THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Learning from assessments of resource efficiency measures and their impact on resource use and the environment

Based on a case of additive manufacturing and a review of assessment studies

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ABSTRACT

Resource efficiency measures have the potential to reduce the environmental and resource impacts of the current linear economy by decreasing the physical flows of material and energy associated with producing and using products and services. In order to investigate this potential, there is a need for assessments from a systems perspective, which for example enables the identification of possible trade-offs between different measures and aspects of resource efficiency depending on the product characteristics. The research was carried out in two parts, firstly by synthesising the learnings from a large number of assessment studies. The analysis was built on typologies formulated for mapping resource efficiency measures and product characteristics to the environmental and resource outcomes of the measures in each case. This resulted in a number of findings detailing under which conditions that resource efficiency measures yield environmental and resource benefits, as well as when there are possible trade-offs and limitations. Furthermore, some product characteristics were identified that are key in determining when resource efficiency measures are effective, namely whether products are durable, consumable, complex or whether they have significant impacts from extraction and material production or from their use. Products with significant impacts from the use-phase are called active products and give rise to trade-offs that are discussed in detail, specifically regarding under which conditions there are environmental and resource benefits from extended use or from reducing use-phase impacts. The second part of the research was a life cycle assessment of one such active product, namely 3D-printed truck engines. The aim was to investigate the resource efficiency potential of this emerging technology. Results showed that 3D-printing could lead to net improvements in life cycle impacts, by allowing redesigns of components for lower weight and thus lower fuel consumption. However, the conclusions were only valid under certain conditions, such as careful material choice and a low-fossil electricity mix for the printing process, without which 3D-printing resulted in environmental deterioration compared to conventional manufacturing. Some results could be generalised to other applications and industries, for example the importance of a low-fossil electricity mix for 3D-printing, which is valid for any application of 3D-printing. In conclusion, useful knowledge on resource efficiency measures was produced both by synthesising many assessment studies and carrying out a single assessment study, especially on the topics of active products and additive manufacturing.

Keywords: resource efficiency; circular economy; reuse; remanufacturing; repair; life cycle assessment; active products; additive manufacturing; 3D-printing; automotive

LIST OF APPENDED PAPERS

Paper I
Böckin, D., Willskytt, S., André, H., Tillman, A-M. and Ljunggren Söderman, M., 2018. What makes resource efficiency measures environmentally beneficial? - A systematic review of assessment studies. Submitted to scientific journal (currently under review).

Paper II
Böckin, D. and Tillman, A-M., 2018. Environmental assessment of Additive Manufacturing in the automotive industry. Submitted to scientific journal (currently under review).

OTHER RELATED PUBLICATIONS

Böckin, D., Willskytt, S., Tillman, A-M. and Ljunggren Söderman, M., 2016. What makes solutions within the manufacturing industry resource efficient and effective? Paper presented at the 12th Biennial International Conference on EcoBalance. 3-6 October, 2016, Kyoto, Japan.

Willskytt, S., Böckin, D., André, H., Tillman, A-M. and Ljunggren Söderman, M., 2016. Framework for analysing resource-efficient solutions. Paper presented at the 12th Biennial International Conference on EcoBalance. 3-6 October, 2016, Kyoto, Japan.

CONTRIBUTION TO APPENDED PAPERS

Paper I
All authors designed the research and formulated the framework and typologies used for analysis and conclusions. The first, second and third authors carried out literature review and data analysis and co-wrote the paper, with valuable assistance and feed-back form co-authors. The author wrote the sections covering Results as well as Discussion and conclusions.

Paper II
The author carried out the bulk of research work, including data collection, analysis and writing the draft of the manuscript. He was aided by the co-author in research design and analysis and in the form of multiple rounds of reviews and comments.

