What makes solutions within the manufacturing industry resource efficient?

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1 Introduction

The linear mode of production and consumption has dominated the last century. Raw materials are extracted, processed and assembled into products that are often discarded after only a short life. This entails a net flow of material from the earth's crust into diluted stocks spread over society and in nature. To achieve long-term sustainability, a shift towards resource efficiency (RE) and a circular economy (CE) needs to take place (see e.g. Ghisellini et al., 2016).

Circular economy is not yet a concept with a universally accepted definition, but according to Ghisellini et al. (2016) the CE is described as a step away from the current linear consumption model of take-make-dispose towards a circular model, where material flows are closed and resources are utilised in an efficient manner. It has the potential to aid in decoupling economic growth from environmental impact and use of natural resources. CE is connected to concepts such as Product-Service Systems (PSS) and the service economy, in that such approaches potentially decrease the material intensity of the economy.

Mistra-REES is a multi-disciplinary research program which, based on circular economy thinking, intends to fill the knowledge gaps associated with resource efficient solutions. The program seeks knowledge on which means for resource efficiency are effective for which type of products or solutions, as well as finding trade-offs between e.g. environmental gains and material use. The objective is to develop guidelines and methods for the design of resource efficient solutions, business models and policies enabling resource efficiency, as well as to study the interrelations between these aspects. The present paper is a part of Mistra-REES and is expected to contribute to said research.

The type of value-chain resource efficiency as studied in the context of the Mistra-REES program can be achieved in an abundance of ways. A manufacturer can attempt to implement various resource efficient solutions, such as car sharing schemes, reuse of electronics and remanufacturing of engines to name a few examples. Such solutions can usefully be divided into three conceptual categories (Willskytt et al., 2016): (a) production efficiency and supply-chain measures (e.g. reducing scrap rate or changing materials), (b) more efficient use of products (e.g. sharing, prolonging the product lifetime, energy efficiency) and (c) closing the loops (reverting material flows back into the product-chain, through reuse and recycling). But, from a life-cycle perspective, how resource efficient are such solutions in actuality?

While there is a large number of assessment studies on cleaner production (i.e. the first of the three categories mentioned) in the literature, significantly fewer studies exist assessing the effects of activities that fall into the other two categories of efficient use and closing the loops (Mont, 2004). Efforts to synthesise knowledge from assessment studies to gain a more general and full understanding of CE and resource efficiency are rare (Tukker, 2015). Goedkoop et al. (1999) point out that when it comes to PSS, a shift to more service-focused business models on average leads to improvements in environmental performance. But the results are highly variable, and exceptions are common. Hence, there is a lack of generic understanding of when a RE solution in fact leads to a net improvement in resource efficiency, and under which conditions (such as product characteristics or market conditions). Goedkoop et al. (1999) recommend assessments to be made on a case to case basis, while Tukker (2015) mentions the need for performing meta-analysis on many quantified case studies, which would enable understanding the mechanisms behinds said variability in results.

To this end, Willskytt et al. (2016) present an analytical framework, built on the ideas of CE and RE. Their purpose is two-fold, and the first is to suggest a typology of different means for RE, which consists of the three above-mentioned categories (see Figure 1). This typology provides a meaningful categorisation of different means for resource efficiency and it allows mapping of related physical and design aspects as well as barriers and drivers for their implementation.

