. This model reflects the production centred recirculation efforts presented earlier in section 1.3.2, but expands them to include the variations observed in the product study of Study 3. It is proposed as a simplified system view that can help identify what actors could be involved, while broadly categorizing the possible recirculation routes.

Comparing it to the recovery routes described in the EU waste hierarchy and Circular Economy literature, this model presents a more neutral route description, where the production and waste system fulfil equally important functions. The model focuses on recirculation at each life-cycle stage, recovered directly at that stage or discarded as waste to be recovered centrally by the WM system. For the sake of simplicity the model does not include discards passed between use, manufacturing and resource extraction stages independently of the WM systems. It is relevant to mention that the three systems presented in the model, i.e. production, consumption and waste management, all correspond to complex socio-technical systems that have been drastically simplified when included in this model.

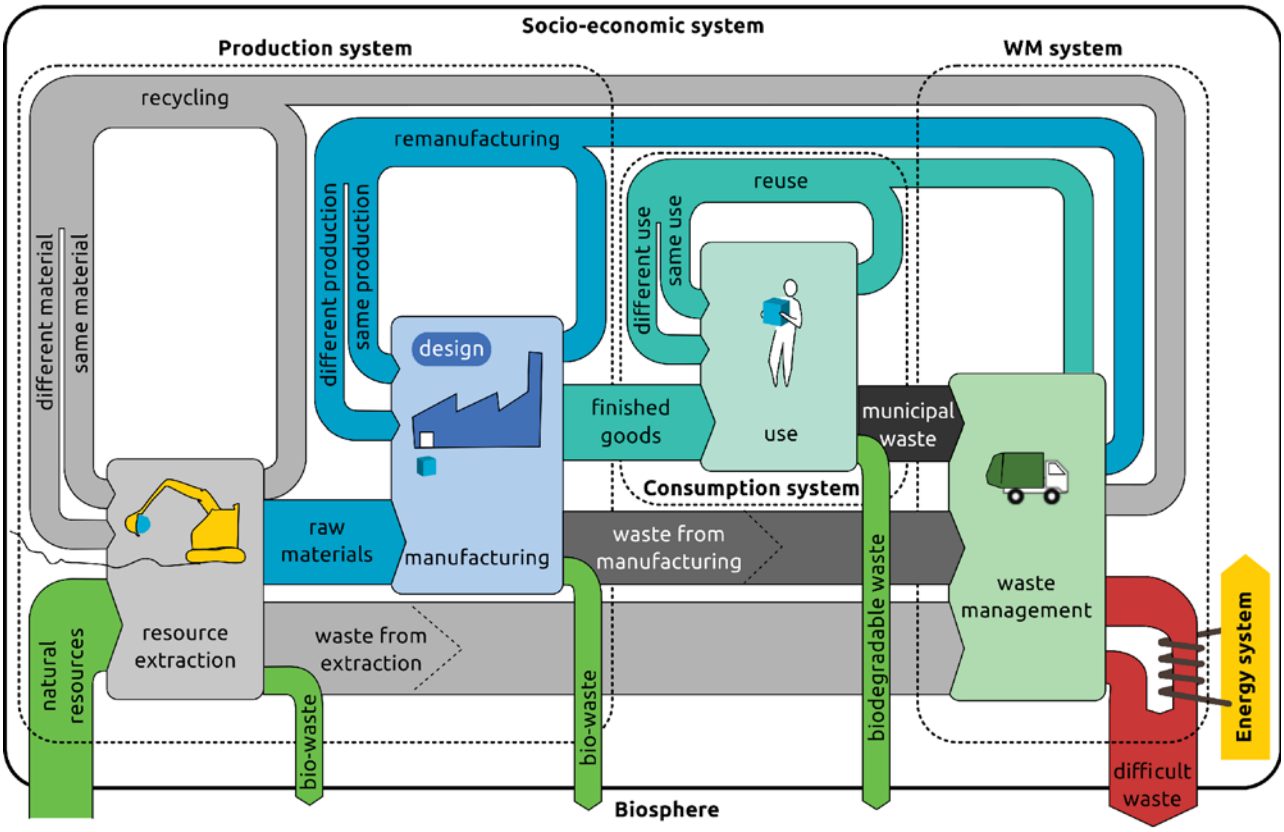

Figure 20: Material flows through society, highlighting the resource recovery routes for discards.

In summary, the resource recovery routes used currently are recycling, re-manufacturing and reuse. The literature shows that most material is recovered today through recycling, since this is the only recovery route that is included in WM statistics. Re-manufacturing is not a well established practice and reuse might happen frequently among users, but is not easily documented. Designers who responded the interview or web survey talked more about reuse, re-manufacturing and strategies for waste minimization than they did about recycling. Given that this is the route that recirculates material into resource extraction it is not surprising that designers do not relate their work to recycling as much as to the other routes. They can choose to use recycled material, but they do not seem to have a role in getting materials recycled.

5.4.2 What type of collaborations are there between designers and waste management?

Only the interview study asked specifically about collaborations between designers and waste management, resulting in the collaboration areas described in Figure 18. However, the collaborations described in the interviews were not only direct results of designers working with WM companies. The examples mentioned in the categories of “design for durability” or “design for end-of-life” were ways in which designers avoided waste generation or planned for a specific type of disposal and by doing so affected WM indirectly, without the need to work with WM professionals. These **indirect collaborations** affect waste volumes, but have no direct collaboration with the WM branch.

The following two collaboration areas in Figure 18, “waste as input material” and “packaging for improved recycling”, aimed at recovering resources, and are easily related to the recovery routes described by the product study, shown in Figure 20. Depending on how the recovery was achieved, it could be done by designers on their own (e.g. designing packaging for improved recycling by choosing a material commonly collected by the WM system), or it could benefit from collaborating with WM professionals (e.g. using waste as input material for production is facilitated if the designers can obtain the desired materials directly from WM actors). Thus, material recirculation can be achieved with or without a close collaboration between designers and WM professionals. These **potential collaborations** have in some cases designers working together with WM actors, but can also be done by designers on their own.

The last collaboration area from Figure 18, “waste system interface”, considers the waste system as a design object, and therefore requires an **intrinsic collaboration**. This is also the case for “products used in WM” that were mentioned in the web survey responses. These are areas where design is put to the service of WM, to develop the products, services and systems that will manage waste. This requires designers to collaborate closely with WM actors, who in these cases are the ones that define the design brief, act as clients and are eventually the users of the elements to be designed. Such intrinsic collaborations can only be done with designers and WM actors working closely together.

The EoL considerations described by the respondents of the web survey repeat some of the collaboration areas in Figure 18 and the recovery routes described in Figure 20. Here too some responses corresponded to indirect collaborations that aimed at avoiding waste generation (i.e. de-materialization, design for longevity), while others were potential collaborations that strived for recirculating materials to a specific resource recovery route (i.e. reuse, re-manufacture and recycling).

In summary, three types of collaborations between designers and WM actors were found; indirect, potential and intrinsic collaborations. Indirect collaborations correspond to designers avoiding waste generation. In this case designers indirectly affect, but do not collaborate with WM. Resource recovery strategies are potential collaboration areas, since they can be done by designers or WM actors on their own, as well as in collaboration with each other. Intrinsic collaboration is needed in the development of products for WM and waste system interfaces, since in this case WM actors are the designers' clients and potential users.

5.4.3 Do designers see a relation between design and waste?

As expected, all the designers consulted in the interview study who had actively worked with waste in some way, saw a relation between design and waste. They described the nature of the relation both in examples that linked design to waste generation (e.g. designing for reuse, long lasting products or smart separation of materials) and possibilities for waste management (e.g. the design of waste containers and the information provided about source separation). Therefore, when developing the web survey, it was deemed relevant to divide this question into two, "Does design relate to waste generation?" and, "Does design relate to waste management?"

The respondents of the web survey had not necessarily worked with waste. Although definitions of waste generation and waste management were provided along with both questions addressing these topics, it seems that the respondents did not fully grasp the difference between the two questions. However, they still said they saw a connection between design, waste and waste management (with 62 of 64 respondents seeing a relation to waste and 58 of 61 relating it to waste management). As did the responses from the interview study, the examples given by the survey respondents included explanations that linked design to waste generation as well as waste management. Some examples were repeated from the interview study, while others were new.

Compiling all the answers from the interview study and survey, it became clear that designers described a wide range of examples to help illustrate how they understood the design-waste relation. They did not necessarily make the distinction between waste generation and waste management, and rarely described more than two or three different aspects of the relation at a time. The designers that responded the interview or survey were, as a group, aware of and discussed multiple aspects of the design-waste relation, but the individual responses normally provided only a narrow view of how design related to waste. In summary, designers identify a relation between design and waste, but usually provide a partial, unstructured description of this relation.

5.5 How could design contribute to material recirculation?

Designers are aware that there is a relation between their profession and waste, and that there are strategies that they can use to positively contribute to resource conservation. They describe several strategies that have different underlying goals, so exactly how designers work, or can work, towards resource conservation remains confusing.

A comprehensive, structured, description of how design can act to prevent waste, based on the reflections designers make about their professional role has been lacking. In an attempt to provide such a description, the answers from the interview and survey studies were grouped into categories that could be organized into a model. This model, shown in Figure 21, attempts to provide an overview of the strategies designers can use to contribute to resource conservation.

