Journal of Cleaner Production 134 (2016) 342–353

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Resource recovery from post-consumer waste: important lessons for the upcoming circular economy

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form
7 November 2015
Accepted 11 December 2015
Available online 21 December 2015

Keywords:
Resource recovery
Circular economy
Post-consumer waste
Re-manufacturing
Product design
Product study

ABSTRACT

A circular economy has been proposed as a sustainable alternative to our current linear economic system, mainly by recirculating material resources for new product development. To understand resource recirculation in practice, this paper analyses over 50 examples of products developed from discarded materials, categorising them into the recovery routes described in the circular economy literature. The examples were obtained during interviews with waste management professionals and designers who had developed products with discards. Practical challenges to implementing a circular economy were identified based on the example categorisation and comments from the interviews. The main difference observed was that the examples mostly recirculate resources to make different types of products, whereas a circular economy requires manufacturing companies to take back their own products to secure their material resources. This is partly because in practice the material collection system in place is waste management, rather than manufacturing-centred take-back systems. A revised model for recovery routes in society in which waste management is allocated an important role in facilitating material recirculation is therefore presented. The study highlights that current product design is facing a new challenge of anticipating social, economic and environmental challenges to realise the goals of a circular economy.

1. Introduction

Several actors have identified potential business opportunities in aiming to achieve more circular material loops in manufacturing and production and describe how possible recovery routes could be defined (cf. Ellen Macarthur Foundation, 2014). They also discuss how designers and manufacturers can help move towards a more circular production model. This paper compares such literature about the circular economy with its potential practice. It does so by presenting examples of 'circular' products, using data obtained from an interview study, and categorising them using the resource recovery routes described for the circular economy. This categorisation was intended to highlights aspects of the circular economy that the theory has not yet addressed. The interview study generated a list of over 50 examples of products that help recirculate materials, while also providing information about the challenges material recirculation has today. This information and the issues raised when categorising the examples were used to examine how well aligned the theory and practice of circular economy are and to identify possible practical challenges not accounted for in the literature.

The article is outlined according to the following: Section 2 provides a brief overview of the resource recovery routes in the literature on waste management hierarchy and circular economy; Section 3 presents the methodology employed in this article to study the product examples; Section 4 presents the important results from the product study and interviews; and finally Section 5 ends the paper with discussion and conclusions.

2. A brief overview of resource recovery routes

Since 1975, when the European Union first introduced its waste hierarchy, it has been adopted by many countries to establish long-term policies to guide the waste sector (Williams, 2015). The waste hierarchy has been described as a "ladder" to be climbed step-by-

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http://dx.doi.org/10.1016/j.jclepro.2015.12.020
0959-6526/© 2016 Published by Elsevier Ltd.

Table 1
Some examples of reuse for different products.

Products	Some facts about material flow patterns			Comments
	New stock	Reuse/Resale	Wastes/Recycle	
Cars in EU (BCA, 2013)	2 million cars	7.1 million cars	**No data**	
Mobile phones in USA (Geyer and Blass, 2010)	**No data**	65% of the phones collected were reused	35% of the phones collected were recycled (Geyer and Blass, 2010)	Only 20% of the total discarded mobile phone were collected, the rest were mostly kept by owners or handed over directly to second-hand users.
Clothing in Sweden (Carlsson et al., 2011)	15 kg/capita & year	3 kg/capita & year sorted out for charity	8 kg/capita & year were discarded into waste streams in the same year.	The outflow of clothing is very rapid and there is huge potential to reuse or recycle the clothing if collected separately.
		In 2008, of the total sorted clothes collected by Myrorna (a second-hand store in Sweden), only 20% were re-sold in Sweden (Myrorna, 2014)	80% was exported for reuse and recycling	

step from bottom (landfill) to top (waste prevention) (Williams, 2015). Since the inception of the waste hierarchy, several amendments have been made to address the issue of waste, the latest being in 2008 (Waste Framework Directives; (EU, 2008)). *The new waste hierarchy contains measures for prevention, preparing for re-use, re-cycling, other recovery and disposal.* However, recent studies (Gharfalkar et al., 2015; Van Ewijk and Stegemann, 2016) have pointed out limitations of the waste hierarchy. These include a lack of guidance on selecting among the levels in the hierarchy, overlaps between various measures within the hierarchy and limited support for decisions that affect other sectors. These studies propose a refined hierarchy of resource use and adoption of value-based conceptions of waste and related collection practices. For example, Gharfalkar et al. (2015) propose an hierarchy of resource use based on the inputs from DG Environment of the European Commission, DEFRA (Department for Environment, Food & Rural Affairs) and WRAP (Waste & Resources Action Programme).

In the current predominantly linear production and consumption systems, resource recovery is considered to be one of the important aspects of waste management (WM) (El-Haggar, 2007; Eriksson et al., 2005; Griffiths et al., 2010; Lavee, 2007; UN Habitat, 2010). Globally, only 30% of the total waste material collected involves resource recovery (material recovery 11% and energy recovery 19%) (Chalmin and Gaillochet, 2009). These WM statistics provide an aggregated view of the established resource recovery operations linked to the total amount of collected waste. For some waste fractions, relatively more information is available on the total material consumption, material stocks and end-of-life waste material handling. For example, the European demand for plastics during 2013 was 46.3 million tons, of which more than 40% was added to the European "plastics stock" in that year, discarding only 25 million tons (~54% of the demand). For the discarded plastics, the share of material recovery, incineration and landfill was 26%, 36% and 38%, respectively (PlasticsEurope, 2014).