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1 INTRODUCTION AND BACKGROUND

Globally, the use of different resources has increased dramatically in the last centuries, as the prevailing linear economy is built on a logic of extracting, using and then discarding materials (Frosch and Gallopoulos, 1989; Stahel, 2010). Populations and economies keep growing along with resource throughput (UNEP, 2011), but there have also been attempts at reducing resource consumption. These can in principle be divided into efficiency, effectiveness and frugality. Resource efficiency (RE) means to use less resources to deliver the same function or output, while effectiveness means to make sure that the demanded function is delivered and not more (Mistra REES, 2018). Conversely, frugality means to use less, which includes to decrease the delivered function and is something that was left out of the scope of this thesis. Measures for resource efficiency (termed RE measures throughout this thesis) can be aimed at closing material flows and maintaining stocks, in line with the concept of Circular Economy (CE), but also at achieving cleaner and more efficient production as well as effective use (Allwood et al., 2011; Ayres and Ayres, 2002; EMF, 2013; Ghisellini et al., 2016; Graedel and Allenby, 2010). Each physical measure such as reuse or remanufacturing can be achieved in a variety of ways, e.g. through policy measures, altered business models or new designs. All these are explicitly being investigated in the Mistra-REES research programme, within which the current research is conducted (Mistra REES, 2018). The programme is a collaboration between academia, large and small companies and societal actors and has the overarching aim of generating contextual knowledge on resource efficient and effective solutions to aid in the transition towards a circular and sustainable economy. Although a specific RE measure like remanufacturing can be achieved by both a new business model or a new policy, the net RE improvements is the result of a change in physical flows of material or energy. The scope of this thesis is delimited to investigating physical measures for reducing flows of material and/or energy, regardless of how implementation of the measure was achieved.

In order to find out when measures aiming for RE actually lead to reduced flows for a product or service[1], depending on the context, the measure in question or the characteristics of the product, there is a need for environmental and resource assessments (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018). These assessments can be done from a systems perspective, which can for example reveal trade-offs or burden shifting between different kinds of environmental impacts or different parts of the product system. Common examples of such holistic assessment methods are Material Flow Analyses (MFA) and Life Cycle Assessments (LCA) (Haupt and Zschokke, 2017; Kjaer et al., 2018). An assessment can be carried out by using a top-down approach, e.g. focusing on the level of an entire industry or nation, or a bottom-up approach, with households, consumers or single products as the starting point (Hellweg and Canals, 2014; Ingelstam, 2012). Cowan (1987) provided early indications of the fact that systems analysis can be done bottom-up rather than only top-down as had predominantly been the case until then.

Generally, a top-down analysis entails the mapping and assessment of large-scale flows on a global, national or sectoral level. They give a wide overview of a system by aggregating its many flows to allow conclusions of the scales and fates of those material flows. Haas et al. (2015) and Allwood et al. (2011), for example, investigate material flows of global relevance, and the UN International Resource Panel recently carried out a notable mapping of global flows to estimate the potential material and economic implications of resource efficiency (UNEP, 2017). Conversely, Wijkman and Skånberg (2015) investigate the economic and societal consequences of CE on a national level. Results of such top-down studies can be useful for formulating political targets and strategies as well as for investigating the scale of a problem and the necessary changes for achieving a goal. However, because of the broad perspective, the results tend to be highly aggregated (Suh and Huppes, 2002). The results are valid for the large-scale system as a whole but can lack concrete directions and recommendations for individual actors within the system, such as producers, service providers or consumers. An example could be a top-down study of national environmental impacts which would identify the energy use of households as an important source of impacts (Hellweg and Canals, 2014). This implies the general recommendation to reduce

[1] Note that throughout this thesis both products, services and combinations thereof will simply be denoted as ”products”, in accordance with the standard for life cycle assessment (ISO, 2006).

household energy use, which provides limited guidance for practical implementation. A bottom-up assessment on the other hand, could for example identify the use phase of household appliances as the main source of household energy use, which would then imply a clear recommendation to reduce the use-phase impacts of appliances (Hellweg and Canals, 2014).

Bottom-up studies can thus provide a complementing analysis to top-down approaches, by carrying out detailed assessments on the level of single products, product systems, households or organisations. They can provide valuable aid in making sense of the overall conclusions and making them concrete and useful for individual actors. An example is the study by UNEP (2017) that, despite being a top-down study, also includes illustrative examples of RE being implemented in specific cases under specific conditions. An advantage of a bottom-up compared to a top-down approach is that it enables an actor-perspective. Because such studies are carried out from the perspective of, and often in collaboration with, a defined actor such as an original equipment manufacturer (OEM), the study will be adapted to that actor and reflect their specific situation (Baumann et al., 2011; Laurent et al., 2014). This actor-perspective can bring to light potential barriers that such an actor encounters when implementing a RE measure, as well as potential opportunities that can be exploited. Thus, it can be argued that the learnings and recommendations from a bottom-up study will be more implementable than those from a top-down study. Conversely, it can be argued that a disadvantage of bottom-up studies is that they can tend to become isolated and fragmented cases from which it is difficult to draw generic conclusions.