The model in Figure 21 organizes the strategies according to the different stages of material flow through society (shown as columns in the figure) and the underlying goals that these strategies have (rows in the figure). When describing the goals, the broader category of resource conservation (described earlier in page 50) reappears. The strategies circled in Figure 21 were not mentioned in any of the studies of Topic 3, but were completed by the author of this dissertation based on sustainable design literature. This means that the circled strategies are not frequently considered by designers as strategies they can execute. It is interesting to note that the term "design for End-of-Life" which is commonly used in sustainable design literature, is more of an umbrella term that refers to several strategies for improved waste handling and is not a single strategy. The design of WM systems initially started with the sole goal of minimizing environmental impact, but as discussed in section 1.2.2, has evolved to aim for resource recovery. For this reason it is shown in the middle row in Figure 21. Since the model categorizes strategies based on their underlying goal, it could assist in the choice of strategy, depending on whether it is more pressing to reduce environmental impact, recirculate resources or minimize resource use. The categorization by life-cycle stages helps identify what actors should be involved in implementing the different strategies, like it does in the description of the resource recovery routes.

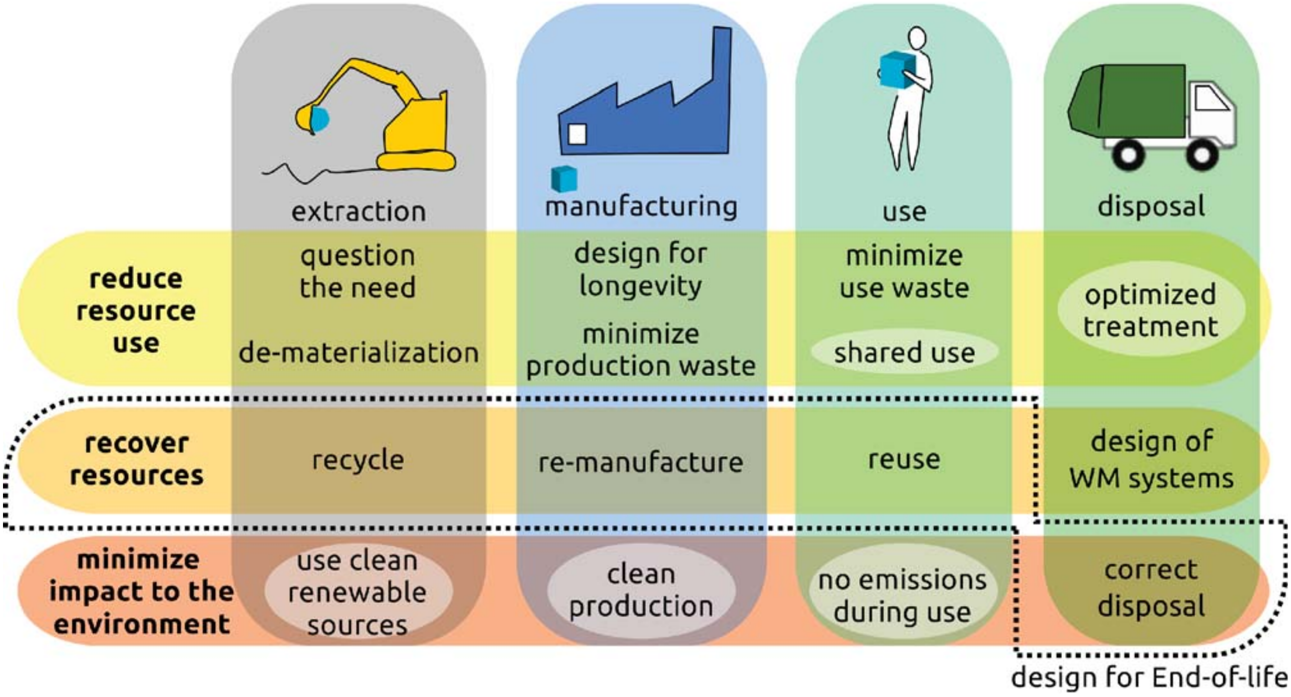

Figure 21: Ways in which designers can contribute to resource conservation organized by stages of material flow through society (columns) and underlying goals for resource conservation (rows).

Figure 21 shows a model that is beyond the original research interest of this thesis (i.e. material recirculation). This is because the questions that were posed to designers about their relation to waste resulted in a broader view of sustainable material use, namely resource conservation. This has the advantage that it provides a broader frame to understand the issue of sustainable material use (including all three goals listed in the rows of Figure 21), but has the disadvantage that it might take away detail from the original topic of interest. Most of the strategies to reduce environmental impact were in fact obtained from sustainable design literature, rather than mentioned by the respondents. The goal of minimizing environmental impact appeared in the model only because respondents described designing for correct disposal of hazardous materials. When that goal was contrasted with the other product life-cycle stages, the author searched to see if there were strategies in the literature that would help fill in the empty sections. This led to investigating if there were other strategies that could complement and support the sections already described by the study results, resulting in also including shared use as a strategy in the model. More strategies could be added if a more extensive literature review were to be done. However, the intention of generating this model was to provide a structure to describe how designers can relate to waste, rather than providing a comprehensive list of all strategies for resource conservation.

According to the survey, a third of the respondents had applied EoL considerations in their latest project. Considering that the designers who answered the survey are most likely interested in waste topics, this result is disappointingly low. The fact that they reported using EoL considerations does not guarantee that materials have indeed been recirculated, it only states that how the products will be handled at their EoL stage has been considered when developing the product; as a designer mentioned in the interview study: "You can design for recycling, but who ensures it will be recycled in the end?" How effective the use of EoL considerations is to enable material recirculation in practice depends on how well the designer understands the possible recovery routes and the roles that relevant actors have in this process. In other words, the designer needs to have a good understanding of "the bigger picture" in which material recirculation happens. To what extent designers are aware of these recirculating systems remains unclear.

Designers are limited by their daily work situations. The main barrier for using EoL considerations at work, after lack of interest, was having to prioritize other aspects in the product development, given the limited time frame designers had (as reported by the survey study in Article G). When waste prevention or sustainable material use are not present in the design brief, these aspects are by default considered to be of lesser importance than the aspects specified in the brief. Tight time frames for product development reduce the aspects that designers can consider when creating solutions, so the features that are not required from the manufacturer or client fall out of the development process. To facilitate sustainable material use being considered in the design stage, it should be explicitly included in the design brief as a functional requirement, as suggested by Deutz et al. 2010. Deutz et al. suggest this as a possible point for policy intervention, claiming that a strong regulatory push is needed to counteract the market-driven pull for the cheapest solution (ibid). With the latest European action plan for a Circular Economy, it seems that policy will start to push for more effective recirculation measures, at least within the EU (European Commission 2015). This was even commented by one of the respondents of the web survey, who did not use EoL considerations and had no interest in using them, claiming that "consumption and fashion are changing because Circular Economy is becoming enforced now". This response gives the impression that if Circular Economy is enforced "externally" by changes in consumption or fashion, then designers would not have to worry about EoL strategies since they would be "taken care of elsewhere". This completely contradicts what Deutz et al. suggest and removes responsibility from designers claiming that consumption and fashion changes, generating changes in design, rather than vice versa.

Based on the product study it can be said that the re-manufactured examples were mostly all recirculation provoked exclusively by designers. Given that designers participate in manufacturing, it seems natural that they would favour re-manufacturing over recycling or reuse. Most of the examples for reuse did not require designers to motivate recirculation, as this was instead enabled by the users themselves. Most recycled examples mention the recycling of different types of materials (e.g. glass, aluminium or PET), suggesting that the existing recycling industries drive that recirculation without needing designers' support. There were however two cases in the product study where designers were the ones that proposed new recycling or reuse paths, i.e. plum core agglomerate used for making planters and glass containers for food designed as drinking glasses. This means that even though designers mostly contribute to recirculation through re-manufacturing they also can successfully design for reuse and recycling. Better insights about how to facilitate material production and reuse might support designers in contributing more to these recovery routes.

The design of WM systems is the only strategy to support resource recovery in Figure 21 that is not covered by the resource recovery routes discussed earlier. Two examples of products designed for WM were described in the interview study (i.e. the development of waste collection trucks and a container for electronic waste disposal), while several other products used in WM are known to have been developed with or by designers (e.g. waste bins, collection points, information campaigns). Five survey respondent commented that design would be a relevant tool to develop better WM systems, with one stating that “WM needs better user experience design”. This is very much in line with the results from Topic 2, which suggest that designers could help improve waste sorting systems, as a way to get WM to have a better understanding for its service users. Given that WM is to some extent a bottle neck in the recirculation flow (consider Figure 20), improving waste systems seems to be crucial to increase for resource recovery. Therefore, for designers to help improve the WM system would be, in the author's opinion, the most substantial contribution to recirculation possible.

In summary, it is argued here that designers could contribute to more material recirculation if they had a clearer and structured understanding of how design relates to waste, the possible resource recovery routes, and the relevant actors linked to each route. Ideally the models presented in Figures 20 and 21 would help facilitate this understanding for designers as well as other stakeholders. Currently designers work from and focus on manufacturing, making them prioritize re-manufacturing when recirculating materials. However, if they can help to define how materials are made, how products are reused and finally discarded, they could significantly expand their potential contribution to material recirculation. Furthermore, if policy would enforce sustainable use of resources as a functional requirement for design, design would be obligated to design for recirculation.

Material Knowledge
More Time
Lack of Info
Complex WM
Solutions
Hinders
Topic 1
Topic 2
Topic 3

6 Transversal analysis

Based on the three topics presented in chapters 3, 4 and 5, this section aggregates the main results in order to provide more general answers to what hinders material recirculation in practice and how it can be facilitated.

6.1 What currently hinders material recirculation?

When comparing the barriers described in the three topics that comprise this doctoral thesis, some common themes emerge. These themes are present in all three topics, though in slightly different forms, providing a glimpse of the underlying issues that persistently work against material recirculation. Table 3 shows the different barriers from the reviewed topics and how they aggregate into six themes.

Table 3: Barriers from the three topics and their common themes.