Furthermore, the amount of materials/products diverted for reuse (repair, refurbishment and remanufacturing) is also largely unknown, except for some specific second-hand markets for high value products and/or reuse enabled by intermediaries (such as local government, waste institutions, second-hand shops or websites). Table 1 presents some examples of reuse of post-consumer products in different regions. These examples indicate that a large percentage of post-consumer goods are stocked in the use phase. Indeed, for many products, there is no data availability on their stocks and therefore their reuse/recycling potential is largely unknown. The data shown in Table 1 are available because the intermediaries organising the reuse/resale are required to keep such inventories for their internal records. Moreover, the remanufacturing potential for many products is unknown. Remanufacturing is not well-established in practice except for some high value products with low technological/fashion/trends changes such as earthmoving machinery (All-Party Parliamentary Sustainable Resource Group, 2014).

Lately, the 'buzz word' circular economy (CE) has been popularised, especially in the industrial economies,[1] by the Ellen Macarthur Foundation (2012). CE is an economic strategy that suggests innovative ways to transform the current predominantly linear system of consumption into a circular one, while achieving economic sustainability with much needed material savings (Stahel, 2013). The principles presented by CE are rooted in different schools of thought, such as industrial ecology, biomimicry and cradle-to-cradle (McDonough and Braungart, 2008; Mentink, 2014; Yuan et al., 2006). CE proposes complicated system operations (such as product-service systems, remanufacturing and repair) for an industrial economy that are restorative and rely on renewable energy (Ellen Macarthur Foundation, 2014). This is achieved by designing and optimising products to eliminate waste by enabling efficient reuse, disassembly and refurbishment. CE advocates separate collection and utilisation of recovered materials (from consumables and durable products) within the same product chain. This would help achieve maximum efficiencies (material, economic and environmental) by collectively managing and sharing the activities among actors within the product value chain. Within CE, industrial systems mainly rely on maintenance, reuse/redistribute, refurbish/remanufacturing and recycling, while minimising resource leakage through energy recovery and landfill. Various sources of value creation in a circular business model employ these operations (All-Party Parliamentary Sustainable Resource Group, 2014).

That source distinguishes various processes within the circular economy – repairing (fixing fault but with no guarantee), reusing (simple reuse without any modifications), refurbishing (aesthetic improvement with limited functionality improvements), reconditioning (potential adjustments to the item to bring it back to working order), recycling (extraction of raw material for use in new products) and remanufacturing (series of manufacturing steps acting on end-of-life part of product to produce as-new, better performing products with warranty).

The difference between the resource recovery routes within CE and in the waste hierarchy lies mostly in the way discarded products/materials are perceived. CE aims at phasing out waste from

[1] Except for China, where CE has been incorporated into national policy for sustainable development since 2002 (Geng et al., 2012).

Table 2
Different resource recovery routes for non-waste and post-consumer waste and their focus.

	Waste hierarchy proposed by EU (EU, 2008)	Resource use proposed by CE
Measures/operations for non-waste	1. Waste prevention by reducing: (i) the quantity of waste through reuse. (ii) the adverse impacts. (iii) the harmful content of generated waste.	1. Energy required to fuel the cycles should be renewable. 2. Product/system design aims to keep the material flows in three circular loops: (i) Maintenance (ii) Reuse/redistribution (iii) Refurbishment/remanufacture
Measures/operations for waste (post-consumer goods)	2. Preparing for reuse (checking, cleaning or repairing). 3. Recycling. 4. Other recovery. 5. Disposal.	3. Product/system design strives to eliminate post-consumer waste: (i) Recycling (ii) Energy Recovery (iii) Landfill
Main Focus	Waste management	Efficient resources recirculation through new product and system design

industrial systems and therefore the recovery routes focus mainly on recirculating post-consumer materials. CE recognises the important role of product design in disassembly, inspection, reassembly and eliminating the use of toxic chemicals. In other words, according to the 'hierarchy of resource use' proposed by Gharfalkar et al. (2015), CE resource recovery routes focus more on operationalising replacement and reduction (which is 'waste prevention' in the EU waste hierarchy), recovery (reuse by resale, repair, refurbish, reconditioning and remanufacturing) and reprocessing (up-cycling, re-cycling and down-cycling), and less on energy recovery and disposal (Table 2).

3. Methodology

Recently, the emerging discussions on the concept of CE have intensified, especially in the developed countries. However, while theoretical projections for the potential economic, employment and environmental benefits of CE are promising, the practical experiences are limited except for some prominent examples of products.[2] These examples demonstrate various routes for resource recovery in CE. However, these examples of 'success stories' of CE provide a limited view of the myriad of challenges facing product designers aiming to close the material loops.

The challenge is thus to find good examples of design practices that aspire to close material loops. Material recovery is considered of the central principles in the circular economy, and therefore the choice was made in this study to investigate existing products that make use of discarded materials. In order to further examine potential resource recovery routes, practical examples of products developed from waste materials were obtained in a series of interviews and analysed to illustrate possible gaps between the resource recovery routes described in the literature and what happens in practice.

3.1. Interview study design

To explore the examples of products in practice, interviews were held with designers and waste management professionals. A total of 25 semi-structured interviews, lasting between 40 and 90 min, were carried out face-to-face (22 interviews) or through a video-conference over the internet (3 interviews). All the designers interviewed had used waste materials for product development (10 interviewees). The waste management professionals (14 interviewees), who had experience of the waste sector, were asked to give examples of products or services that could facilitate resource

Table 3
Information on the interviewees used in the study.

Country	Total interviewees	WM	Designer (D)	Internet interview
Chile	5	3	2	–
Egypt	1	1	–	–
Germany	5	2	3	1 (D)
India	1	1	–	1
Sweden	13	7	6	1 (WM)

recovery from the waste streams. One extra interview was held with a designer working for a waste management company. The interviews followed a semi-structured guide with the following main questions:

1. How do you perceive a relation between design and waste management?
2. What impression do these product examples give to you?
3. Do you know of other such product examples?
4. Have you worked with product designer/waste managers?