Indeed, there is an abundance of individual assessment studies of RE solutions, but a lack of reviews attempting to synthesise their findings. Some of the few examples can be found in a study by Tukker (2015), who reviewed studies of Product Service Systems (PSS) for a resource efficient and circular economy. Another example is a study by Kjaer et al. (2018), who studied cases of PSS in the textile sector. Outside the field of business models related to PSS there is a study by Ghisellini et al. (2018) who reviewed assessments of CE measures in the construction sector as well as a study by Laurent et al. (2014) who reviewed 22 assessment studies on solid waste management, including attempts at generalising the conclusions of the reviewed studies. Hence, there is a research gap for synthesising knowledge from many individual assessment studies, especially across several product types and sectors. The purpose of this thesis is to fill this gap in order to investigate how the outcome of different RE measures, in terms of reduced physical flows or environmental impacts, depends on different product system characteristics.

There is a wide range of RE measures to investigate, and a large number of product characteristics to take into account. For this thesis, out of the many possible product characteristics, a specific type of product was chosen for particular investigation, namely active products (products that use energy or material during use), which especially give rise to some significant trade-offs. A brief background on such trade-offs associated with active products can be found in section 1.1. Similarly, one example of a RE measure was chosen for particular scrutiny, namely the implementation of new manufacturing technology, specifically Additive Manufacturing (AM) which has a large future potential for RE. Section 1.2 gives a brief background on the environmental and resource implications of AM.

1.1 Trade-offs for RE measures on active products

Implementing RE measures for a product can, as mentioned, give rise to trade-offs. An example is the extended use of products, e.g. by remanufacturing or repairing, which improves RE by decreasing the need for new production. However, if the product in question is active, and if there is on-going technological development that significantly improves material or energy efficiency during use, then replacing the product could potentially be more resource efficient (ISO, 2002). Early works that investigated the trade-off between extended use and replacement include a study by Tomiyama et al. (1997), who discussed life cycle design of vehicles and identified the contradiction between scrapping old vehicles to replace them with new fuel-efficient cars and prolonging the life of vehicles to reduce waste and material consumption. On the same topic of vehicles, van Wee et al. (2000) carried out an assessment over a car life cycle and concluded that prolonged life of vehicles is preferable over replacement, unless the yearly improvement in fuel efficiency would increase further compared to the preceding years. Ciantar and Hadfield (2004) studied the durability and energy efficiency of refrigerators and reached the opposite conclusion for this type of product, that a shorter lifetime would be preferable considering the developments in efficiency at that time.

Several more assessments investigating the trade-off have been carried out throughout the years since, where Smith and Keoleian (2004) concluded that remanufacturing of car engines yields environmental benefits. Conversely, Spielmann and Althaus (2007), in their study of prolonged life of vehicles, could not draw clear conclusions because of large uncertainties, e.g. regarding the reduction rate of fuel consumption. Other than for vehicles, assessments for different household appliances have disagreed in their recommendations, where Boustani et al. (2010) found that remanufacturing of washing machines, fridges and dishwashers gave a net increase in life cycle energy use (though they only considered energy use and no other types of impact). Ardente and Mathieux (2014), on the other hand, concluded that prolonged life of washing machines is environmentally beneficial, although they pointed out that there are many factors of uncertainty that could affect the results. Bobba et al. (2016) found that prolonging the life of vacuum cleaners by repairing them gave environmental benefits, while Iraldo et al. (2017) investigated the durability of refrigerators and electrical ovens and found that the durable option was only environmentally preferable if production and end-of-life stages are more impactful than the use phase. Overall, the assessments vary widely in their recommendations on whether active products should be replaced or if their life should be prolonged. Hence, there is a need for synthesising several of the individual assessments to attempt to reach conclusions across cases, product types and sectors, which can shed light on this specific trade-off as well as other potential trade-offs.