Themes	Designing with Waste	Waste Sorting	Waste & Design
Complexity of sustainable WM	Needs materials well sorted, collected and processed	Sorting is affected by several variables and involves many actors	Designers need to understand waste handling to plan for it.
Material knowledge	Need of reliable material information	Different views on material types	Recycling needs more material knowledge
Lack of information	Lack of material info. and a design brief	Uncertainty in sorting possibilities	Extent of re-use is largely unknown
Undefined responsibilities	Unclear who should push for using discards	"Tragedy of the commons"	Other people take care of it
Lack of control	Unavoidable material irregularity	Aggregated waste gives anonymity and lack of control	Designer loses control after the product is made
Requires additional time / effort	Longer development times, since more steps are needed	Requires more effort to sort, than not to sort	Little time for development, so other aspects are prioritized

Of the themes that emerge from Table 3, the complexity of sustainable WM and material knowledge are themes that are specific to the challenge of material recirculation. The remaining four themes can be grouped together as problems common to project management; lack of information, undefined responsibilities, lack of control and more time/effort required. This is interesting, since converting material use in society to a circular production model can be considered to be a project. If so, recirculation efforts could make use of project management research to address recurrent problems. However, the main difficulty is that material recirculation is a project to be done by society as a whole, involving people in their different roles of material providers, manufacturers, users, waste generators, waste handlers and eventually recirculators. Since so many actors are involved and the project aim is a vision for sustainable material use, recirculation might be better classified as a societal transformation challenge, that has a broad overarching goal that needs to be executed through changes in all the different levels of the system.

6.1.1 Complexity of sustainable waste management

As presented in the introduction (i.e. section 1.2) WM is considered a complex socio-technical system. When waste systems are expected to contribute to material recirculation by sorting discards into separate fractions to be handled in different ways, the situation becomes even more complicated. As presented in Topic 2, waste sorting is affected by several variables, involves several actors and is user and context dependent. These characteristics make improving waste sorting a challenge. However, as discussed in Topic 1, adequate material sorting is crucial to be able to use secondary materials in new production. Waste sorting is therefore a challenge that cannot be avoided if material recirculation is to be achieved. Another aspect that contributes to WM complexity is that it varies from one location to another (as described in Article E). This location variability makes it difficult for designers to plan for a specific EoL solution for their products. Designers do not necessarily know what WM options will be available where and when their products are eventually discarded. This is aggravated by products being sold on a global market, so the same product will eventually be discarded into several different waste treatment possibilities.

In summary, sustainable WM is a complex system that is difficult to understand and thereby develop, given that it takes on so many forms, different solutions and involves such a multitude of actors. Models and frameworks to understand WM exist and are crucial tools in working towards WM improvement. It is important that these tools are spread among all relevant stakeholders, and not only used by WM actors.

6.1.2 Material knowledge

Given that the subject matter of this thesis is material recirculation, it is not surprising to see that material knowledge is a recurrent theme in all the topics covered. The material knowledge required in Topics 1 and 3 are basically the same; a good understanding for the material, its properties, how it would vary with use, production processes, material contamination and reprocessing. This type of information is necessary for recirculating agents to understand how these materials will react if eventually recycled or re-manufactured. This type of material knowledge is currently mostly lacking for non-recirculated materials. The material knowledge needed for waste sorting is easier to come by. The main problem in Topic 2 is that the material types offered by the collection system do not always match the service users understanding of what they want to discard. This mismatch leads to confusion and makes sorting difficult for the user.

Also, accurate information of what materials products are made of is essential to be able to make use of the constituting materials or components again. This might seem obvious, but it remains difficult to implement. The main barrier is that manufacturers do not openly share their bill of materials, since this would be to give away what makes their products unique and their competitive advantage. This has made recirculation promoters suggest extended producer responsibility (EPR) so that manufacturers who know the exact composition of their products would be the ones to take them back for recirculation (Lindhqvist 2000). Unfortunately the implementation of EPR has gone through Producer Responsibility Organisations, created to aggregate the efforts of producers in a specific sector. This allows for the sector to jointly finance the collection and treatment of products at their EoL, improving recycling and safe disposal, but rarely resulting in re-manufacturing, component recovery or improved eco-design of products (D. E. European Commission 2014).

Shortly put, more transparency around what materials products are made of is necessary to allow for recirculation by many actors. This needs to be complemented by good understanding for the materials recirculated, their properties, how to handle eventual impurities, what production processes they can be submitted to and how they are expected to vary with use. For these materials should be adequately separated the sorting categories should be well understood by all.

6.1.3 Lack of information

Besides the lack of adequate secondary material knowledge, other types of information have been noted to be missing in the studies that conform the topics. The lack of a recognizable design brief in

Topic 1 contributed to more uncertainty among the students who tried to design with waste. They had to define a more specific brief by investigating possible application areas and identifying possible product improvement opportunities. If they would have collaborated with a manufacturer, the manufacturer could have provided a brief based on their product development experience. However, to identify a relevant manufacturer is challenging when feasible application areas for the targeted material are still undefined. The confusion around sorting possibilities experienced by tenants in Topic 2 (i.e. confusion when sorting paper, the observed sorting errors in packaging and mixed waste) were due mainly to a lack of communication between the tenants and the housing company that provided the sorting infrastructure. The case studies carried out were a first approach from the housing company to better understand how their tenants sort waste, collecting their opinions in a survey with an invitation to suggest improvements and voice their complaints. Hopefully this was a first step in continued work to establish better communication between them. Topic 3 mentions that the extent to which objects are re-used is largely unknown. This information is lacking because it is the result of the actions of several individual users. When re-use is done by intermediary agents (i.e. like second-hand shops or web pages) this data can be aggregated and collected. Product users are important actors in recirculation, but they are not an organized group, making this a difficult stakeholder to address when promoting recirculation.

Briefly, the main reason that lack of information was observed in all three topics was because of poor communication with the relevant stakeholders that could have provided such information. In the example from Topic 2, both stakeholders were easily identified and already had an existing relation to each other. They just failed to communicate effectively. In the examples from Topics 1 and 3, the relevant stakeholders could not be addressed because these were either unidentified (as in Topic 1) or were not a single stakeholder, but a broad group acting independently (as in Topic 3).

6.1.4 Undefined responsibilities

The W2D project in Topic 1 was an attempt to bring waste materials to production, promoted by the industrial recycling partner in the project. As such, it was a WM actor that tried to push this specific case of recirculation. However, the project lacked production know-how and would have benefited from having manufacturers involved. It is yet unclear if production or WM should take on the role of recirculators, if both sectors should do this as independent efforts, if they should attempt recirculation together or if a third recirculating sector should appear. In Topic 2, although it is clear that tenants are intended to sort their waste and since they collect the waste in a central location, the responsibility of the total collected waste is shared among all tenants. However, this shared responsibility dilutes the sense of accountability for each individual tenant, making it also practically impossible for the housing company to address the problem of tenants who make sorting errors. Similarly in Topic 3, some designers responded in the web survey that EoL considerations were taken care of by other people in the production system, whereas one third of the respondents said that they implemented EoL considerations when designing. EoL strategies need to be applied in production, but who should apply them might differ between manufacturers and might even be unclear in some cases.

In general, it can be said that when several actors are involved in achieving a goal, who should do what, and even who does what might become unclear. Large groups provide anonymity and with shared responsibility there is the possibility of shifting blame to other actors not performing as desired. Since material recirculation is a task involving the entire society, this is bound to happen.

6.1.5 Lack of control

It was mentioned in Topic 1 that discarded materials are unavoidably irregular. This is because, in the case of post-consumer waste, these have been handled by so many actors in varying conditions that they have worn differently. It is impossible for anyone to control how different materials are worn out, making secondary materials irregular. The lack of control described in Topic 2 originates from aggregating the waste sorted, making it difficult for the housing company to identify tenants who are not participating in waste sorting efforts. Despite the housing company being responsible for getting the waste collected and treated, they have no control over how it is generated or sorted and so can only react to the volumes generated. Similarly, designers may have an intention with the products they develop, but they are not the ones who use and later discard these items. In the best of cases designers can try to influence user behaviour to get them to use and discard products in an environmentally friendly way, but it is only the users who can decide to control their actions.

It can be concluded that lack of control appears when there are many actors involved in a task, as do undefined responsibilities. All the examples of lack of control from the topics discussed here point to different stakeholders not being able to control how users will behave (i.e. material providers in Topic 1, housing companies acting as sorting actors in Topic 2 and designers in Topic 3). Users are the most unpredictable of stakeholders since they are so many individuals that act independently. Users are practically impossible to control, but they can be influenced. Marketing is a great example of how people's actions can be steered. Influencing people to behave in more sustainable ways should therefore also be possible. This is in general terms what the field of Design for Sustainable Behaviour aims to do (Strömberg et al. 2015; Renström et al. 2013).

6.1.6 Additional time and effort

Topic 1 showed that designing with waste takes more time than regular product development. Respondents in Topic 3 talked about limited time for product development, in which aspects such as EoL considerations ended up not being prioritized. This suggests that since product development is already done under tight time frames, the additional steps needed to design with waste will not be welcome in current production systems. In a profit driven production paradigm, the additional efforts needed to design with waste will only be accepted if they can be economically justified. If, for instance, secondary material were always cheaper that the virgin material it replaces, then this price difference might pay for the additional effort of designing with waste. However, given the material markets volatility, this is not necessarily the case.

Although time was not directly mentioned in Topic 2, the results suggest that waste sorting requires more effort than not to sort waste. Users need to consider this additional effort justified in order to want to engage in sorting. Most survey respondents from case study A in Topic 2 claimed that they sorted waste because it was better for the environment (18 of 19 respondents) or that it made waste collectors' work easier (15 of 19 respondents). However, these responses account only for tenants who were engaged in sorting and voluntarily answered the survey which had a low response rate (21% of the tenants responded). Some tenants may not consider these reasons enough to justify the additional effort that is required of them, and therefore do not engage in waste sorting.