All the interviews were recorded for future referencing and analysis. The participants were selected from different countries, representing different types of waste management (WM) systems and contexts, to provide cultural diversity in the study (for a detailed list of interviewees, see Table 3). The selection of country was not representative in any way, but was rather where the authors successfully established contact with participants. The number of years of experience in the field varied among the interviewees, ranging from a person who had started working with waste issues in 1988 to one who started working with these issues recently (in 2011). The group consisted of 10 female and 15 male interviewees, ranging between the ages of 28–59 years.

The objectives of the study were briefly explained to the interviewees and the definitions used in the interview for (1) waste, (2) municipal solid waste and (3) professional designer were then introduced as follows:

Waste: Substances or objects which are disposed or are intended to be disposed or are required to be disposed of by the provisions of national laws (UNEP, 2007).

Municipal Solid Waste: Waste collected and treated by, or for, municipalities. It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, yards and gardens, street sweepings, contents of litter containers, and market cleansing. Waste from municipal sewage networks and treatment and municipal construction and demolition waste are excluded (OECD, 2010).

[2] Michelin, Caterpillar, Renault, Rocoh and Desso.

Professional Designer: Person that engages in product development as their profession. The product development process is the entire set of activities required to bringing a new product concept to a state of market readiness (Otto and Wood, 2001).

Two examples printed on cards were used as visual aids to illustrate new product development from discarded materials (Fig. 1). These examples were used as 'mediating objects' to enable further discussions during the interviews. Engelbrektsson (2004) describes a mediating object as something that stimulates discussion, enhances the users' understanding of a product or product concept, and/or simplifies the dialogue between the user and the developer. Table 4 summarises the content and purpose of the visual cards used.

The results of the interviews were summarised, coded and categorised following the qualitative data analysis approach suggested by Miles and Huberman (1994). Other aspects of this same interview study have been described previously (Ordonez and Rahe, 2013).

3.2. Practical example categorisation

The interviews provided more than 70 examples of products made from waste materials. These products were further investigated by reviewing published material about their production, often consulting directly with the products' manufacturers or sales representatives. Some of the designers interviewed in the study were involved in the development of some of the examples in the list and therefore more information was available for those products. Some of the examples were mentioned in several interviews, while some examples were provided with very little information, making it difficult to follow up in the reviewing stage. Because of this, the final list of examples reviewed only comprised 58 unique examples, some of which consist of several products of similar type of application, material or product.

The review focused on gathering information in order to classify the examples into the recovery routes described in CE and to describe the examples using the following criteria:

- **Product type**: Does the redesigned product/recovered material close the material loop by making the same type of product (=) or a different one (≠)?
- **Value**: Has the value of the redesigned product/recovered material been reduced (<), maintained (=) or increased (>) compared with the original end-of-life material/product? The value may be the commercial value, material quality or the use-related value.

Fig. 1. Visual cards used in the interviews.

- **Production**: Was the redesigned product/recovered material made by hand or using a serial production process?
- **Waste type**: Which waste material was used to redesign or recover material: industrial waste or post-consumer waste?
- **Recycling system**: Does the waste material have an existing, well-established recycling system or not? (The materials that were considered not to have an established recycling system were: electronic waste, textiles, wood, ceramics and vehicle tyres.)

The criteria used to describe the examples were deemed relevant for a better understanding of the nature of the examples obtained during the interviews. An early categorisation of these examples has also been presented previously (Ordoñez and Rahe, 2012).

The various steps performed during the study are summarised in Fig. 2.

4. Results

All the examples of products or solutions that enable resource recirculation obtained from the interviews were reviewed and summarised with their relevant information (see Appendix 1). Table 5 presents an overview of classification of the product examples based on the criteria described in Section 3.2. While classifying the product examples into the recovery routes defined in CE (Maintenance, Reuse/Redistribute, Refurbish/Remanufacture, Recycle and Energy Recovery), there was a need to simplify the terms used and to reorganise the order of the routes presented, as can be seen in Table 5.

A route that was necessary to include covering the examples obtained was biodegradability. This route is discussed in CE as an entirely separate "biological nutrient" pathway that should not be mixed with the technological nutrient pathways. This resource recovery does not feed into the ideally closed technical manufacturing system, but rather to the biosphere.

Some of the examples obtained from the interviews involved a broad category of products (e.g. second-hand markets or small-scale decorative products). These examples were difficult to analyse according to the criteria presented in Section 3.2. For instance, small-scale decorative objects can be made of glass (a waste category with an established waste collection and recycling system) or of electronic waste (which does not have an established collection and recycling system). However, some of the criteria were still applicable to these products. For example, according to the interviewees, small-scale decorative products are generally handmade. Therefore, that example was easy to classify within those criteria.

Three examples did not fit in any of the recovery routes, but they were relevant for the analysis. One of these examples was product leasing, which is a business strategy rather than a specific example for material recirculation. It was mentioned in general terms in the interview, so it was deemed to enable reuse, remanufacturing and recycling, depending on what product was being leased and how worn its components were. The second example that did not fit into one recovery route was 'Remade in Chile', a design contest for products made from discarded material. The contest has generated a number of examples over the years, some involving remanufacturing or recycling. The latest example is Armo shoes, by the Chilean designer Rodrigo Alonso. Armo are flexible handmade shoes made by people in extreme poverty in Chile as a part of small-scale businesses. The flexible design allows users to: (i) transform the shoes into different types of shoes to improve the product utility, thereby avoiding the need for new shoes; and (ii) to replace worn-out parts of the shoes, thus minimising waste generation.

Table 4
Content and purpose of visual cards used as mediating objects in interviews.