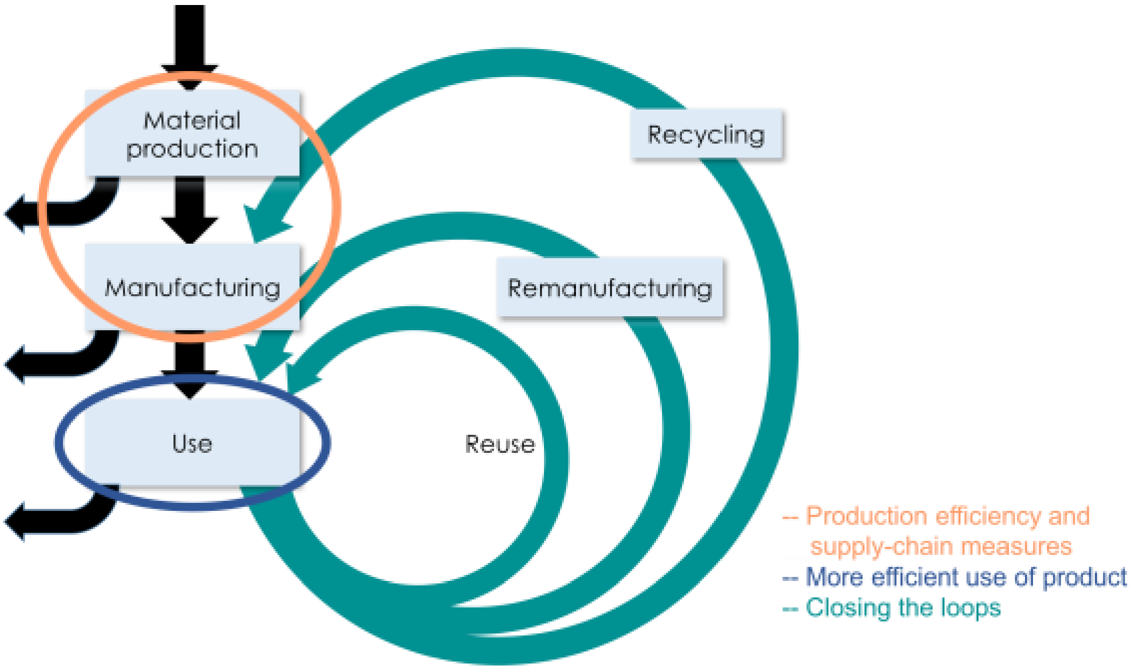

Figure 1: Conceptual image and typology of the analytical framework, from Willskytt et al. (2016), showing material flows through a simplified product life cycle and highlighting the three main ways of achieving resource efficiency, namely production efficiency & supply-chain measures, more efficient use and different ways of closing the loops.

The second purpose of the framework is to be used as a tool to help systematize learning from assessment studies on resource efficient solutions. Such systematic analysis of many different assessment studies is expected to allow the analyst to draw generic conclusions about resource efficient solutions, which can lead to an increased understanding of why certain solutions are successful or not.

The present paper is a pilot study where said framework is applied and tested for the first time. The purpose is to achieve some generic understanding about what characterises resource efficient solutions and what makes them resource efficient or not, as well as identifying important trade-offs, e.g. between reduced energy consumption and increased use of scarce materials. To this end, a number of assessment studies evaluating the environmental and economic consequences of implementing resource efficient solutions have been collected from literature. The framework is systematically applied on each assessment study and subsequently the relevant results and conclusions are gathered, processed and synthesised in different ways. The resulting understanding of the mechanisms behind RE can be used to develop guidelines for planning or designing for resource efficiency and CE, be it products, services, business models or policies. Since this is a pilot study the foundation of data and assessment studies is yet limited, which prevents any robust statistical or quantified analysis and therefore the results are largely presented in qualitative terms.

Another purpose of this study is to evaluate the suitability of the analytical framework as a tool for analysing assessment studies and achieving general knowledge of resource efficient solutions.

When it comes to the scope of the study the focus is on physical aspects of resource efficiency and achieving reduced material flows. What is sought is the underlying reason for a successful reduction in material flow. New business models and organisational or policy innovations are potential ways of generating and achieving resource efficiency, but the business model itself is only a means to an end (Tasaki et al., 2006). Hence the focus is less on organisational aspects, and more on physical ones. The intended audience of this article is various actors who wish to learn about and implement solutions that form a circular economy, be it researchers, companies, policy-makers etc. It also aids in building a foundation of knowledge for the Mistra-REES program and its participants.

2 Method

A number of assessment studies on resource efficient solutions gathered from literature were analysed by applying the analytical framework on each study.

Firstly, a number of choices needed to be made regarding the scope of the selection of assessment studies to be analysed. The literature search was focused on studies assessing attempts at reducing material flows for products in the manufacturing industry, preferably from a life-cycle perspective. The studies were chosen to exemplify as much as possible of the three categories of resource efficient solutions mentioned above.

Consequently, a majority of the studies are Life Cycle Assessments (LCA) on varying types of products and services, but also other types of studies are included, such as Life Cycle Cost Analysis (LCC) and Material Flow Analysis (MFA). The literature base of the present article constitutes a mix of articles from scientific journals as well as studies by the companies involved in the Mistra-REES program and master's theses. The studies cover a wide range of offerings from different sectors, for instance products from the automotive, electronics, tools and construction industries as well as cleaning services etc. Note that the list of offerings is not meant to be exhaustive, instead it is a first selection meant to cover enough different products to provide a first test of the framework and allow for an initial analysis. 17 assessment studies were ultimately gathered and analysed, and they are presented in Section 3.

The way that the analytical framework works in practice is that a number of forms are filled with information relevant to the analysis. When analysing a case study, the first step is to identify the different ways to improve resource efficiency that have been assessed in the study. Each identified activity can be categorised according to the typology described above, into one or more of the three categories of production efficiency, efficient use or closing the loops. Under each of these categories there are specific activities presented in Figure 2 and explained as follows.