1.2 Environmental and resource implications of additive manufacturing

AM, or 3D-printing[2], is an emerging technology, which means that it is in an early stage of development but is expected to spread on a large scale in the future. The technology is believed to have a large potential for disrupting or revolutionising many different industries (Walachowicz et al., 2017). AM includes several different techniques for gradually building 3D-structures, often one layer at a time, out of materials such as plastic or metal. Furthermore, there is a large future potential for RE, although there are many uncertainties when it comes to the environmental consequences and resource use because of a lack of quantified assessments (McAlister and Wood, 2014). One of the potential benefits of AM is that it allows redesigns that can reduce the weight of components. This means that e.g. the automotive and aerospace industries especially can benefit from employing the technology since they manufacture active products (see section 1.1) whose fuel consumption depends on a lower vehicle weight (Mami et al., 2017). Moreover, 3D-printing can allow the integration of several components to facilitate dismantling (Lifset, 2017). Components can also be redesigned to provide additional functionality, for example improved cooling by integrating cooling channels into the product structure (Ford and Despeisse, 2016). Specialised parts can be produced quickly and on demand, benefitting prototyping and repairing (Jamshidinia et al., 2015). Lastly, spare parts can be printed on demand, lowering costs for producing and storing sufficient quantities of spare parts. However, in addition to these potential benefits, there are also possible risks and potential barriers to the environmental and resource improvements enabled by AM technology. Some examples are the high electricity consumption from printing and that there are limitations regarding what materials can be used for 3D-printing and what sizes of components can be printed (Gutowski et al., 2017).

When it comes to metal 3D-printing specifically, only a handful of previous papers have quantitatively assessed the environmental effects (e.g. Faludi et al. (2017) and Huang et al. (2017)), and most studies consider only energy consumption or only the printing process itself (Lifset, 2017). Consequently, there is a need for assessing the potential environmental and resource implications of metal AM from a systems perspective, which is especially important considering the early stage of development and the future RE potential of the technology.

[2] The terms “3D-printing” and “Additive Manufacturing” will be used interchangeably throughout this thesis as well as in the appended papers.

1.3 Research questions

To fulfil the purpose and fill the research gaps indicated above, the following research questions were formulated:

- RQ1: What useful knowledge can be produced by synthesising many individual assessment studies that investigate when resource efficiency measures do or do not reach their intended outcomes for various products and services?
- RQ2: What useful, more generic, knowledge can be produced from a single assessment study on a resource efficiency solution?

RQ1 was formulated in order to take on the mentioned lack of synthesised knowledge from assessments of RE solutions. It is addressed in paper I, where a systematic literature review is carried out synthesising the findings of a large number of assessment studies on RE measures. Of these assessment studies, one was conducted by the author of this thesis to address RQ2. Specifically, it was an assessment of the environmental consequences of 3D-printing a truck engine, as reported in paper II.

Several findings from the analysis in paper I concerned active products and under which circumstances that they can be made more resource efficient or when they give rise to trade-offs. Additionally, the assessment study in paper II provided further insights on these potential trade-offs for active products (see details in section 4.2). Hence, it was relevant for this thesis to investigate the opportunities and risks with applying RE measures on active products. The following research question was formulated to address this:

- RQ3: What are the environmental and resource implications of resource efficiency measures for active products?

Lastly, as indicated above, there is a large RE potential in implementing new manufacturing technologies, and one notable such technology is 3D-printing, particularly 3D-printing in the automotive industry. Consequently, the final research question was formulated as follows:

- RQ4: What are the environmental and resource implications of using metal additive manufacturing?

RQ4 is addressed in paper II, which aims to fill the knowledge gap of the lack of quantified life cycle environmental assessments of metal 3D-printing. It is done by carrying out a holistic assessment of the environmental consequences of additive manufacturing of truck engines.

Addressing the four research questions together in this thesis gives an opportunity to create and consolidate knowledge on RE solutions, with a special focus on active products and additive manufacturing. Table 1 shows which research questions are addressed by which paper.

Table 1: Overview of which research questions are addressed by which appended paper

	RQ1	RQ2	RQ3	RQ4
Paper I	x		x	
Paper II		x	x	x

2 METHODS

The research in this thesis was carried out partly by synthesising learnings from a large number of assessment studies and partly by conducting a life cycle assessment of the 3D-printing of a truck engine. The methodology for the former is described in section 2.1 (with further details in paper I), and for the latter in section 2.2 (with further details in paper II).