Visual card	Source and intended purpose
LCD recycling	This example (developed by designers from BOID[a] and CIT) uses the surface components of LCD screens to generate illuminating surfaces using some LED lamps fixed to an aluminium armature. This case was shown to exemplify reuse of components from electronic waste, while giving an example of elegant, high-tech use of waste components.
Chair	The RCP2 chair by Jane Altfield[b] is an early example of products designed with waste (© Victoria and Albert Museum, London). It has to some extent become an iconic example, where the irregularities present in the waste material used are evident in the final product. It was used as an example that people normally associate with designing with waste.

[a] BOID is a multidisciplinary design bureau. More information at: http://boid.se/.
[b] Victoria and Albert Museum, London. Available at: http://collections.vam.ac.uk/item/O114267/rcp2-chair-atfield-chair-chair-atfield-jane/ [Accessed August 14, 2012].

The final categorisation of the products studied suggested that most of the examples represented two resource recovery routes: remanufacturing and recycling. The distinction between these routes was based on two factors: (1) the recycled examples produce a material, rather than a finished product; and (2) the production process used to recycle materials alters their molecular/chemical properties, rather than just their physical properties by means of mechanical alteration. Although we had the same number of examples for recycling and remanufacturing (cf. Table 5), the volumes processed by recycling were larger.

4.1. Characteristics of examples

4.1.1. Product type

Most of the redesigned products closed the material loop by developing a different product type (see Table 5). This could be due to fact that the actors involved in developing most of these examples were not the original product manufacturers. Therefore, this is different from the proposed recirculation in CE, where the original manufacturers would take back the products once they had been discarded. This was the main difference between the products reviewed in this study and CE theory. Both CE and the examples reviewed considered it important to keep the material resources within the socio-economic system rather than opting for solutions such as energy recovery or disposal. However, the examples provided cases of different actors recirculating materials, rather than separate industries operating in isolation.

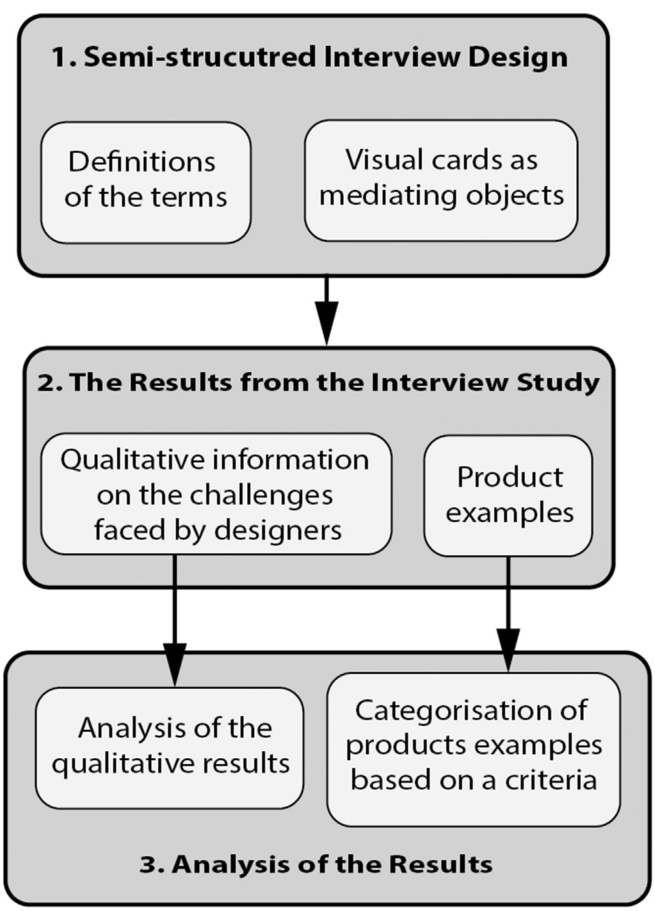

Fig. 2. Summary of various steps carried out in the study.

As expected, the reuse route examples recirculated the same product. As regards the examples for maintenance, it was difficult to define whether they recirculated materials into the same product or not. Since they were all broad examples of maintaining and repairing electronic equipment, it was considered that in some of the cases the resources were used in the same way (e.g. replacing a faulty component) and in others not (e.g. using parts from several devices to put together a new functioning device with enhanced features). It could be argued that these two possible ways of performing maintenance correspond to enabling reuse though repair, or remanufacturing the components into a new product. This led us to question maintenance as a recovery route per se, and view it rather a strategy used in order to reuse or remanufacture.

The examples from the recycling route that could deliver the same product were metal, aluminium and glass recycling, since the material properties in these cases do not degrade by recycling. However, these materials can also be recycled into different products, so it is not always the case that they end up delivering the same product. The only clear example of recirculation to the same product outside the reuse route was Reline, one remanufactured example. Reline collects second-hand tableware items that are mismatched and gathers them into sets using simple visual connection elements (Fig. 3).

Energy recovery, as expected only makes use of the energetic content of the material, destroying the original product in the process.

4.1.2. Production

Most of the examples were made in serial production processes. This implies that most of the examples could be mass-produced if desired, strengthening resource recirculation in society. Most of the handmade products belonged to the remanufacturing route. This indicates that this route requires more control over the material collected, in order to inspect it and evaluate its condition before recirculation. It can be expected that many of the handmade examples could be developed in serial production, but this is currently not the case. It might also be expected that even though more serial remanufacturing processes are developed, they will never be fully automated, requiring manual inspection of the collected material or outcome at some point.

4.1.3. Value

The value of most of the reviewed examples exceeded that of the original end-of-life material/product. This conforms to the central

Table 5
Examples grouped by recovery route and described following the chosen criteria.1

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**

Repeated examples that belonged to multiple categories

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

idea of CE, where resource recirculation aims to conserve as much value as possible. This is also the case in the waste hierarchy.