"Production efficiency and supply-chain measures" includes activities for optimising production processes by reducing losses, scrap rates and energy use, or to reduce the material requirements in products (by making them lighter or changing to another material). The second category, "Efficient use of products", regards the use phase of a product and includes three activities. "Prolong life" is an activity which delays the end of life of a product. "Intensify use" means to use a product more efficiently by e.g. sharing or leasing and "Maintenance & repair" are activities such as cleaning, painting, exchanging components etc. that are done during the product's use phase, i.e. before its end of life.

The final category, "Closing the loops", happens after a product has reached its end of life and the product is returned to use, in some shape or form. "Closed-loop reuse" means that the product is used again by another owner, but that the product still fulfils the same function and purpose, while ”Open-loop reuse" means reuse of the product for another purpose. "Remanufacture & repair" means to restore a product to its functional state after its end of life. This is done by disassembling the product, repairing or exchanging components and any aesthetic enhancements necessary and subsequently assembling the product again. Repairing simply restores functionality to a product, while remanufacturing should leave the product in a state equal to or better than the original one, though it can contain varying amounts of new and reused components and materials (variations of these concepts, like "refurbishment", are for simplicity assumed to fall under this definition). "Functional recycling" means to recycle the materials of a product while maintaining the material properties. "Non-functional recycling" is when the material is downgraded to a lower quality which does not fulfil a similar function as the original material.

Production efficiency and supply chain measures	Reduced material use in products Reduced scrap rate
More efficient use of products	Prolonged life Intensified use Maintenance and repair
Closing the loops	Closed-loop reuse Open-loop reuse Remanufacture and repair Functional recycling Non-functional recycling

Figure 2: The three categories and their specific activities to achieve RE as described in the analytical framework.

The framework also allows for mapping the design measures and physical and infrastructural changes in each case, as well as some external facilitating conditions relating to the product chain such as market or policy forces and user behaviour.

To fulfil the second purpose of the framework, a supporting set of forms were constructed for the analyst to fill with information regarding the characteristics of the system, of the study itself as well as any relevant results and conclusions. The first of these concerns the offering characteristics and includes information such as what function is fulfilled, whether the product contains scarce materials or has a long lifetime. This list is intended to reflect the characteristics influencing the performance of resource efficient solutions, and for this pilot study these will form the basis for structuring the analysis below.

Secondly, there is a form meant for gathering details on the assessment study itself in order to provide context for the results of the study which is often strongly dependent on methodology choices such as system boundaries and functional unit. Thirdly, there is a form for presenting the results of the study, in terms of material use, environmental impact and economic performance, along with information on key assumptions, identified trade-offs, limitations, risks or drivers. Finally, there is room for the analyst to write their own comments and gather conclusions of particular interest identified in the study.

The method of analysis, to apply the framework itself, was to systematically read through every study, and fill in the forms of the analytical framework. This enabled the extraction of relevant information and the mapping of activities and characteristics. In practice the analysis in this paper and the development of the analytical framework has been on-going in parallel. This means that the process of development and analysis has been iterative in nature, where analysis has led to insights and changes in the framework itself and so on.

3 Results

The results are structured by first presenting all the different assessment studies included, as well as different relevant details around these, such as methodology, identified resource efficient activities and results. Finally, the main part of the results is an analysis of the trade-offs related to different product characteristics identified when applying the framework on all the collected studies.

The assessment studies cover various offerings which are presented in Table 1, along with the main resource efficient activity identified in each study.

Table 1: List of the collected assessment studies and the offerings that they assess, as well as a note on the main resource efficient solution that they focus on.

Offering	Sector	Main resource efficient solution	Authors	Year
Photocopier	Equipment manu-facturing – office prod.	Remanufacturing	Kerr and Ryan	2001
Car engine	Transport - automotive	Remanufacturing	Smith and Keoleian	2004
Drill	Equipment manu-facturing - tools	Leasing and sharing	Mont	2004
Lawnmower	Equipment manu-facturing - tools	Leasing and sharing	Mont	2004
Car	Transport - automotive	Lifetime extension	Kagawa et al.	2006
Dairy production	Food industry	Reduced waste (by optimised sequencing of production)	Berlin and Sonesson	2006
Electric and electronic equipment (EEE)	Equipment manu-facturing - electronics	Reuse and leasing	Tasaki et al.	2006
Floor care	Construction/cleaning	Improved maintenance	Larsson	2009
Protection sheets	Hygiene	Reuse	Hegelstrand et al.	2011
Washing machine	Equipment manu-facturing - White wares	Sharing scheme	Allen et al.	2012
Lithium-batteries	Transport - automotive	Alternative propulsion system	Olofsson and Romare	2013
Temporary building	Construction	Reuse, leasing, takeback-schemes	Smidt Dreijer et al.	2013
Core plugs	Paper industry	Reuse, remanufacturing	Lindahl et al.	2014
Facade cleaning	Cleaning/maintenance	Ultra-clean water to avoid the use of chemicals	Lindahl et al.	2014
Soil compactor	Equipment manu-facturing - tools	Leasing	Lindahl et al.	2014
Bike sharing	Transport	Sharing	Amaya et al.	2014
2nd hand store	Retail	Reuse through 2nd hand market	Castellani et al.	2015

When analysing assessment studies it is important to put them into context, especially when interpreting their results. The outcome of an assessment is often highly dependent on the method used and key assumptions made, such as system boundaries and functional units. Table 2 shows a summary of the methodological choices of the studies related to each offering.