Summarizing, implementing circular use of materials in society will require more time and effort than simply using materials linearly, mainly because of the inertia we currently have built into the production, consumption and disposal systems. The perception of these additional efforts differ between the participant actors and a clear definition of responsibilities to allocate these efforts, as well as the motivations to justify them for each actor, are unfortunately lacking.

6.2 How can material recirculation be facilitated?

The three topics that comprise this thesis end with suggestions for facilitating recirculation for each specific topic. Table 4 aggregates the main suggestions from each topic in two main themes. These themes are described in this section to then be visually summarized in Figure 22. Afterwords, specific emphasis is made to highlight critical aspects that differ between WM and production systems, to provide starting points for potential collaborations among these stakeholder groups.

Table 4: Suggestions to support recirculation per topic, grouped in two main themes.

Themes	Designing with Waste	Waste Sorting	Waste & Design
Regulations to support material recirculation	Process secondary materials to ensure quality and relevant properties	-	Policy can be used to require recirculation by producers at the design stage
	Collect more materials than what is currently recyclable		
Better understanding among actors	Collaborate with material experts and potential manufacturers	Sorting infrastructure should meet user needs, so understanding users is vital	Involve designers also in areas other than manufacturing
		Intermediaries between users and WM could be proactive to improve sorting	Better understanding of the resource recovery routes and the actors involved
		Better integrate the social and technical aspects of WM	

6.2.1 Regulations to support material recirculation

Knowledge about secondary material needs to be systematically developed. Secondary material is inevitably irregular, so when discarded these materials will need to be processed and tested to assure a certain material quality. This happens today with materials that have existing recycling markets (e.g. metals, glass and paper) but is still noticeably lacking for other materials, such as plastics and textiles. Research efforts should be made to develop processing procedures for the materials that currently can only be re-used or downgraded. Within the action plan for a Circular Economy the European Commission states that they will launch work to **develop quality standards for secondary materials** where they are needed (European Commission 2015). Such standards would be a great support to facilitating more recycling and re-manufacturing in the future.

Furthermore, the material and chemical content of products should be made more transparent. As commented earlier, manufacturing today does not disclose the exact composition of the products they make. Policy can regulate that specific materials or chemicals should be declared or banned from certain types of products (e.g. toxic substances in toys or materials in contact with food), but current regulation aims at avoiding "substances of high concern" based on their potential negative effects on human health or the environment (European Chemicals Agency n.d.) rather than providing an overview of the material composition of the products traded in society. Urban metabolism models try to give an overview of the material and energy flows through cities, and as such could be useful to make estimations about the materials that are traded within a city or region. However, **more transparency about the materials used in society** is needed if we wish to recirculate those materials back into new production. Given that EPR efforts have failed to bring materials back to their manufacturers of origin and other actors have taken over the task of recycling them (as explained previously in section 6.1.2), a reliable system to pass information and enable collaboration between manufacturers and their respective recirculating agents might enable a recovery of higher quality than the level possible today.

WM has to be able to provide materials that can meet the future material quality standards for production. Currently however WM still struggles with sorting the fractions that have established recycling markets. This needs to be significantly improved so that **all useful materials should be recirculated and the recirculated materials should aim to cover the totality of the materials used**. Given that waste sorting is so crucial for material recirculation, the design of waste management systems (focused on waste sorting) should be given the highest priority among the strategies for resource recovery identified in Topic 3. In recent years WM actors have increasingly moved into their role as material providers for production. As an example, during the time span of this PhD work, the WM company in Gothenburg has gone from not seeing their role in resource recirculation (as expressed in Article E) to engaging in the re-manufacturing of plastic tubing from the construction waste they collect (presented in their yearly environmental seminar in early 2016). In this case it was the WM company that carried out the re-manufacturing, initiated the idea and produced it. As a pilot test to see if it was possible, this was done in parallel to their regular activities, but to scale up the process collaborating with a manufacturer is probably needed. The question here is: who is best suited to find uses for discarded materials? In this case it was done by the WM company. In the W2D project it was expected from the design students at the request of a recycling company. In both cases WM actors initiated the search for material use. However, as suggested in Article A, the students might have come further in their product development process if they had a receiving industry that could manufacture their suggested products. WM actors know what materials they have available, but manufacturing industries know what materials they can use.

6.2.2 Better understanding among actors

Material recirculation is a joint social project and as such can not be achieved by one branch working on its own. It has been argued that isolated material recirculation efforts are not enough for achieving long term sustainability (Singh 2013). Singh argues that there is a need for a **shared vision among actors involved in production, consumption and disposal activities** (ibid). However, here is where project management problems start to arise; who should take the initiative to create a common vision? Given that it is a project to transform society, this role may fall on the governing authorities. Within Europe this topic has been taken on by the European Commission and regulations around WM and production have been influenced by a desire to support material recirculation. How representative such regulations are of a common vision and how many actors will be included when developing said vision and specific goals will depend on the political structures available and will most probably influence whether or not the goals will be achieved.

If considering a simplified material circulation system, three groups of stakeholders remain crucial; producers, users and waste managers (as also described by Singh). It is important to mention that the users are consumers of the finished goods made by producers, while at the same time being users of WM services. The design profession has specialized in taking in user requirements to product development at the production stage. WM requirements for manufacturing have appeared as design strategies, such as design for recycling, design for repair or design for end-of-life, to mention a few. As is done in production, WM should strive to take their users' requirements into consideration. If seen as a service provider, WM systems have two main user groups; On one side, citizens who generate discards that have to be handled, and on the other, production industries that generate waste, but can also make use of discarded materials for new production. The better WM systems can address the needs of both these user groups, i.e. facilitating sorting and discarding, while also providing quality consistent secondary material, the easier it will be for WM to recirculate material resources though society. Design as a discipline that fosters understanding for users and links it to what is technically possible could provide valuable input in developing WM systems so that they better meet the needs of these two different types of users. In other words, **to advance in designing out waste, we need to have designers not only at the manufacturing stage, but also have designers who are more active and present in the WM branch**.

WM has been regarding waste as a source of valuable resources since the 1990s and because of this has been **improving waste sorting and collection** gradually since then. By including waste prevention and material recirculation as goals for WM (EU 2008; European Commission 2010), authorities have expanded the possible actions to manage waste from traditional collection and disposal to also include actions at the production and use stages. Some of the aspects relevant to connecting WM to production have been presented earlier (i.e. quality of secondary materials, better communication through collaborations), but, in what way can WM influence user behaviour? Topic 2 shows us that the design of the waste systems already does this. Infrastructure influences behaviour, therefore sorting and collection infrastructure should be developed to support effective waste sorting. Despite that there is much research and several projects that have tried to improve waste sorting infrastructure, the materials sorted are still far from the total of discarded materials, making this a well studied but still unsolved problem, even in places like Gothenburg that has well established recycling infrastructures. Topic 2 argues that a **user-centred development approach might be helpful in identifying how to support sustainable sorting behaviour**. Currently sorting and collection systems are not developed with user-centred considerations, since the optimization of the more technical aspects of WM tend to guide the overall system design (as reflected in the literature review results in Topic 2).

In order to summarize the suggestions made in this section and to help the reader gain a integrated view of how such suggestions could affect a potential recirculating system, they have been visually summarized in Figure 22. Further detailing into what aspects could be addressed to help bridge the material flow gap between WM and producers, follows in section 6.2.2.1.