The commonly used terms ‘up-cycling’ and ‘down-cycling’ refer mostly to the increase or decrease in value when recirculating resources. These should not be considered recovery routes per se, but rather a characteristic of recirculation depending on how the value has been managed.

Value is very subjective and difficult to define, however. For most products studied, the economic value was gained during the resource recovery process but it was uncertain whether the quality of the material was improved or not. For this categorisation, material quality conservation was considered, as well as user appreciation evaluated through the cost of the recirculated materials/products. Examples such as jewellery made from electronic waste generated interesting analysis of this criterion. The material properties of the electronic components, such as conductivity or magnetism, were not needed for making jewellery. Nonetheless, these pieces may sell for a higher price than the previous use. This raises questions such as: Is it better to recirculate such materials in ways that their inherent properties would be most appreciated? or Should this be regulated in a future CE?

Fig. 3. Reline tableware. Source: Bormann (2012).

4.1.4. Waste type

Most of the examples studied made use of post-consumer waste. CE postulates that industrial waste is the result of suboptimal production processes and should be avoided by means of optimisation and industrial symbiosis. However, the current reality is far from such an ideal system and there are still large volumes of industrial waste generated. If these wastes are not recyclable (e.g. textiles), remanufacturing can be investigated as a possibility for recovery, as some of the remanufactured examples show (e.g. T-shirt seat).

Two examples used a mixture of post-consumer waste and industrial waste. One of these was Polyplank (Fig. 4). Polyplank is recovered thermoplastics (post-consumer) mixed with wood fibre or sawdust (by-product of wood production), generating a composite wood-like material that can be string or injection moulded (Polyplank, 2012). The company producing this material claims that it can be recycled up to seven times. However, the question this example poses is: Would it be better if the plastic had been kept in a clean stream?

Fig. 4. Polyplank products Source: Polyplank (2012).

4.1.5. Recycling system

The examples were almost evenly divided between cases that used materials with an existing recycling system and materials that did not. Most of the examples with established collection and recycling systems, as expected, belonged to the recycling route. Of the five recycled examples that made use of materials without existing recycling systems (cf. Table 5), one example used biodegradable material (i.e. Inplum) and another was developed when there was no recycling alternative but now it has a mainstream recycling solution (i.e. Tectan from Tetrapack), while the other three used waste incineration ash to make different products.

It can be questioned whether the remanufactured examples that use a material with an established recycling system are worth pursuing, given that they target a material that already has a functioning recirculation route. However, since remanufacturing in general uses less energy in its recirculation process, while generating a product of higher value than recycling, these are still desirable endeavours.

4.2. Revised resource recovery routes

Based on the categorisation of the examples studied and the questions presented in the previous section, a revised version of the resource recovery routes was developed (Fig. 5). In this definition, the routes are classified based on the stage of the product life cycle into which they recover material: use phase (reuse), manufacturing stage (re-manufacture) or material production (recycling). Maintenance is not considered a route per se but, together with repair and relocation, is a strategy used in order to recirculate material into any of the existing routes. Each of the three main routes is further classified based on whether: 1) the materials are recovered locally (i.e. at the use or manufacturing phase) or centrally by the WM system; and 2) the materials are used for the same purpose as previously or for a different purpose (same or different product type).

The proposed model is intended to highlight recirculation possibilities for materials through society. By linking the routes to the different product life stages, the model hints at the actors who may be involved in the recirculation. It also provides a more neutral view of resource recovery, where existing waste management is seen as an important stage and actor to enable future take-back systems. Unlike the recirculation model proposed by CE, there is no direct link from users back to manufacturing companies. This route could of course be developed in a future situation, but the proposed model presents routes based on existing material distribution and collection systems.

4.3. Main challenges for designers identified in interviews

4.3.1. Uncertainties at the use and end-of-life stages

Product development from waste is a huge challenge without control or accurate prediction of the composition of the waste streams available. Products can be handled very differently in their end-of-life and use phases. For instance, two chairs from the same production process can end up in differing condition when discarded, depending on how they were used and for how long. One of the chairs may be sorted out for re-manufacturing while the other is discarded with mixed waste, and consequently the recovery process further deteriorates the material and components in the chairs differently. This irregularity is unavoidable, especially for specific products. These issues were explicitly raised during the interviews:

> “It is hard to standardise a product from something (waste streams) that is not standard.”

Similarly:

> “You can never mass-produce something like that (BOID LED lamp), because you don't know if you will have enough components to produce it (new product).”