The majority of the studies were LCAs of different types, while some were complemented with an LCC study as well. The remaining studies (on cars and EEE) applied some form of modelling that was not performed according to any existing frameworks. In regards to geography, most studies were centred around Sweden and the EU, with some exceptions from the US, Asia and Australia.

Table 2: A list of the assessment studies and their respective methodological choices.

Offering	Methodology	Functional unit	System boundaries	Time perspective	Geography
Photocopier	LCA	12 million copies over a period of ten years	Cradle-to-grave	Present system (2001)	Australia
Car engine	LCA	Lifetime distance of 193 tkm of 1995 generic vehicle	Cradle-to-gate	Past system (1995 engine)	US
Drill	LCA	Function of drilling for 10 years for 100 households	Cradle-to-use	Present system (2004)	Sweden
Lawnmower	LCA	Function of lawnmower, 15 years for 100 households	Cradle-to-use	Present system (2004)	Sweden
Car	Modelling life-time extension	-	Cradle-to-grave	Past system (1990-1995)	Japan
Dairy production	LCA	Dairy A: 219000 kg, Dairy B: 182000 kg	Cradle-to-gate	Present system (2006)	Sweden
EEE	Calculating Annual product demand	100000 units for 15 years	Cradle-to-gate	Hypothetical scenarios	Japan
Floor care	LCA, LCC	Clean corridor floor of 1m2 during one year	Cradle-to-grave	Present system (2009)	Sweden
Protection sheets	LCA, LCC	One care recipient's use of products during one year	Cradle-to-grave	Present system (2011)	Sweden
Washing machine	LCA (Carbon footprint)	Laundry service for 360 households	Cradle-to-grave	Present system (2012)	Taiwan
Lithium-batteries	LCA	One full automotive energy storage system (3 year life)	Cradle-to-grave	Present system (2013)	Global/EU
Temporary building	LCA	790 m^2 of office space	Cradle-to-grave	Hypothetical scenario	Denmark
Core plugs	LCA, LCC	Core plug service for paper rolls	Cradle-to-grave	Present system (2014)	Sweden
Facade cleaning	LCA, LCC	Cleaning of 1 m^2 of building exterior	Cradle-to-grave	Present system (2014)	Sweden
Soil compactor	LCA, LCC	0,55 m^2 of compacted soil	Cradle-to-use	Present system (2014)	Sweden
Bike sharing	LCA	Fulfilling the function of 20,000 bike users	Cradle-to-gate	Hypothetical scenario	France
2nd hand store	LCA	Selling 2nd hand products during 1 year	Cradle-to-store	Present system (2015)	Italy

3.1 Identified activities

Every collected study was analysed using the described framework, and the appropriate tables were filled with the collected data, according to the description of the framework in

Section 2. These data were compiled, rearranged and ordered in several ways, in order to visualise the aggregate findings and to enable the authors to discern patterns as well as to categorise the findings in a relevant and useful way. The first step was to summarise the specific identified ways to achieve resource efficiency in each case, as seen in Table 3. Most offerings were focused on efficient use and closing the loops, while only the studies on dairy products and façade cleaning focused solely on production efficiency.

Table 3: List of offerings and the specific ways of achieving resource efficiency in each case, divided into the three categories described in the analytical framework

	Production efficiency and supply chain measures	Efficient use	Closing the loop
Photocopier			Closed-loop reuse, remanufacture & repair, (non-) functional re-cycling
Car engine			Remanufacture & repair
Drill		Intensify use	
Lawnmower		Intensify use	
Car		Prolong life	
Dairy production	Reduce scrap rate		
EEE		Prolong life	Closed-loop reuse
Floor care	Reduce material use in service, reduce scrap rate	Maintenance & repair	
Protection sheets		Prolong life, maintenance & repair	Closed-loop reuse
Washing machine		Prolong life, intensify use	
Lithium-batteries			Closed-loop reuse, open-loop reuse, remanu-facturing & repair, (non-) functional recycling
Temporary building	Reduce scrap rate	Maintenance & repair	Closed-loop reuse, non-functional recycling
Core plugs	Reduce material	Prolong life	Closed-loop reuse, functional recycling
Facade cleaning	Reduce material use in service		
Soil compactor		Prolong life, maintenance & repair	Closed-loop reuse, remanufacture & repair
Bike sharing		Prolong life, intensify use, maintenance & repair	
2nd hand store			Closed-loop reuse