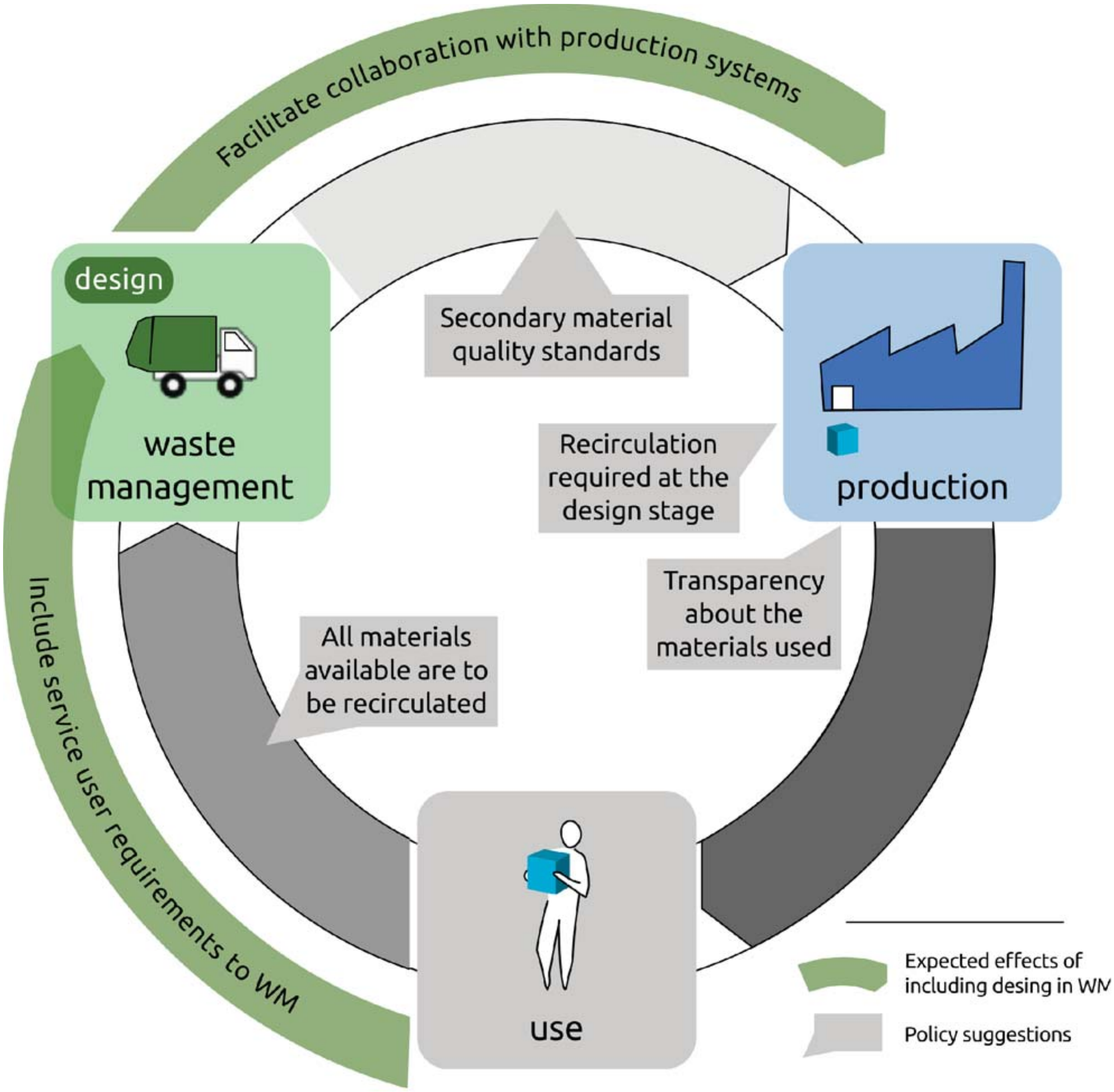

Figure 22: Suggestions that would facilitate material recirculation: four policy instruments and incorporating the design profession into the WM branch.

6.2.2.1 Critical aspects to bridge the WM - Production gap

To increase the material flow between waste managers and producers a constructive open dialogue is needed to match secondary materials to production requirements. WM has the potential to provide the inverse logistics needed by industry, if there were clear requirements from the productive sector for WM to comply with. WM is limited in what it is able to supply based on what has gone into the waste streams and how it is sorted. So the quality of the material they can recirculate will have to be evaluated, tested and communicated to producers. Such dialogues happen in active collaborations where all parties respect and understand their differences but strive to reach a common goal in a way that is beneficial to all.

Current material flow fails to effectively pass materials from WM actors to producers. This failure can be described as their inability to overcome inherent differences between these two sectors. Table 5 presents how production systems differ from WM on aspects that are critical to address in an open dialogue to enable material recirculation between these actors.

Table 5: Aspects that differentiate production systems from waste management, which are critical to allow for recirculation.

Aspects	Production Systems (PS)	Waste Management (WM)
Main purpose	Optimize production to generate revenue	Efficiently treat waste as required by law
Value creation	PS increases value of raw materials by product development	WM aims to generate value by waste separation and recirculation
Quality definition	Based on user satisfaction and control in production	Based on environmental protection and resource recovery
User requirements	Are used to develop products	Are not used to develop the system
Scale and location	PS serve international markets and often span several locations	WM is geographically constrained and developed by local authorities
Relation to waste	Addresses waste prevention	Does waste treatment
Type of recirculation	Planned recirculation	Planned and improvised recirculation
Position in the material flow	PS still see themselves at the start	WM still see themselves at the end

The aspects in Table 5 and how they differ between production systems (PS) and WM are based on the findings presented in this thesis, but are extrapolated from the empirical data presented in an attempt to synthesize the findings at a system wide level.

That PS and WM differ in their main purpose is not surprising. However, their purposes could be revised to redefine and make explicit the relation these actors have to each other. Value creation is critical to material circulation, being in many cases value what determines if an object is considered waste and discarded. In general terms, value fluctuates along the material flow cycle as illustrated in Figure 23. The ways in which the different actors create and maintain value might prove to be a fruitful topic to address when exploring possibilities for collaboration.

As commented earlier (i.e. the last section of Topic 1) quality is a tricky concept. PS and WM define quality differently, with production's definition of quality being critical to allow for material recirculation. Secondary material quality standards need to be developed (as stated earlier in section 6.2.1), based on the quality standards required for production. Therefore, it is desirable to adapt the quality definition in PS so that it considers the risks and benefits associated to the use of secondary materials.

Topic 2 showed that the development of waste sorting systems, which can be considered the "user interface" of WM, could be improved by better including user requirements when designing the system. As argued in the last section of Topic 2, PS has more experience in incorporating user requirements to develop solutions, varying in the degree of how much involvement users have in the product development process. This experience could be shared with WM actors by including designers in WM development.

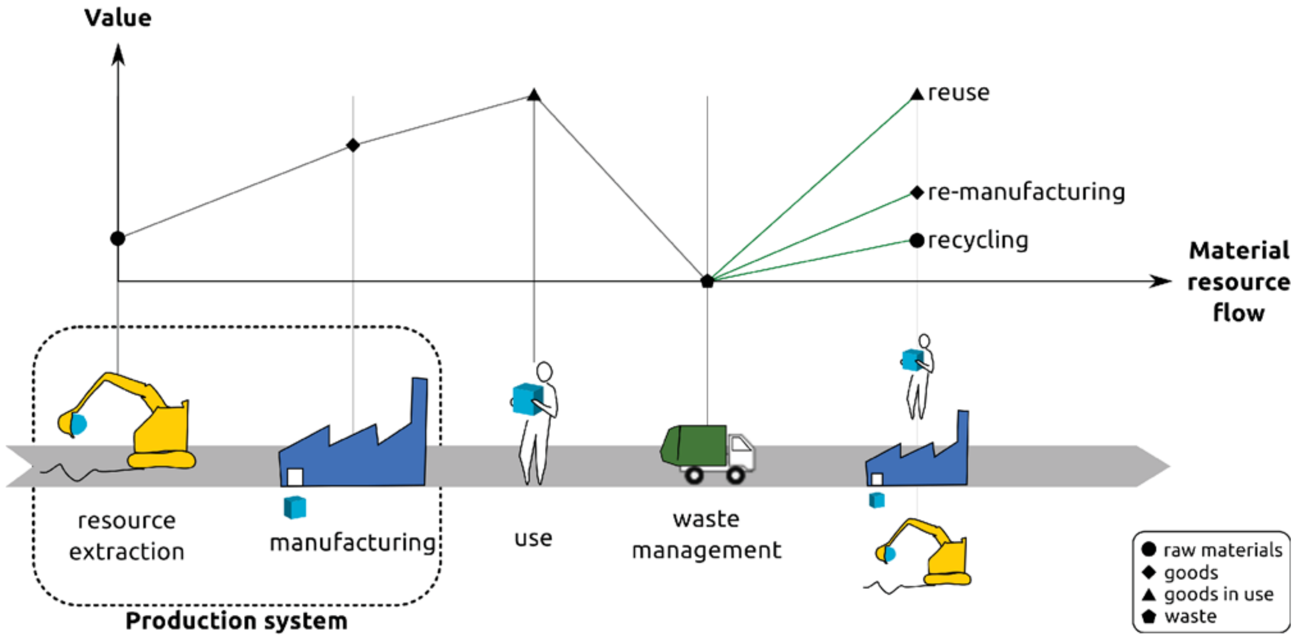

Figure 23: Value fluctuation along the material flow cycle. Note that the different possible resource recovery routes recirculate materials by conserving different value levels.

The scale and geographical differences between competitive global PS and localized WM makes collaboration between these actors quite a challenge. However, a good starting point might be to address local production for close collaboration with WM. If local collaborations are fruitful, they might strengthen local production and eventually seem attractive also for global producers.

The waste hierarchy considers it preferable to prevent waste than to have to handle it (as described in Topic 3 and Article F). The exact definition of waste prevention is however a matter of interpretation. Waste prevention could be defined as activities done by PS or individual users to avoid waste generation, while WM is defined as the system that handles and treats the waste generated, not the material that has been prevented from becoming waste. Such definitions make it impossible for WM actors to engage in waste prevention, therefore a reinterpretation of these concepts is desirable. For example, a user could give away a product for somebody else to reuse, preventing waste generation. However, if that product is discarded and later sorted by the WM system to be sold through second-hand markets, reuse is also achieved. Should this be considered waste prevention? These definitions are important since they allocate responsibilities and influence the action spaces available for recirculation stakeholders. In some cases, these definitions even affect the allocation of funds for WM activities.

The types of recirculation mentioned in Table 5 need to be clarified, since these have not been defined before. The production-centred recirculation initiatives presented in the introduction (i.e. industrial ecology, C2C and CE) have until now been focused on getting producers to change the way they do business in order to promote material recirculation. This can be denominated **planned recirculation**; recirculation that is planned for at the design stage of the product, service or system and is executed accordingly. When recirculation is not planned for, waste is generated. In such cases recirculation will only happen if it can be "improvised" by the WM actors at the end of the material flow. This is what is referred to as **improvised recirculation**. WM engages also in planned recirculation by sorting materials to their intended end-of-life treatment, e.g. by sorting recyclable packaging and delivering it to recycling industries.

Both planned and improvised recirculation are difficult to do. On the one hand, planned recirculation requires designing for several life-cycles when developing a product, and like any plan it might fail. On the other hand, improvised recirculation needs to match the available secondary materials to possible uses and production technologies, making it a work intensive task (as seen in Topic 1). Using the definitions of planned and unplanned recirculation together with the distinction between materials that effectively get recirculated and those that do not, we can divide the materials used in society into four groups as seen in Table 6. These material categories can be used to identify different ways to approach material recirculation; use materials currently not recirculated by improving a failed recirculation plan or recirculating material from disposal, or work towards establishing a new recirculation path based on improvised recirculation successes.