2.1 Synthesising learnings from assessment studies

Synthesising learnings from a large number of assessment studies entailed the collection of studies, to systematically extract and consolidate relevant information from each, and to subsequently analyse the studies together in order to find patterns and draw general conclusions. Assessment studies were collected mainly from a systematic literature search, both from peer-reviewed journals and reports from research institutes and similar (search words used and other details can be found in paper I, section 3.1). These formed a library of studies that were supplemented by studies carried out within the Mistra-REES consortium, either by the companies in the programme or through collaborations between its academic and non-academic partners. The library, which totalled 58 studies (mostly LCAs) comprising 122 cases covering a wide range of products and sectors, was then used as the basis for synthesising and analysing the learnings of the different studies.

The study in paper I departs from the hypothesis that the net environmental impacts of implementing RE measures depends highly on the characteristics of the product rather than which sector the product belongs to. This is in contrast to previous literature presented in section 1, such as the studies by Kjaer et al. (2018), Ghisellini et al. (2018) and Laurent et al. (2014) which are all delimited by sector. Additionally, IVA (2015) carried out a top-down study of RE in Sweden according to different sectors within the Swedish manufacturing industry. In order to identify how product characteristics affect the outcome of RE measures, the characteristics in each case were mapped against the RE measure that was implemented as well as the outcome in terms of the indicators used in each study. Hence, three things were required to systematically carry out the mapping, namely 1) a typology of RE measures to distinguish different RE strategies and activities, 2) a typology of product characteristics hypothesised to be of importance for RE and 3) a way of expressing the results of each study in an aggregated manner. In addition, details on the methodology used in each study were noted, e.g. scope, time frame and which indicators were used to express the results, see paper II, section 3 for full details.

The typology of RE measures was formulated in order to classify the measures in each case. The typology is divided into three overarching categories, distinguished by where in the life cycle the physical measure can be implemented: *extraction and production*, *use phase* and *post-use*. These overarching categories were further detailed as presented in Table 2, drawing on frameworks in the CE literature (Allwood et al., 2011; EC, 2008; EMF, 2013; Stahel, 2010; Stahel and Clift, 2016). This was complemented by life cycle thinking, based on the collected assessment studies, experience from other studies and eco-design literature, like the Ten golden principles (Luttropp and Brohammer, 2014), the Eco-design strategy wheel (Brezet and van Hemel, 1997) and other eco-design guidelines as described by e.g. Ceschin and Gaziulusoy (2016) and Sundin (2009).

A common way of achieving RE is to reduce material and energy use in extraction of raw materials and production of materials and products. This can be accomplished through *reducing losses* of material or energy in production, e.g. by re-introducing scrap and energy flows into the production process. The production phase can also be made more efficient through *reducing the amount of material* in the product, which might also make subsequent phases more efficient. Finally, products can be made more resource-efficient and less environmentally burdensome through *changing their material composition*, for example by substituting fossil, toxic or scarce materials or using recycled instead of primary materials. Reducing or changing materials requires that the product is redesigned.

The use of a product can be improved in two principal ways, through *using the product effectively and efficiently* and through *extending its use*.

Table 2: Typology of physical RE measures.

Life cycle phase	Measure
Extraction and production	
	Reduce losses in production
	Reduce material quantity in product
	Change material in product
Use	
	Use effectively and efficiently
	Use effectively
	Reduce use of auxiliary materials and energy
	Share
	Extend use
	Use more of technical lifetime (including reuse)
	Increase technical lifetime
	Shift to multiple use
	Maintain
	Repair
	Remanufacture
	Repurpose
Post-use	
	Recycle material
	Digest anaerobically or compost
	Recover energy
	Landfill

Use effectively means to make sure that the appropriate function is provided for the user's needs. It also includes to reduce losses during use. Less resource consumption in the use phase can also be accomplished through *reduced use of auxiliary materials and energy*. *Sharing* a product between several users is a different strategy for use-phase efficiency through which the product is used more intensively during its lifetime.

To *extend the use* of products means to prolong their lifetime. This can be done by *using more of the technical lifespan* of the product, by the same user or a new one (the latter often denoted reuse in literature). The product may also be redesigned for *increased technical lifetime*. And a single-use product can be redesigned to *a multiple-use product*.

The use of a product may also be extended through restorative interventions such as *maintenance, repair*, *remanufacturing or repurposing*. *Maintenance* involves activities where products are inspected, maintained and protected before breakdown or other problems occur. *Repair* takes place after wear, malfunction or failure. *Remanufacturing* is the process of restoring a non-functioning product to its functional state and bringing it back to a state as good as new or even better (Sundin, 2004), through disassembly, repair or exchange of components, re-assembly and quality assurance. *Repurposing* means reuse of a product in a different function than the original one.