3.2 Results of assessment studies

The majority of the collected studies compare one (or more) supposedly resource efficient solution to a conventional solution, both alternatives fulfilling the same function. Each study assessed different aspects, and the presentation of the results in Table 4 is thus divided into *Resource use (materials and energy)*, *Environmental impacts* and *Economic performance*, and, for each respective category, shows if the resource efficient alternative led to an improvement or not. A margin of error was defined as +/- 10%, which means that results that only show a difference of less than 10% is interpreted as showing an equal result.

Table 4: The results of the assessment studies, divided into "Resource use", "Environmental impacts" and "Economic performance". "+" indicates an improvement over the conventional solution. "-" indicates worse performance. "=" means that the results were within the margin of error of +/- 10%, and thus set to be equal. An empty box indicates that no results were presented in the study for that particular category.

	Resource use (materials and energy)	Environmental impacts	Economic performance
Photocopier	+	+	
Car engine	+	+	+
Drill (leasing)		-	-
Drill (sharing)		+	+
Lawnmower (leasing)		-	-
Lawnmower (sharing)		+	=
Car	+		+
EEE	=		
Dairy production	+	=	
Floor care	+	+	+
Protection sheets		-	-
Washing machine	+	+	
Lithium battery			
Temporary building	+	+	
Core plugs	+	+	+
Soil compactor	+	+	+
Facade cleaning	=	+	+
Bike sharing	+	+	
2nd hand store	+	+	

Most studies reveal an improvement in at least one of the categories. Still, there are a few studies that are worth pointing out in particular. The first is the study on Li-batteries, which was the only one that was not a comparative study. Instead it was an attributional LCA where no quantified comparison was made to a conventional alternative.

Secondly, the study on electronic and electric equipment showed a slight improvement with systems of leasing and reuse, but these improvements were within the margin of error mentioned above.

Finally, Mont (2004) contains both the assessments on drills and lawnmowers respectively. In the study there are three compared alternatives, a conventional scenario with product sales, a scenario where equipment is rented and a scenario with a sharing scheme. The latter two generate differing results and are thus presented separately. The main reason for the differing results are increased transportation needs in the renting scenario.

3.3 Trade-offs related to product characteristics

Shown in Table 5 is a mapping of the studied offerings against their characterising traits. The list of different characteristics is taken from the analytical framework in Willskytt et al. (2016) and it was generated in order to capture the features with significant impacts on the performance of resource efficient solutions, based on life-cycle thinking. Each characteristic can form the basis of one or more hypotheses regarding trade-offs related to different

Table 5: List of products and their characteristics. Coloured boxes mean that the offering in question has that characteristic. If the specific characteristic was discussed or altered in the respective study, it has a darker colour

	Fast technological development	Energy intensive use phase	Fashion-driven	Long lifetime	High product structure complexity	High material diversity	Consumable product	High maintenance needs	Consumable components	Low frequency of use	Component in larger product	Contains scarce materials	Contains toxic materials
Photocopier	■	■		■	■	■			■			■	■
Car engine	■	■		■	■	■		■	■		■	■	■
Drill		■		■	■	■			■	■ (dark)		■	■
Lawnmower		■		■	■	■			■	■ (dark)		■	
Car	■	■	■	■	■	■		■	■			■	■
Dairy production							■		■				
EEE	■	■	■	■	■	■						■	■
Floor care		■		■	■	■		■	■				
Protection sheets		■ (dark)					■ (dark)	■ (dark)					
Washing machine		■		■	■	■			■	■ (dark)		■	
Lithium batteries	■	■			■	■					■	■	■
Temporary building		■		■	■	■		■				■	■
Core plugs							■		■				
Facade cleaning		■		■			■						■
Soil compactor		■		■	■	■		■	■			■	
Bike sharing				■	■	■		■	■	■ (dark)		■	
2nd hand store			■	■									

aspects of resource efficiency. The limited number of collected studies means that there are not products that exemplify every aspect. Instead, some characteristics are only described shortly towards the end of this section, to be further explored in future studies. The hypotheses investigated are presented below. The selection of hypotheses is not exhaustive, but rather aims to show how the analytical framework can be used to formulate and confirm or falsify hypotheses as well as potentially identify knowledge gaps.

It is worth mentioning that some characteristics are more common than others in this sample. The majority of studied offerings have an *energy intensive use-phase*, a *long lifetime,* require *consumable components* or are products with *high structural complexity* and *high material diversity*. Other traits are less well represented like *consumable products*, products that are a *component in larger product* or being under *fast technological development*.