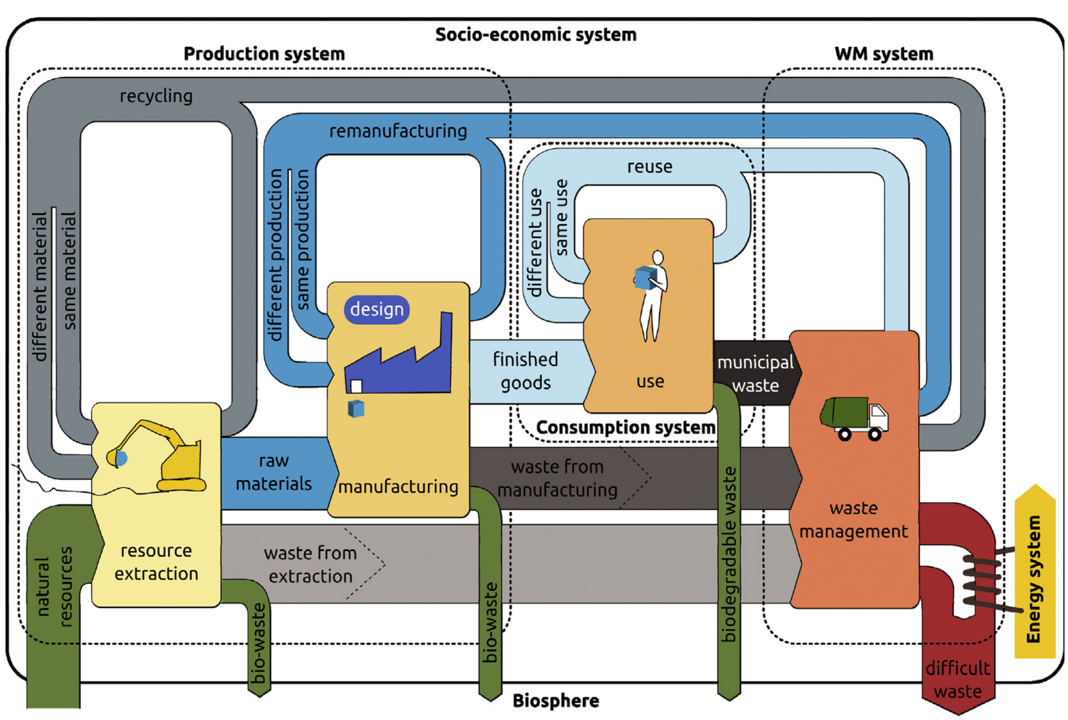

Fig. 5. Proposed model to illustrate possible material flows through society, including resource recovery routes.

Furthermore, the material composition of waste streams changes seasonally, over time and depending on the location where the waste is collected.

Some of the issues regarding end-of-life uncertainties are easier to address when product design uses industrial waste (instead of post-consumer waste), since this waste is typically leftover material from production with a well-known composition. Such initiatives are demonstrated by some ongoing projects (Ordoñez and Rahe, 2012). However, utilisation of industrial waste in new product development should not be favoured over prevention of production waste by means of production optimisation.

Designers have a limited influence over how products are discarded.

> "You can design for recycling, but who ensures it will be recycled in the end?"

This presents a challenge for designers to include broader aspects (such as cultural values) into the design process in order to *successfully* communicate this information to consumers. This challenge escalates when product development takes place in diverse global markets with no international standards for WM.

4.3.2. Quality of products from recovered materials

Reflections about the quality of products made from discarded materials emerged in several interviews. The interviewees made a clear distinction between products made with discarded materials that were simply not appealing and those which were:

> "You can use old things to make other stuff, but there are so many examples in the recycling world that are not nice, that lack the final steps of design to make them desirable objects again."

> "You see many bad reuse or recycling examples, these are not going to solve the big environmental problems."

Furthermore, one of the experts interviewed raised concerns about the competitiveness of products developed from discarded materials:

> "It is not enough (to be recycled or reused) to sell products."

Therefore, designers should not have the preconceived idea that products developed from discarded material will be preferred over new products. On the contrary, perhaps, designers need to make the product attractive enough to compensate for the prejudice about poor quality linked to products made from discarded materials. There is no specific market for products made from recovered materials, meaning that these products have to compete within the existing markets. This implies that conventional product quality standards must apply to the products made from recovered materials. Product cost also plays an important role. If the price difference between recovered materials and virgin materials is small (which is currently the case for many materials), there is no monetary incentive to justify material recovery (which is very often more difficult to do). One designer even stated:

> "We have to fool the public as long as possible that this is smart new design. They do not need to know it is recycled."

4.3.3. Product complexity

Due to rapid technological innovations, the complexity of product composition has increased significantly (Singh et al., 2014). Indeed, electrical and electronic products are becoming more complex and smaller than ever. The fractions of each type of materials used have been reduced, meaning that there is less value to be recuperated by separating them, as brought up by one of the interviewees:

> "Now producers tend to put in less and less value into products, which leaves less value for recyclers."

Consequently, only scaling up the collection of such products could maintain the profitability of the process of recovering such materials. Extended Producer Responsibility (EPR) proposes that producers are responsible for reusing, recycling and finally disposing of the products and components they manufacture. This is an important driver to recover the materials they produce and to enhance sustainable product design (Lindhqvist, 2000). However, in several cases, instead of individual product responsibility, producers outsource the responsibility to other organisations (Wilts et al., 2011). Producer Responsibility Organisations (PRO) often provide a more economically efficient way of recovering and recycling recovered products, given their larger volume of operations. Since these PRO are external to the manufacturing companies, the original aim of EPR to advance product design is lost. Furthermore, this increases the complexity of the 'take-back' system, where the PRO takes care of the discarded products of their associated producers but with no real means of reintegrating them back into the same manufacturing industry, as would be desirable in a circular economy.

4.3.4. Agency and ownership issues

Another problem the designers we interviewed reported was material ownership. It was not always straight-forward to get access to the material they wished to use for their product development:

> "We spend a lot of time going around looking for stuff, while waste management companies just get the material."

Another designer had tried collaborating with waste management companies, but considered it difficult:

> "They have their core business to focus on. They are not used to product design, so they do not see the possibility to develop products."

This difficulty was even mentioned by a waste management professional, who explained that they were bound to dispose of the material they receive in the best possible way. This means that any recirculation of their material has to be carried out by serious and certified actors, excluding the possibility of "design exploration".

5. Discussion and conclusion

Resource recovery routes defined in the literature vary in meaning due to the value-based conception of waste and related collection practices. The WM hierarchy defined for the EU still focuses on post-consumer waste, in contrast to CE where the focus is to achieve resource recirculation through new product and new system design. However, there are only a few 'success stories' of CE to provide an inclusive view of the myriad of challenges facing product designers attempting to close the material loops. This study made an attempt to classify the resource recovery routes based on practical examples of resource recovery from waste material streams. These routes can serve as a 'menu' for product designers and businesses when approaching recovered materials.