Table 6: Categorization of the materials used in society according to if they get recirculated or not (columns) and if they are handled with planned or unplanned recirculation (rows).

Recirculation type	Recirculated	Not recirculated
Planned	Established solution	Failed recirculation
Improvised	Potential solution	No one has addressed it

Both planned and improvised recirculation are needed. Planned recirculation has not been used widely enough to address most materials in society. It might not even be possible or desirable that planned recirculation covers all materials, since more crucial uses for secondary materials may appear with time. Also, planned recirculation fails quite often (as can be seen by the volumes of unsorted recyclables observed in Topic 2). To determine why planned recirculation fails is an excellent task for WM and PS actors to engage in together, that might allow for these stakeholders to adapt their ways of working, by either changing the plan or management of the resource in question, to eventually achieve successful recirculation.

Given that this research has focused on recirculating waste, it can be said that this thesis has focused on moving materials from the last column to the second one in Table 6. Each topic has attempted this is different ways. In Topic 1 several of the students participating in the W2D project mentioned that using discards for new product development without considering how the resulting product would be handled at its end-of-life stage felt like a waste of time. They engaged in improvised recirculation by making products with planned recirculation principles. Topic 2 explored why planned recirculation fails at the material sorting stage in WM. And in Topic 3, both types of recirculation were discussed by designers and present in the recirculation examples (e.g. design for longevity and designing with waste materials). This suggests that both recirculation types are needed and complementary, rather than excluding.

That PS still regards themselves as the start of the material flow and WM as the end (i.e. the last aspect of Table 5) shows that the material flow through society is still predominantly linear. If a truly circular material flow were to be achieved, there would be no actor that could identify themselves as being the beginning. In a way, this is what recirculation from production or waste actors attempts. However, by remaining in separate branches, rather than one unified waste to resource system, they risk imposing their position as a starting point or end destination.

7 Discussion

This section relates the research presented in this thesis to other research relevant to recirculation, to later contrast the contribution of this work with existing results in this field. Then it critically reflects on the choice of research approach and methods used, to finish by suggesting what could be addressed in future research.

7.1 Positioning the present research in the recirculation field

Environmental sustainability has been an underlying goal for the work presented in this thesis. The thesis addresses the broad question of what hinders material recirculation in society, with the intention of helping to achieve a more sustainable use of material resources. The question of material recirculation is based on material flow accounting principles (i.e. the application of material flow analysis to entire socio-economic systems). Material flow accounting has shown strong development over the past 30 years, achieving enough maturity for material flow indicators to complement traditional economic and demographic indicators as tools to inform policy (Fischer-Kowalski et al. 2011). This methodology has allowed our global use of material resources to be described, making it evident that the existing productive system is mostly linear with only 6% of the global resources being recycled. Recirculation is low because a large amount of materials are used for energy generation (44%) or are continuously added to the material stocks in society (27%) (Haas et al. 2015). So, even if all waste materials were recirculated, this would only represent a fraction of the total materials processed by society (around 20%, ibid.). This thesis has focused only on **materials used in the production of goods**. These are the materials that are added to the stock within society and eventually discarded. This delimitation originates from the disciplinary approach from which this thesis has been done (i.e. Industrial Design). Material and energy use are however closely related and have both proven to be relevant aspects for the research presented in this thesis (e.g. biodegradable used for biogas generation, recycling requiring less energy than extraction). Nonetheless, the focus of the present research has been on identifying what hinders the recirculation of materials used in the production of goods.

Material flow accounting is a good tool to provide global and regional material balance status information, however it only explains the flows observed in very broad terms. Figure 20 (in page 53) provides such an overview in a schematic diagram, highlighting the interconnectedness of three complex socio-technical systems that circulate material in society; the production, consumption and waste management systems. Since these three sectors are crucial for the circulation and eventual recirculation of goods, research that provides more detail about how goods are **made**, **used** and **discarded** generate results that are relevant to the work done in this thesis.

Production systems are well established worldwide, creating a fruitful, varied and very active research area. How production systems can allow for material recirculation has been one of the starting points for the present work, as described earlier in section 1.3. Industrial Ecology uses material and energy flow analysis to provide a more detailed understanding of how materials are used in industrial production, with the intention of making them imitate how ecosystems work in nature to reduce the environmental impacts of production (Duchin & Hertwich 2003). Other production centred recirculation efforts (i.e. Cradle to cradle and Circular Economy, also presented earlier) have gone beyond production systems to include the use stage of products.

Design is a specific aspect of production that is central to the present research. Within the design field, the research done in eco-design has been the most influential for this thesis. Eco-design or Design for Environment (DfE) is focused specifically on the environmental sustainability of products, services and systems. It initially appeared in the 1990s, within the Design for X approaches, and has since its origins been moulded to address the environmental impact of design at all life-cycle stages (Brezet & van Hemel 1997). Design for Sustainability (DfS) was coined later as an umbrella term for design methodologies that would support the three aspects of sustainability; economic, environmental and social (Arnette et al. 2014). Much research was already available to support economic sustainability (since economic gain is one of the main driving forces in production), while research on social sustainability has been notoriously less frequent (ibid.). Within the DfE taxonomy developed by Arnette et al., several of the strategies mentioned are related to material use and its potential recirculation, providing a fundamental background to the work presented in this thesis: i.e. design for recycling, re-manufacturing and reuse, design for waste minimization and recovery, design for material conservation and design for safe disposal of hazardous materials. Such strategies have been available in the literature since the late 1990s without generating much effect on the waste volumes. Therefore, how these strategies are understood and applied by designers was investigated in Topic 3, resulting in a model that summarizes how designers describe these strategies shown in Figure 21.

To better understand the **use of material goods**, both materialistic and psychological approaches are needed. Household metabolism applies material flow tools to analyse what passes through households and the environmental impacts that are generated by household consumption (Harder et al. 2016), while consumer research analyses consumption patterns and the behavioural aspects of purchase decision-making. A materialistic view of the use of goods is useful to describe the material flows at the use stage, but does not explain it. Consumer research aims to provide such explanations with the help of behavioural psychology. The research fields mentioned here are relevant too, and complement the work presented in this thesis, despite only being mentioned superficially. They have been mostly excluded because the drive in this doctoral work has not been to understand people per se, but rather to facilitate material recirculation.

Consumption has long been recognized as a central motor that drives the exchange of material goods, and with this large environmental impacts (Jackson 2005). Therefore, sustainable consumption has been included in the policy discourse, despite it being unclear whether this implies to consume differently, responsibly or less (Jackson & Michaelis 2003). Institutional consensus has favoured the idea of consuming differently rather than less by supporting the consumption of sustainable products rather than questioning the scale of consumption (ibid.). Consuming less is difficult to promote, since this questions fundamental assumptions of a materialistic society and our own personal choices (ibid.). The work done in this thesis also falls into the trap of not questioning consumption, accepting that even a reduced level of consumption would benefit from being supported by an economic system that favours resource recirculation. Although this work does not question consumption, I agree that strong measures to reduce consumption to levels that our ecosystems can support are necessary to mitigate environmental degradation. More can be done by limiting consumption than by trying to change consumer habits, but this requires that policy moves away from the success measure of economic growth to embrace development defined in terms of individual and social welfare (Sanne 2002). To hint at this political position, people are addressed as users rather than consumers in this thesis. This highlights my interest in people´s role as active agents who make use of goods and systems to achieve their goals, rather than merely consume resources (similar to how people's behaviour is described in Selvefors et al. 2015).

Given that this thesis focuses on what hinders material recirculation it was natural to investigate what is discarded from the socio-economic system, making waste material central to this research. **Waste research** has a long history of describing waste volumes depending on their generation source, composition, toxicity or how they are to be treated (Baker et al. 2004), since the flow of materials is central to the functioning of waste systems. This makes it easy to associate waste research to material flow perspective that supports this work, as described in the introduction. Waste research is a multidisciplinary field grounded in technical systems engineering, but that has over the years expanded to include several disciplines from social sciences, including behavioural studies (e.g. Meneses 2005; Thøgersen 1994; Tonglet et al. 2004), social psychology (e.g. Nigbur et al. 2010; Jackson et al. 1993) and social capital research (e.g. Tsai 2008; Miliute-Plepiene et al. 2016). Waste and recycling topics have often been addressed by social sciences, referring mainly to the public's participation in sorting initiatives and eventual policy decisions. The waste research field addresses many other stages of WM that have a very strong technical character, such as environmental assessments of different WM options (e.g. Song et al. 2013; Eriksson et al. 2009; Liamsanguan & Gheewala 2007; Kirkeby et al. 2006), economic and ecological optimization of WM options (e.g. Ljunggren Söderman et al. 2016; Sonesson et al. 2000; Dong et al. 2013), analysis of WM systems and models (e.g. Pires et al. 2011; Morrissey & Browne 2004; Eriksson & Bisaillon 2011) and technological developments for different WM options at all stages (e.g. Beltrami & Bodin 1974; Bernstad et al. 2013; McKay 2002). Although waste research has been central to the work in this thesis, the present work has not contributed neither to the exclusively social, nor technical approaches summarized earlier, but has rather investigated how such social and technical aspects can be integrated when developing waste management systems. Such an integrated approach to WM development has been proposed before, but mostly on a large scale, integrating stakeholders at municipal or national levels (e.g. Guerrero et al. 2013; Wilson et al. 2015; Scheinberg et al. 2001). This thesis applies the same integrated approach, but at a lower waste system level, i.e. for the development of waste sorting systems in apartment buildings addressed in Topic 2. This seems to be new in the WM branch and was addressed by using user requirement elicitation methods common to design research. The involvement of design research in the development of complex socio-technical systems, is also a recent phenomenon that is still being established (Norman et al. 2016).