The products that were identified to have a *low frequency of use* were all from studies that were directly concerned with assessing the benefits of a higher frequency of use. Furthermore, there seems to be a correlation between some characteristics. Products with a high structural complexity also tend to have a high material diversity, an energy intensive use-phase and a long lifetime. If this correlation indicates some causality can only be studied further in future research, with a broader base of case-studies to analyse.

3.3.1 Fast technological development and energy intensive use-phase

Is the product under fast paced technological development? Does the energy efficiency or other technical specifications of the product change from year to year? An example is computers, which become significantly more powerful every year.

Another important characteristic in this context is if the product has an *energy intensive use phase* and requires large inputs of energy or materials. An example is a lawnmower.

The hypothesis formulated in relation to these two product characteristics is: When remanufacturing a product under fast technological development or with an energy intensive use-phase, it is vital to upgrade it as well.

The study on photocopiers (Kerr and Ryan, 2001) mentions that if the product-efficiency improves greatly from year to year due to technological change, then remanufacturing simply prolongs the life of an inefficient and obsolete product. This is also supported by Tukker (2015) who claims that a high speed of innovation undermines the economic potential of reuse and of leasing schemes. This link between fast technological development (or frequent design changes) and undermined benefits of remanufacturing or reuse activities is avoided if the remanufacturing process also includes measures to improve the efficiency or performance of the product, as for e.g. the car engine (Smith and Keoleian, 2004).

Furthermore, said study on car engines discusses the importance of “efficiency effects” from remanufacturing under certain conditions. If there is fast technological development and if the use phase is energy intensive, then it is vital that the remanufactured product matches the original product in efficiency. The authors bring up an example mentioning that if a remanufactured car engine is 1% less efficient than a new engine, then most of the environmental benefits of remanufacturing would be negated. For the success of remanufacturing it must thus be assured that the remanufactured engine at least equals a new engine in efficiency (even though in this case a remanufactured engine likely has a *better* efficiency than the original). This also implies that increasing the efficiency of reused and remanufactured products can give significantly improved environmental performance from a life-cycle perspective (Smith and Keoleian, 2004).

3.3.2 Fashion-driven

If the demand for a product depends largely on changing design trends and aesthetic considerations it can be said to be in a fashion-driven market. A fashion-driven product is discarded before the end of its functional lifetime, due to "artificial" obsolescence, although this could also lead to a second-hand market of functional products. This characteristic is usually related to products sold to end consumers, and an example is clothing and to some degree also cell-phones.

The first hypothesis is connected to section 3.2.1. i.e. that upgrading can be important in enabling reuse and remanufacturing. The same is true, but for different reasons, for a product where fashion and trends are important. If remanufacturing and reuse are to be feasible activities, they must also include upgrading of aesthetic or superficial details in order for the product to stay up-to-date.

Another possible hypothesis is that for modular products, there is a trade-off between lowered resource use and increased customisation and fashion-drive. A consumer product with modular, and thus interchangeable, parts may create an increased demand for customised and personalised modules. In other words, there is a possible risk of creating a fashion driven market for modules, that are discarded and exchanged, not because they break down, but to allow the user to keep up with current trends. Unfortunately, none of the studied cases included a discussion on this trade-off, which will thus be examined in future research.

3.3.3 Long lifetime

A product with a long lifetime has a durability which enables it to fulfil its function during many years. Examples include furniture and buildings.

One of the hypotheses is that a long lifetime is a precondition for product sharing schemes. A short lifetime prevents sharing because the product breaks down after using it a small number of times, according to the study on bike sharing (Mont, 2004). Conversely it is likely possible to reuse large parts of a durable product, even when it has reached its end of life. Thus a long lifetime can be seen as a characteristic that enables not only intensified use but also closing the loops, and that the product can go through many cycles without significant degradation.

Another hypothesis is that there is a trade-off between robust, durable products and increased material use. This is actually contradicted by the study on temporary buildings (Smidt Dreijer et al., 2013), which claims that a long lifetime often provides overall improved sustainability, despite the somewhat increased material use in the product itself. Furthermore, the trade-off can potentially be avoided by e.g. implementing a sharing scheme, as indicated by the study on bike sharing (Amaya et al., 2015).

3.3.4 High product structure complexity or material diversity

If a product has a complex structure with many components that are integrated and difficult to reach, it can be said to be a product with *high structure complexity*. An example is a cell phone or a building.

A closely related characteristic is *high material diversity*, which means that there is a large variety of different materials present in the product. A typical example is a car.