To highlight the potential for remanufacturing and reuse based on practical experiences, a choice was made in the beginning of the study to investigate existing resource recovery systems. In contrast to CE, which proposes new resource recovery systems to 'take back' products, the results obtained this study highlight the potential of current resource recovery systems in facilitating CE operations. The results also illustrate the potential for resource recovery based on practical experience, rather a limited number of examples often described in reports on CE. Furthermore, the results provide some important insights into the challenges faced by the product designers aiming to close material loops. These practical experiences could assist product or system designers working with CE in recognising and addressing these challenges at the start of the design process. Thus, the information presented in this study can act as a stepping stone in linking existing systems for resource recovery to CE developments.

5.1. Limitations of the study

In this study, the defined resource recovery routes were based on the analysis of 58 distinct product examples encountered during semi-structured interviews with designers and waste management professionals. We recognise that the robustness of the study results depends directly on the number of examples investigated and therefore it could be questioned whether the proposed resource recovery routes would still be valid if the number of examples were increased.

The examples were classified based on product type, value of the product, production type, waste type and availability of collection and recycling system. This classification was utilised to define the resource recovery routes based on these examples. The availability of more product examples could have influenced the choice of these indicators.

Some of the interviews were longer and therefore more information was available from those interviews. Furthermore, for some products, the interviewees were personally involved in the development of the product and therefore more reliable and detailed information was available for these products. These factors could have influenced the inferences drawn in this study.

Limited information was available on: (i) the type of design philosophy involved in developing the product examples studied; (ii) whether these products were initially developed for demonstration or business purposes; and (iii) whether these products were developed by self-motivated individual designers or as a part of the job, with limited freedom to design. These factors could also limit the applicability of the findings of this study.

5.2. Relevance to CE

The products investigated in this study represent innovative modes of doing business with recovered resources, using pathways similar to CE. The product study conforms to the principles describing CE. Therefore, the challenges highlighted in the present study, although specific for WM and product design with discarded materials, are also relevant for the ongoing systems transition towards CE.

The products studied utilised a range of discarded materials and most of the products showed an increase in value. This indicates that there is huge potential for material recirculation through reuse, remanufacturing and recycling rather than opting for traditional WM practices in a linear way. These examples challenge the CE aspirants to broaden the realm of CE to include several product categories such as potential business areas, especially when CE has been limited to only a few products.

Furthermore, these examples illustrate an important role of product (or system) designers in closing material loops. Four major challenges to be addressed by designers were identified: managing uncertainties at the use and end-of-life phase; maintaining product quality throughout the life cycle of a product; maintaining quality of products made from recovered materials; and addressing issues relating to agency and ownership of products.

Product designers face a new challenge of anticipating these social, economic and environmental challenges in their design process and helping to realise the goals of CE. Thus product designers must: (1) holistically address the issue regarding product complexity; and (2) adjust to upcoming design challenges where they need to start the design process from discarded materials and rely on uncertain waste flows. The present study indicates that the end-of-life uncertainties and their relation to product design process may not affect the design process in the CE concept, since material handling on mass scale could help designers to predict material collection in advance. However, the management of product design in a situation with rapid technological innovations, e.g. for products such as mobile phones, will be a great challenge for designers.

Appendix 1. Summary of the examples of products or solutions that enable resource recirculation.

Product	Designer	Material	Recovery route (CE)	Same/different product	Value	Clarification	Hand made/ Serial	Waste type	Availability of recycling system	Web page
Armo sneakers	Rodrigo Alonso	Handmade shoes in micro-factories as means of poverty alleviation	–	–	–	Fair trade policies, allows for a diverse production system and flexible use	HM	–	No	Link
*	Remade in Chile	Several examples	–	–	–	Design contest with several examples and done in many locations	Varies	Varies	Varies	Link
Janipad		Biodegradable sanitary pad	Composting	–	Increased	Biodegradable	S	PCW	No	Link
Eco envases	Several actors		Composting	–	Increased	Biodegradable	S	PCW	Yes	Link
Peepoo	Peepoople		Composting	–	Increased	Biodegradable	S	PCW	No	Link

(*continued*)