7.2 Regarding the scientific contribution of this work

The main contribution of this work is the integrated overview of what hinders material recirculation, identified through the three topics that comprise this thesis, as well as suggestions for how to address such barriers (as presented in chapter 6). The hindering themes described in chapter 6 manifest themselves in different ways depending on the context of the research done (i.e. they are described differently in each topic). Therefore, the step of comparing the results from each topic to generate an understanding for the underlying barriers for recirculation is useful and necessary to be able to address the challenge of recirculation at its broadest system level. This section discusses only the main contribution of this thesis, since the specific contributions from each topic are considered to be discussed in the appended articles.

Studies that review how Circular Economy (CE) has been implemented in China (a country that formally accepted CE as a national strategy in 2002) provide well documented insights into what hinders circularity. Many efforts to implement CE in China are isolated, done at the micro, meso and macro levels in areas of production, consumption and WM, lacking a unified measure of progress (Su et al. 2013). Challenges identified for CE implementation include a shortage of advanced technology, poor enforceability of legislation, weak economic incentives, lack of reliable information, poor leadership and management and lack of public awareness (ibid.). Further, it has been suggested that legislation to support CE should define the responsibilities of the concerned actors, define administrative and economic measures needed and incentives to encourage public participation (Zhijun & Nailing 2007). The challenges and suggestions presented in chapter 6 corroborate the results of both these Chinese studies, despite that they are based on material obtained in a Swedish context. This suggests that the lack of a common vision among recirculating actors might be a generalizable barrier. This lack of a common vision for CE and material recirculation translates into difficulties in assessing the circularity of specific companies or regions. Much work has been done recently to create circularity assessments, but this has been lacking a common framework to establish the purpose, scale, criteria and principles such assessments should have (Camacho Otero 2015). Note that the barriers and difficulties to assess circularity mentioned here assess the implementation of CE, which includes but is not limited to material recirculation. Material recirculation can be said to be the "simple measure" of circularity only addressing the material flows through society. Nonetheless, the difficulties to achieve material recirculation described in this thesis reflect the complexities present in implementing CE in society.

As stated in the introduction, material recirculation has been proposed by both WM and manufacturing actors. These actors refer to recirculation from their role in WM or manufacturing, considering only what actions they could take for recirculation and not considering other societal actors as active agents. The last section in chapter 6, argues that if WM or production actors would consider each other as active, adaptable agents, that are open for collaboration they could effectively bridge the gap that currently separates these two sectors, allowing for a significant increase in material recirculation. This would be a significant change from the current approaches where WM and production stakeholders try to implement recirculation on their own, not triggering the necessary changes in the other sector recirculation is intrinsically dependent on.

The results of this thesis also highlight the importance of users in enabling or hindering recirculation, both as waste system users and users of manufactured goods, making them crucial active actors for recirculation. Just by including users as important stakeholders, material recirculation becomes a broad societal challenge. Such an inclusive view has recently appeared among CE proponents as well (e.g. Su et al. 2013; Camacho Otero 2015; European Commission 2014). Transition management has been suggested as a model to help public policy address such societal challenges, by steering society into more desirable future scenarios (Rotmans et al. 2001). This model proposes that social change can be achieved by reflective iterations of directed incrementalism (Kemp & Loorbach 2007), arguing that a conscious process of social change can be achieved using a managerial approach. This seems promising, given that several of the aspects hindering material recirculation mentioned in chapter 6 can be described as common management problems (i.e. lack of information, more time/effort required, undefined responsibilities and lack of control). Recent studies have applied transition management to different cases to prove and validate this framework empirically (van den Bosch 2010), with one documented case that uses transition management on WM and resource recovery topics (Loorbach & Rotmans 2010). The results from this thesis support the idea that material recirculation is a challenge likely to benefit from being addressed with a transition management approach.

The three suggestions for policy presented (i.e. to require recirculation by producers at the design stage, to process secondary materials to ensure material quality and to collect more materials than the amounts that are currently recycled) have all been addressed to some extent by the European action plan for the CE. This document states that 1) Future work on the Ecodesign directive will promote repair, component reuse and recyclability, among other aspects, 2) The commission will launch work to develop quality standards for secondary raw materials where they are necessary, and 3) Waste collection and sorting needs to significantly improve to obtain high-quality recycling, improving collection of recyclable plastics, wood packaging and bio-waste (European Commission 2015). It is positive that the suggestions made are in some way reflected in the plans for developing European regulation, however their implementation in practice is certain to present several challenges. As they are currently formulated, these three actions mentioned earlier do not address all the materials used, nor do they cover any specific fraction at all stages of the material flow. As an example, product design has been addressed by European regulation mainly through the Ecodesign Directive, targeting only energy related products with the aim of increasing energy efficiency, while also improving performance at all life-cycle stages, including the EoL stage by facilitating reuse, re-manufacturing and recycling of components and products (European Council 2009). Energy related products are considered to be a critical product type given that they generate significant environmental impact during their use phase, however similar regulations should also be enforced for non energy related products. This is at the moment lacking within European regulation. Besides this limitation to energy related products, the regulations around ecodesign are reported to have little effect on product development. Research has pointed out that social and psychological aspects have a strong influence over ecodesign implementation in industry (Boks 2006) and that EPR has been a weak tool to promote ecodesign, implying that a broader mix of policy measures are required (Gottberg et al. 2006). This thesis suggest that the policy measures should be consistent, cover all materials used and address all stages of the material flow to be able to support recirculation fully.

To develop quality standards for secondary materials is not a minor challenge. As commented earlier in section 3.4, quality is an elusive concept and irregularity is an inherent property of secondary materials. To define quality as “conformance to requirements” or “fitness for use” (Crosby and Juran respectively as quoted in Hoyer & Hoyer Brooke 2001) leaves space to discuss what is meant by requirements or fitness. This opens up the possibility to propose definitions of material quality that could potentially benefit the use of secondary materials. However, some requirements regarding material toxicity and environmental damage should not be neglected nor taken lightly. Some materials are problematic and their use should be downgraded or avoided completely. So, to define what materials should be banned from recirculation, or recirculated into limited use applications, is another difficult task that should be addressed by future standards for secondary materials.

This thesis suggests to have designers take up a role as facilitators for collaborations among actors. To view designers as facilitators for the transition towards sustainability is not novel (e.g. Joore & Brezet 2013; Wahl & Baxter 2008; Papanek 1984). This work adheres to that line of thought, highlighting that designers' contribution to a sustainable transition cannot only be bound to the development of products, but should be expanded to other aspects of society.

7.3 Regarding the research approach

The research presented in this thesis explores broad questions. It does not fully respond these questions, but rather provides initial insights into these topics, providing rough mappings for future more specific research.

The work presented in the studies fluctuates between the very macro, talking about global use of material resources, to the very micro, looking at the composition of mixed waste in specific apartment buildings. The aim of sustainable material use is broad and global, however its implementation transcends through many levels of complexity to very concrete cases of product design and waste sorting, as covered in Topics 1 and 2. How broad societal challenges relate to product and system development has been previously described by the Multilevel Design Model (Joore & Brezet 2013). This model is intended as a framework to support the widening role of the designer from creator of artefacts to facilitator of complex societal change processes by, among other things, describing the design process and the societal change processes in consistent, comparable ways. This model fits perfectly with the type of challenge undertaken by this thesis, even relating societal changes to the development of different hierarchical system levels (i.e. products, product-service systems, socio-technical systems and societal systems). This supports the approach taken by this doctoral thesis, that the abstract societal goal of sustainable material use has to be supported by concrete products, services and systems. The ability to connect the larger social goals to the specific products or systems is needed to ensure that the innovations suggested are working for the same ultimate goals. So a fluctuation between the macro and the micro is necessary and useful for this type of work.

However, these fluctuations and the broad research questions may give this research some sense of inconsistency and lack of definition. This is to be expected when working with wicked sustainability problems, since even the problem that is the starting point for the research is poorly defined (Lönngren 2014). These challenges require open exploration and an intention to iterate for solutions on different aspects of the issues using several perspectives. These problems are unstructured and so the research around them may appear to be unstructured as well. This does not mean, however, that the research has not been carried out as thoroughly as possible. Borrowing methods and definitions from different disciplines, the studies presented in this thesis have put much effort into trying to contribute to understanding the barriers for material recirculation.

It might not be surprising to see that the conclusions of this thesis suggest that more design is needed in WM to support recirculation, since the author is an industrial designer herself. Our professions form the way we view and interact with the world and that has with no doubt affected the research presented, but this does not make the conclusions less valid. Yes, the results are presented from a designer's point of view, but multidisciplinary efforts are needed to address the wicked problem of material recirculation. The research presented here contributes with a perspective that is not well represented in the WM field, therefore broadening the ways of addressing this problem. The fact that the design of WM systems is currently still addressed as a technical problem to be optimized, despite being recognized as a socio-technical system, makes a strong point for including a field such as design, which has always focused at conciliating user requirements to the technical possibilities.

7.4 Regarding method selection

The studies in this thesis have used a variety of data collection methods. Interviews, surveys, field observations, product studies, empirical data and literature were all used to inform the studies. A mixed methods approach was deemed most useful given that the problems addressed in this research are multifaceted and complex. The main problem encountered by using several methods is that this provides large amounts of data to review and analyse, making it easy for the researcher to get lost in the data and forget the initial aim of the inquiry. Also, the results finally reported and presented are a selection of the total results obtained, leaving out results that could still be relevant and worthy of further investigation. Another issue encountered when using mixed methods is the difficulty of integrating the different methods to be able to draw joint conclusions (as happened with the surveys carried out for the case studies in topic 2). Good understanding of the limitations of the methods used and how they can be analysed together would allow for future studies to integrate results from different data collection methods in more integrated ways.