The main postulation is that products with high complexity or material diversity hinder disassembly, thus decreasing the potential for remanufacturing and functional recycling. Possible ways to counteract this drawback is to include clear labelling of components, to make sure that similar materials and components are clustered together or to design the product to be easily disassembled, e.g. by making it modular (Sundin (2009)).

Typically, a complex product is not easily disassembled. Therefore, design for disassembly not only facilitates remanufacturing but also provides an incentive for it, by making remanufacturing easier and hence more profitable (Smith and Keoleian, 2004). Analysis of the assessment studies on Li-batteries (Olofsson and Romare, 2013), photocopiers (Kerr and Ryan, 2001) and temporary buildings (Smidt Dreijer et al., 2013) revealed design for disassembly as a design measure that is central to the successful implementation of remanufacturing and reuse, thus corroborating the conclusion drawn from Smith and Keoleian (2004). One approach to facilitating disassembly is making a product modular, but in that case there is a trade-off that needs to be addressed, between potentially improved resource efficiency and increased material use due to the need for passive materials, as described in the studies on Li-batteries and temporary buildings.

3.3.5 Consumable product

A consumable product is expended quickly, or has a deteriorating performance. Any kind of food is an example, as are non-rechargeable batteries.

The first hypothesis is that if a product is consumable, the available options for achieving resource efficiency are limited. Specifically, the only options are to focus on efficient production, to change the function or material content of the product or to recycle the material, either through functional recycling (for e.g. batteries) or non-functional recycling (for e.g. nutrients in food). These limitations are suggested by the study on dairy products by Berlin and Sonesson (2006), which focuses on production efficiency by reducing losses in production and processing.

Another hypothesis is that if a product has a deteriorating performance, then open-loop reuse can be preferable over direct reuse or remanufacturing. The study on Li-batteries for buses (Olofsson and Romare, 2013) provides a good example. The battery performance will deteriorate as it is used and after ca 3 years it needs to be replaced. Because of the lowered performance, it is appropriate to install a new battery in the vehicle instead of reusing or remanufacturing the old battery. In this case, an “Open-loop reuse” activity is a possible solution, i.e. to reuse the used battery for another application, namely as a stationary battery for a home solar PV system or a weather station, where performance-demands are lower.

3.3.6 High maintenance needs or consumable components

High maintenance needs means that a product requires regular care and maintenance during its operation, either to maintain function or to ensure a long lifetime. A floor in a public building is an example that typically needs regular cleaning and periodic polishing.

Connected to this characteristic is that of consumable components. Does the product contain consumable or dissipative components that need to be exchanged regularly? A product with this characteristic is likely to have high maintenance needs as well. An example is an ink cartridge in a printer.

A hypothesis is that shifting ownership of the product to the producer instead of the user (through e.g. leasing or selling function) the producer gets an incentive to improve the maintenance and reduce the use of consumable components. It then lies in the interest of the producer to sustain the products in their care for as long as possible in order to maximise the utility from each produced unit. Similarly, it would lie in the producer's interests to decrease the use of consumables, because it directly decreases the running costs of operation.

There are no cases in the collection which directly address this issue, but, in future iterations of this research, at least two studies (currently being performed, on selling the function of trucks and construction equipment respectively) will look into the effects of shifting ownership on maintenance activities.

3.3.7 Low frequency of use

Is the product used seldom or sporadically? An example is a drill owned by an average household, which is only used a few times per year. A product with high frequency of use on the other hand is for example a cell-phone, used daily in most cases.

The hypothesis is that if there is a low frequency of use then a sharing scheme is suitable in order to intensify use and consequently lowering the environmental impact per delivered function. This is indicated by Mont (2004) and Amaya et al. (2015) in their studies on sharing schemes of drills, lawnmowers and bicycles. These products typically do not have a very high frequency of use, and they all showed positive results on the benefits of sharing in each case (see Table 4). However, the lifetime of some products is limited by the number of uses, rather than ageing, in which case an intensified use through sharing would simply expend the product faster. Consequently, such products are exceptions to the hypothesis and resource use is not reduced by sharing.

Furthermore, it is worth adding that there is a trade-off related to solutions intensifying use. Depending on the total required travel distance for users to acquire the shared assets, the impacts from transportation can cancel out the benefits of intensified use, which is something that needs to be taken into account when implementing sharing schemes (Mont, 2004).

3.3.8 Remaining characteristics

Here follows a brief discussion on the remaining characteristics that have not yet been studied in detail. In addition to the characteristics of "component in a larger product", “contains scarce materials” and “contains toxic materials”, the categories of “type of business” and “product sector” are discussed as well, which are details captured by the framework that are not shown in Table 5.