The last category, post-use, addresses the end-of-life of products and components. *Recycling* restores materials and returns them to use. In recycling without quality loss, the properties and function of a material are maintained, why the recycled material can replace virgin raw materials and be used for the same function (Graedel et al., 2011; Guinée et al., 1999). However, recycling usually leads to quality loss, why the material properties and hence function are deteriorated.

Biodegradable materials and products can be *digested anaerobically or composted* (yielding biogas and/or recovering plant nutrients). *Energy recovery* converts the energy stored in products and materials into usable energy carriers. *Landfill* is a last measure to manage disposed products and limit their environmental impact.

The typology of product system characteristics was formulated based on aspects relevant for RE, see Table 3. The typology was based on previous literature on eco-design (e.g. Sundin (2009) and Ceschin and Gaziulusoy (2016)), product obsolescence (e.g. Cooper (2010) and Proske et al. (2016)), PSS (Tukker (2004) and Tukker (2015)) and assessment studies, such as LCA and MFA.

Table 3. Typology of product (system) characteristics.

Product characteristics	**Description**
Type of product and/or service	Free text
Function of product and/or service	Free text
Sector	Sector according to SNI 2007*
Product category	Product category according to SNI 2007*
Type of business	Business to customer (B2C), Business to business (B2B), Business to government (B2G)
Product system hierarchy	System, PSS, product in PSS, product, stand-alone component, component in product
Lifetime	Measured as time, number of uses or delivered function such as distance or number of rotations
Consumable or durable	Consumable or durable
Number of components in product	Low 1-20; Medium 20-50; High >50
Number of materials in product	Low 1-20; Medium 20-50; High >50
Content of scarce materials	Yes/No
Content of critical materials	Yes/No
Content of toxic substances	Yes/No
Possibility to disassemble for remanufacturing/repair/upgrading	Yes/No. If Yes, exemplify how disassembly was enabled (free text)
Possibility to disassemble for recycling	Yes/No. If Yes, exemplify how disassembly was enabled (free text)
Intensity of use	Time per use: Low < 30 min; Medium 30 min-2 h; High > 2 h
Frequency of use	Number of uses per period: Low: few times/year; Medium: once/month; High: at least once/day
Use of energy or auxiliary material during use phase	Yes/No
Describe maintenance needs of product/service	Free text
Need for auxiliary components during maintenance	Free text
Environmental relevance of user behaviour	Describe in what way user behaviour affects total impacts
Development in terms of efficiency, functionality, price, appearance	Indicate type and pace of development from low to high

* see Statistics Sweden (2007)

The first aspects describe the product system in general terms, such as type and function of product, sector and product category according to the SNI 2007 classification (Statistics Sweden, 2007). Further, specific product system aspects for each study in the library were noted, in terms of the product as such (e.g. lifetime, number of components), its use (frequency of use, energy consumption) and other external factors (e.g. technological change).

The key results of each study in the library were noted as well. Since the scope and method varied widely between studies, the results were first noted in terms of the indicators for RE that they used. Subsequently, the results were classified into either *material*, *energy* or *environmental impact* and expressed as a percentage improvement or deterioration. With *material* is meant the material use over the life cycle of a product system, while *energy* means the life cycle energy use, and *environmental impact* refers to different categories like global warming potential and ecotoxicity.

Using the typologies of RE measures and product characteristics as well as the assessment results, a systematic mapping of these aspects was carried out to identify how the environmental impacts of implementing RE measures depend on the product system characteristics. Firstly, the cases were sorted based on the different RE measures assessed and secondly based on the results reported in each assessment study. This sorting allowed for identification of product characteristics that correlated to positive or negative results in each case. Several patterns could be identified and generalisations could be made, both about how the outcome of each measure depends on various product characteristics, as well as about potential trade-offs arising in different circumstances, for example that when doing maintenance and repair of products to prolong their life, as a result there can be an increase in transportation.