Other case studies could have been done and other case studies are needed. The examples and case studies presented in this thesis are expected to be compared to other cases to jointly provide better understanding of the investigated topics. The case studies done were chosen for practical reasons; the possibilities for collaboration were at hand within a certain time frame to contribute to the research for this thesis. The collaborations were relevant to the aim of this research and so were easily taken on as case studies. The case studies presented do address topics of interest for improving material recirculation and, although limited, have provided relevant information.

Specific methodological difficulties were encountered in Topic 2, dedicated to waste sorting in apartment buildings. It is particularly challenging to separate the effects that infrastructure may have on sorting behaviour from the widely variable waste generation patterns. The volumes and composition of the waste generated from one household to another are known to vary with lifestyle choices, consumption patterns, age, etc (Dahlén et al. 2009). The influence that these aspects have on sorting behaviour are difficult to understand without going into deep socio-demographic characterizations of the participating households. However, the literature review in Topic 2 showed that there was little to no consensus among the articles that tried to explain waste sorting behaviour using socio-demographic factors. To make matters worse, waste generation changes over time as well. These variations may be easily explained in individual cases (e.g. the family travelled away for a couple of weeks, there was a big party) but they make waste generation inconsistent over time and difficult to predict or explain when aggregated for several households. As a result, the empirical data obtained about sorting behaviour could not be tracked back to individual households, nor associated with the survey results. Because of this no conclusions can be made about the relation between user opinions on waste sorting and their actual sorting behaviour. Future work should address this aggregation issue by tracking waste flows of individual households, if possible. It should also aim to include users' opinions in a more substantial way, by means of more explanation through rich investigation methods that would allow tenants to highlight possible causes for their sorting behaviour (such as interviews, focus groups or workshops). Research that investigates waste issues from a household perspective often use such tools to better understand the actions taken within households (e.g. Metcalfe et al. 2012; Åberg et al. 1996; Åberg 2000).

The models that have resulted in this thesis (e.g. recovery routes linked to life-cycle stages, process diagram for how to design with waste) are simplified ways of explaining the phenomena studied and by no means cover the complexity of the reality. They are only intended to facilitate the understanding, communication and debate needed to advance the knowledge around these topics.

7.5 Future work

There is still substantial amounts of work needed to reach a socio-economic system that recirculates the material resources it uses. This section describes only a few of the possible ways forward that I personally find interesting to develop further.

7.5.1 Establishing recirculation hubs

In order to support recirculation, collaborative hubs could be established to help connect local producers, secondary material providers, waste managers and makers. Such a hub would allow for collaborative knowledge development about available secondary materials and the production possibilities to transform these materials into something new. The space could act as a secondary material library, where makers could match materials to the future products they envision. Most of all, such a hub would provide a space for collaboration, where producers, material providers, users or makers could meet each other, learn, share and create a common vision to work with.

Several initiatives exist that could support, or be associated with, such a recirculation hub. To facilitate local production, initiatives such as Make Works, that maps regional manufacturing possibilities in order to make them more accessible (Make Works 2016), could provide a way forward. Also, several examples of Do-it-yourself (DIY) spaces currently allow makers to develop things; hacker-spaces, maker-spaces, clothes repair libraries and bike kitchens are all part of such a movement. In their way they facilitate recirculation, providing the possibility for people to make their own things, but do not aim to make this sort of manufacturing a well-established form of production. Nonetheless, such initiatives are niche actors that support recirculation and they could be "levelled up". Here quality assurance seems to be key. As discussed in Topic 1 and section 6, secondary material quality standards need to be established, but finalized product quality should also be controlled in some way if these products are going to be sold.

Transition management has described the need for what they call transition arenas, where new visions are developed, processes supported and niche actors collaborate and influence each other and the regime (Loorbach & Rotmans 2010), counting even a case of an arena dedicated to sustainable resource use in Belgium (Plan C n.d.). It has been argued that such transition arenas benefit from being located in urban hubs, and so urban transition labs have been developed in the European MUSIC (Mitigation in Urban areas: Solutions for Innovative Cities) project aimed at CO2 reduction in urban environments (Nevens et al. 2013). It would be wise to acknowledge the lessons learned from such experiences when trying to implement a hub for recirculation.

7.5.2 Decentralized recirculation solutions

WM currently works as a centralized system to allow for efficient investments and centralized control. The energy system, based also originally on centralized generation, has understood that a move to decentralized generation allows for an overall more resilient energy system. In a decentralized system a plethora of actors can develop minor scale solutions that together make up a more varied energy generation landscape. Similarly, decentralized waste treatment solutions could provide possibilities to enable recirculation among a variety of actors.

Decentralized waste treatment can be extremely varied in its nature and much work is needed to develop a portfolio of solutions that can address all the materials used in society. Using bio-waste to feed animals, compost at home or make biogas are decentralized treatment possibilities that already exist. Reuse rooms (mentioned in article D) or DIY spaces (mentioned in section 7.5.1) can also act as resource treatment spaces that enable reuse and re-manufacturing respectively. These examples of decentralized recirculation could be better promoted within urban areas, turning them into established treatment approaches, rather than one-off solutions.

In general, such decentralized solutions make the benefits of waste sorting and treatment more evident for the participating households and could help to better motivate their engagement in recirculation. However, decentralized solutions should still conform to some sort of centralized regulation, to help ensure that materials are handled and treated in a way that is not harmful, either for users or the environment. How this can be actually implemented still remains a challenge.

8 Conclusions

This section summarizes the lessons learned during the doctoral studies presented in this thesis, to provide a short overview of the main conclusions that can drawn from this work.

The work that constitutes this doctoral thesis has investigated what hinders material recirculation in society, to later suggest possible ways to support recirculation in the future. This is a societal challenge that implies drastic changes in the existing socio-technical systems which produce, consume and discard material goods.

To address such a task, empirical research was done on three separate topics that are interrelated in the broader system for material recirculation. First, two case studies where used to explore the barriers for recirculation from production systems and waste handling in two specific cases. These two case studies addressed the topics of designing with waste and sorting waste, presented in this thesis as Topics 1 and 2, respectively. Then a third topic was addressed, as a way of providing a broader context for the case studies. Topic 3 investigated specifically how design currently relates to material recirculation. Finally, a transversal analysis was done to better understand how the barriers identified in each topic relate to each other and to highlight the critical aspects to address to be able to work towards material recirculation.

Designing with waste proved to be a difficult endeavour, mainly due to the lack of a traditional design brief and reliable information for secondary materials. Topic 1 presents a process diagram for how to design with waste, based on generic design process models. This process diagram is complemented with two previous steps needed to enable designing with waste: 1) Collect and sort the discarded material in an adequate manner, and 2) Investigate and test secondary material's properties.

Waste sorting is therefore a precondition to designing with waste. Improving the way waste materials are sorted and collected is a topic that couples behavioural and societal aspects that are difficult to explain, to elaborated technical solutions, resulting in a challenging and complex socio-technical system. Topic 2 shows that several relevant suggestions for waste sorting system improvement can be made based on a better understanding of waste service user's preferences (e.g. provide the possibility to sort textiles or items for reuse). Such understanding can be obtained by using user requirement elicitation methods common in the design discipline.

Topic 3 concludes that design currently does not sufficiently support material recirculation. Although designers see and describe the effect that their profession has on resource use and waste generation, in practice it is only a third of the consulted designers that had actively used EoL considerations in their latest project. In order to aid designers in recirculating materials and contributing to material conservation, Topic 3 presents two models: 1) A resource recovery route model, based on recirculation to different life-cycle stages, and 2) A model of ways in which designers describe how they can address resource conservation.

The factors that hinder material recirculation found in the three topics could be grouped into six main themes; the complexity of sustainable waste management, the need of reliable material knowledge, lack of information, undefined responsibilities, lack of control and more time/effort required. These barriers are similar to the ones identified for the implementation of CE and seem to point strongly to a lack of guidance and common vision around what material recirculation should mean for the different actors in society.

To generate a common vision among the main stakeholders (i.e. producers, users and waste managers) policy regulations and collaborations that foster better understanding among the actors are suggested as possible ways forward. Four policy suggestions, that address different stages of the material flow cycle are made, i.e. develop secondary material quality standards, require that all materials available are recirculated, require recirculation at the design stage, implement more transparency about the materials used in production. In an attempt to provide starting points for potential collaborations among production and waste management actors, some differentiating aspects between these branches were presented. These aspects might be fruitful grounds for dialogue among potential recirculating agents. The aspects presented are i.e. the main objectives of production and WM, how value creation is addressed, how quality is defined, how user requirements are identified and used, what the scale and location of the operations are, how waste is addressed, what type of recirculation is used and where in the material flow the operations are carried out. Planned and improvised recirculation are presented and suggested as complementary ways of achieving recirculation.

There is still much to be done to achieve a more sustainable use of material resources in society. Work is needed to establish material recirculation hubs in urban areas, where local producers, secondary material providers, waste managers and makers can meet and create new ways of collaborating to enable material recovery. This could be supported by the development of a greater number of, more efficient, decentralized waste management solutions. Decentralized solutions to handle materials commonly discarded by households might help engage users in material sorting, since they generate resources that become available closer to where they can be used. This might in turn result in a reduced demand for central waste management, as well as in the generation of small and medium scale recirculation entrepreneurs.

The political and social will to work towards a society that recirculates the materials it uses seem to be now wide spread and ripe for action. This makes it an exiting time to work with these topics, since it might be possible to engage several actors in up-scaling recirculation. The hope is that the work presented in this thesis has contributed, at least a bit, to help the reader understand current barriers for recirculation and to start to sketch ideas for how to achieve that goal. As said by the Italian zero waste promoter Rossano Ercolini “Zero waste is not a destination, it is a journey. We won't achieve it tomorrow, but we have to start today.”

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