If a product is a component in another product it might have implications for which business models can be implemented, and can also affect the reusability or remanufacturability of the component. The perspective of products containing scarce and critical materials, such as rare earth metals, will be included in future iterations of the research. It can still be surmised that scarcity and criticality could put demands on disassembly, labelling, separation of materials and recycling. Similarly, products with toxic constituents will be investigated in the future, as it might have consequences for recycling, in terms of the work environment at the facility as well as contamination of recycled materials.

Finally, the two characteristics of *type of business* and *sector* are discussed briefly. The former is meant to distinguish between products or services intended for different types of customers, i.e. private consumers (Business to consumer, B2C), other companies or businesses (Business to business, B2B) or public organisations or government (Business to government, B2G). Depending on the category in question different business models can be more or less viable, different types of regulations are important and the user behaviour is different as well as the demands put on products in economic and environmental terms.

The sector of a product is another aspect that is often hypothesised (implicitly or not) to have bearing on the characteristics and performance of products and services (see e.g. IVA (2016)). Sector is often used as a basis for comparison, but from a life-cycle perspective it is difficult to argue that this is a fruitful approach to analysis. This is because the life-cycle of a product often spans several sectors, it can for example start out in the mining industry, be used in the transportation sector and eventually end up in the recycling industry. Furthermore, there are product characteristics that are shared among different sectors and, conversely, products within the same sector that do not share common traits of relevance. Further research will reveal whether sector is a characteristic meaningful for analysis of resource efficiency.

4 Discussion

The discussion is in two parts, firstly an evaluation of the used framework as a tool for analysis and secondly a discussion on the limitations and gaps of this study.

One of the purposes of this study was for it to be a pilot test of the analytical framework of Willskytt et al. (2016). Thus, an evaluation of the framework, and how useful it was as a tool for analysis, is in place.

The authors' view is that the framework successfully enabled gathering relevant and comparable information from widely diverse studies. Without the framework, different studies would be so dissimilar that comparison and analysis on the same level would not be possible, whereas the framework fixes this issue and allows for an expedient analysis when researching resource efficient solutions. The results and details of assessment studies can be mapped and compared, allowing the analyst to draw generic conclusions around resource efficient solutions.

A tentative conclusion from the initial analysis performed in this paper is that the framework manages to capture the important aspects of resource efficiency and circular economy. The list of activities and the three categories proved to be useful delimitations that encompass the most important parts of resource efficient solutions from a life-cycle perspective. Furthermore, the list of product characteristics is deemed to be exhaustive for the purposes of research on resource efficient solutions. Consequently, the authors believe the framework, although still under development, fulfils its purpose and serves as a useful tool for gaining deeper knowledge on resource efficiency.

When it comes to the present paper, analysing diverse studies and products and trying to aggregate the information into comprehensible and easily presentable parts is difficult without losing important details along the way. Some of the data collected need to be interpreted in some way and are thus in part dependent on the analyst's prior knowledge and perspectives. Furthermore, it is practically impossible to make a complete analysis of all aspects of resource efficiency, due to the area being so wide. Hence some judgement must be made on the part of the analyst on when the analysis is complete enough and when it is possible to draw generalised conclusions.

Regarding the selection of assessment studies the list was not expected to be exhaustive. Some things that were not included were mainly studies on cleaner production (the only exception was Berlin and Sonesson (2006)) and studies focused on recycling, waste management and scarce and toxic materials. Furthermore, there is a possible bias in the collection of case studies, where the results proved to be mostly positive (see Table 4). This cannot be directly interpreted as if all similar solutions will always produce improvements in resource efficiency, since the list is not yet large enough to allow more robust conclusions.

5 Conclusions

The analytical framework of Willskytt et al. (2016) was applied on 17 assessment studies. This formed the basis for an analysis on trade-offs related to different product characteristics, allowing the authors to draw some conclusions. An example of such a conclusion is that upgrading is important for remanufacturing of products with fast technological development, an energy intensive use phase or a fashion-driven market. Other examples are that shifting ownership of products potentially leads to improved maintenance, that design for disassembly is important for remanufacturing and that improving resource efficiency for consumable products is preferably done by focusing on production efficiency or recycling. Likewise, a long product lifetime is a precondition for sharing schemes, which is a suitable solution for products with low frequency of use. Finally, some trade-offs between modularity and customisation, as well as between durability and material use, were discussed.

Furthermore, the suitability of the framework for systematic study of literature was evaluated. It was deemed suitable for its purposes, but the framework will be subject to further change in future iterations of this research. Additionally, more assessment studies will be included for analysis, to form a more exhaustive empirical base which should cover studies on e.g. cleaner production, toxicity and scarce materials. This will be done both by additional and broader literature searches and by performing studies within the Mistra-REES program. To conclude, the framework is a suitable tool for studying resource efficiency, and it is expected to serve even better when used in a broader context, with more studies, allowing the analysts to draw more conclusions and investigate additional aspects of resource efficiency.

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