Product	Designer	Material	Recovery route (CE)	Same/different product	Value	Clarification	Hand made/ Serial	Waste type	Availability of recycling system	Web page
		Biodegradable plastic toilet bag								
Biochar as fuel		–	Energy recovery	Different product	Reduced	–	S	PCW	Yes	–
Tires as fuel for concrete production	Several actors	Tires	Energy recovery	Different product	Reduced	–	S	PCW	No	–
Fixing WEEE, component recuperation	Several actors	–	Maintenance Remanufacture	Same/different product	Maintained or increased	Repair done with technical competence	S	PCW	No	–
WEEE fixing and disassembly	Recycla Chile WEEE	WEEE components	Maintenance Remanufacture	Same/different product	Maintained or increased	Repair done with technical competence	S	PCW	No	–
orange.at/recycling	Several actors	Cellphone collection	Maintenance Remanufacture	Same/different product	Maintained or increased	Repair done with technical competence	S	PCW	No	–
Inplum, planters	Genoveva Cifuentes	Plum core agglomerate	Recycle	Different product	Increased	Biodegradable	S	IW	No	Link
Weather resistant planks	Polyplank	Recovered thermoplastics with wood fibre	Recycle	Different product	Increased	Mixes materials	S	PCW & IW	Yes	Link
Bricks	Several actors	Waste incineration ash	Recycle	Different product	Increased	Incineration by products	S	PCW	No	Link
Pavement	Several actors	Waste incineration ash	Recycle	Different product	Increased	Incineration by products	S	PCW	No	Link
Tiles	Several actors	Waste incineration ash	Recycle	Different product	Increased	Incineration by products	S	PCW	No	Link
111 Navy chair	Emeco	PET coke bottles	Recycle	Different product	Increased	–	S	PCW	Yes	Link
Flower pots	Several actors	Recycled plastics	Recycle	Different product	Increased	–	S	PCW	Yes	–
Recycled polyester clothes	Patagonia	PET bottles, manufacturing waste and worn out garments	Recycle	Different product	Increased	–	S	PCW	Yes	Link
Recycled aluminium chairs	Several actors	Aluminium cans	Recycle	Different product	Increased	–	S	PCW	Yes	–
Packaging for fruit exports	OKSCU	Recycled plastics	Recycle	Different product	Increased	–	S	PCW	Yes	–
Waste sorting containers from recycled plastic	Triciclos.cl	Recycled plastic boards	Recycle	Different product	Increased	–	S	PCW	Yes	Link
Garden furniture from recycled plastics	Several actors	Recycled plastic	Recycle	Different product	Increased	–	S	PCW	Yes	Link
Recycled pallet	Hans Andersson Recycling	NA	Recycle	Different product	Increased	Made a prototype for a pallet from recycled materials in the 80s	S	PCW	Yes	–
Shredded plastic for roadmaking	Several actors	Recycled plastics	Recycle	Different product	Maintained	–	S	PCW	Yes	–
More recycled materials in cars	Several actors	Recycled plastics	Recycle	Different product	Maintained	–	S	PCW & IW	Yes	–
Tectan	Tetrapack	Agglomerated Tetrapack packaging	Recycle	Different product	Reduced	Not developed further, but still done in some areas	S	PCW	Not then	–
Cardboard furniture	ReturDesign	Cardboard	Recycle	Different product	Reduced	Designed for recycling	S	Waste prevention	Yes	Link
Glass recycling	Several actors	–	Recycle	Same/different product	Maintained	–	S	PCW	Yes	–
Metal recycling	Several actors	–	Recycle	Same/different product	Maintained	–	S	PCW	Yes	–
Aluminium recycling	Several actors	–	Recycle	Same/different product	Maintained	–	S	PCW	Yes	–
Paper recycling	Several actors	–	Recycle	Same/different product	Reduced	–	S	PCW	Yes	–
PET recycling	Several actors	–	Recycle	Same/different product	Reduced	–	S	PCW	Yes	–

(*continued on next page*)

(*continued*)

Product	Designer	Material	Recovery route (CE)	Same/different product	Value	Clarification	Hand made/ Serial	Waste type	Availability of recycling system	Web page
Profil belts	Yeayea	Bike tires	Remanufacture	Different product	Increased		HM	PCW	No	Link
Furniture	Showraum	Reclaimed wood, furniture	Remanufacture	Different product	Increased	Designer network that showcases remanufactured products	HM	PCW	No	Link
Bags	Retape	Magnetic tape	Remanufacture	Different product	Increased		HM	PCW	No	Link
*	Taller Re-Crear	Several examples	Remanufacture	Different product	Increased	Workshop for handmade upcycled products	HM	PCW	Yes	–
Bags	Demano	Discarded PVC advertising	Remanufacture	Different product	Increased	–	S	PCW	No	Link
Wretman-stället	Torstensson	Silverware production discards	Remanufacture	Different product	Increased	–	S	IW	Yes	Link
*	Creatables	Laminated industrial discard	Remanufacture	Different product	Increased	Sometimes even performs production symbiosis	S	IW	Yes	Link
Hacking & DIY movements	Several actors	–	Remanufacture	Different product	Increased	Creative reuse, user repurposes not manufacturer	HM	Waste prevention	Varies	–
WEEE jewellery	Several actors	WEEE components	Remanufacture	Different product	Increased	–	S	PCW	No	Link
Refurbished old drawers to new bureaus	SchubLaden	–	Remanufacture	Different product	Increased	Same type of product, not exactly the same product	S	PCW	No	Link
T-shirt seat	Maria Westerberg	Metal frame with woven scrap textiles	Remanufacture	Different product	Increased	–	S	IW	No	Link
Small scale decorative stuff	Several actors	–	Remanufacture	Different product	Increased	–	Varies	PCW	Varies	–
Backpacks of BSR uniforms	–	Worn out waste picker uniforms	Remanufacture	Different product	Increased	–	HM	IW	No	–
Sorensen RCY men shirts	Cecilia Sörensen	Textiles, men shirts	Remanufacture	Different product	Increased	–	HM	PCW	No	Link
Tire baskets	Several actors	Tires	Remanufacture	Different product	Increased	–	S	PCW	No	Link
Bag made of knitted plastic bags	Several actors	–	Remanufacture	Different product	Increased	–	HM	PCW	Yes	–
Playgrounds and landscaping with discard	Several actors	Industrial waste	Remanufacture	Different product	Increased	–	HM	IW	Varies	Link
Ass-savers	–	PP cutouts from another industrial process	Remanufacture	Different product	Increased	production parasites	S	IW	Yes	Link
School gym equipment as furniture	–	–	Remanufacture	Different product	Maintained	Creative reuse, user repurposes	HM	PCW	No	–
WEEE chair	Rodrigo Alonso	WEEE encased in transparent resin	Remanufacture	Different product	Reduced	Done as an artistic installation	S	PCW	No	Link
Bags made of sails	Several actors	Old sails	Remanufacture	Different product	Reduced	–	S	PCW	No	Link
Reline tableware	Anna Bormann	White tableware	Remanufacture	Same product	Maintained	–	HM	PCW	No	Link
Second hand markets	Several actors	–	Reuse	Same product	Maintained	Relocation of goods to other users	–	PCW	Varies	–
Charity organizations	Several actors	–	Reuse	Same product	Maintained	Relocation of goods to other users	–	PCW	Varies	–
Glass containers for ketchup or mustard used as glasses-	Several actors	Glass	Reuse	Same product	Maintained	Designed for reuse	S	Waste prevention	Yes	Link
Product leasing	–	–	Reuse Remanufacture Recycle	–	–	Business model strategy	Repair	Waste prevention	–	–

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