2.2 Environmental and resource assessments

The environmental and resource implications of RE measures and technologies can be assessed by investigating what changes in physical flows would be caused by implementing the measure or technology. These physical flows can be material resources as well as other energy or environmental resources. Keeping a systems perspective gives a holistic view of the studied product system which can e.g. reveal burden shifting between life cycle stages and environmental impacts. LCA was chosen for carrying out the assessment of additive manufacturing in this thesis, since it is a well-established methodology for assessing the environmental and resource impacts related to the life cycles of products and services from a systems perspective (Baumann and Tillman, 2004; ISO, 2006). LCA is often employed to support decision-making, e.g. in companies or organisations, for purposes of strategy, marketing and improving environmental performance.

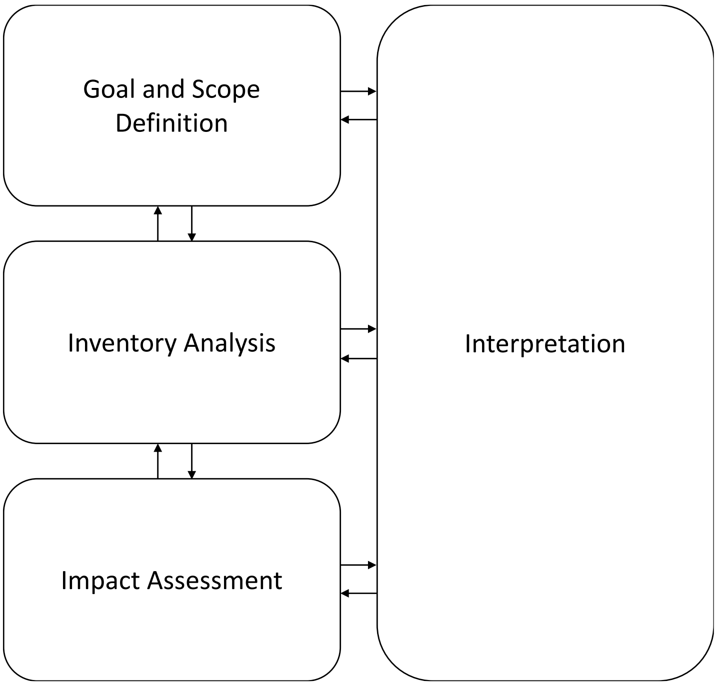

Figure 1: Schematic representation of the LCA procedure (ISO, 2006).

The method is carried out in four iterative parts, as seen in Figure 1 (ISO, 2006). The initial step is to define the goal and scope of the study, which determines the purpose, functional unit, environmental impact categories and system boundaries such as geographical location. These choices guide the subsequent parts of the assessment, not least the inventory analysis in the second step. Here, relevant data are collected for each process within the defined system boundaries, including inputs and outputs of material, energy and emissions. The life cycle inventory is built by calculating mass and energy balances and relating the data to the defined functional unit. The third step is the impact assessment, where the life cycle inventory is translated to different impact categories by using characterisation factors, e.g. for different greenhouse gases in terms of CO_2-equivalents. The last step is interpretation, where the results of the impact assessment are interpreted in relation to the goal and scope definition, which includes for example sensitivity and dominance analyses. Note that all steps are iterative in nature, and that e.g. interpretation and impact assessment can occur in parallel or that the scope can be revised as the analyst learns more about the system.

The final results of a LCA can either be presented as inventory results, as more aggregated impact categories, or weighted to a single score. Weighting gives an overview for studying relative results between different options, but also entails the loss of nuance and detail in the results. Furthermore, every weighting method is based on different values, assumptions and logic (Hauschild and Potting, 2005). Different methods thus tend to emphasise different aspects of the Life Cycle Inventory. An example is the Environmental Development of Industrial Products 2003 (EDIP) (Wenzel et al., 1997), which is a method that uses a distance-to-target approach to estimate weighting factors, hence expressing impacts in relation to political targets. Another example is Eco-indicator 99 (EI99) (Goedkoop and Spriensma, 2000) where weighting factors are instead set by a panel of LCA experts. A third example is Environmental Priority Strategies (EPS) (Steen, 2015), where weighting factors are expressed in monetary terms, based on people's willingness to pay for restoring changes in a safeguard subject. In addition, EPS takes both present and future generations into account in the valuation of abiotic resources.

The specific subject of the LCA in paper II was AM of a truck engine and because AM is an emerging technology, the assessment was a prospective LCA (Arvidsson et al., 2017). The purpose of prospective LCAs is to assess the potentials and risks of emerging technologies, and they are inherently uncertain but their results can be used as guidance to steer the technological development in a desired direction, e.g. to minimise environmental impacts (Villares et al., 2017). In practice, when building a life cycle model technological development is a factor that will lead to changes that need to be taken into consideration. These changes occur not only in the foreground systems being investigated but also in the background systems, for example a changing electricity supply or transportation system (Arvidsson et al., 2017). In paper II, a changing background system was represented by assuming a future low fossil electricity supply. The remaining background systems were modelled according to their present state, as part of a conservative approach that underestimates the environmental benefits of the new technology. Changes in the foreground system were taken into account by formulating scenarios to represent different levels of development. Specifically, two scenarios were formulated, one for the present state of additive manufacturing (named S1) and one for a potential future state (named S2), in addition to a reference scenario (named S0) representing conventional truck engine manufacturing. S2 was placed roughly a decade in the future, and hence several potential technical performance factors had to be estimated, such as the possible size of components that can be 3D-printed and what materials are available for printing. Making conservative assumptions was a way of improving the reliability of the results in paper II. Another challenge relates to uncertainties, which are inherent in prospective modelling and in estimating data for emerging technologies (Arvidsson et al., 2017). These uncertainties were dealt with by carrying out sensitivity analyses and thus tuning many different variables within relevant ranges and noting the effects on the overall results.

3 TECHNICAL BACKGROUND ON METAL 3D-PRINTING

Because some parts of the results will deal with 3D-printing (or additive manufacturing) here follows a brief background for any reader not familiar with the technology. As mentioned in section 1.2, AM is an emerging technology that has the potential to disrupt or revolutionise many industries (Walachowicz et al., 2017). The technology comprises many different techniques for assembling 3D structures, usually binding together one layer at a time until a desired shape is achieved (Rombouts et al., 2006). Examples include Electron Beam Melting (EBM), Fused Deposition Modelling (FDM) and Laser Beam Melting (LBM) (Yang et al., 2017). Each technique uses a different principle for achieving the printing of 3D structures and each technique uses different types of feedstock materials, such as metal powder or plastic pellets. In the LCA study of paper II, Laser Beam Melting (LBM) of metal powder was the chosen technique, since it is one of the most ubiquitous forms of 3D-printing (Wohler's Associates, 2016).

In LBM, a feedstock material in powder form is placed in a chamber and a laser selectively melts parts of the top powder layer. Then, another layer of powder is spread on top and again selectively melted, thus fusing with the layer beneath. This process is repeated until a solid structure is achieved, according to the digital specifications (Louvis et al., 2011). The thickness of every layer (ca 20-40 μm) depends on the powder and machine specifications and settings, which in turn affects the resulting surface quality and need for post-processing (Dawes et al., 2015).

Several metallic materials are available as feedstocks, e.g. powders made from aluminium-alloys, steel-alloys, nickel-alloys and titanium-alloys (Wohler's Associates, 2016). The method for producing these powders is called *atomisation,* where a pressurised gas, liquid or plasma is shot at molten metal falling in a chamber. This breaks it into droplets that solidify into spheroids on their way down (Dawes et al., 2015; Yule and Dunkley, 1994). The resulting powder particle diameters can range from 0-500 μm for gas atomisation. The particles are then sieved into fractions of different size distributions, to be used for various applications, including but not limited to AM.

4 RESULTS AND DISCUSSION

The results are divided into two sections. The first presents the learnings from synthesising a large number of assessment studies (this will address RQ1 and RQ3) and the second presents what can be learned from a single assessment study (this will address RQ2 and RQ4).

4.1 Learnings from synthesising a large number of assessment studies

A bottom-up approach was used to synthesise the results of 58 assessment studies comprising 122 different cases, according to the method outlined in section 2.1. This resulted in several findings regarding for which product characteristics what RE solutions really lead to improved resource efficiency, as well as the identification of potential trade-offs and limitations to be aware of in different contexts. The findings are summarised in Table 4, ordered according to the different RE measures defined in the typology in section 2, starting with measures aimed at the life cycle stage of extraction and production, followed by use phase and post-use. A brief summery is presented here, with examples for a number of RE measures. For a full description including all measures, see paper I, section 4.

Table 4: Summary of findings from paper I, sorted according to the different RE measures in the typology (presented in section 2.1), detailing the characteristics for which each measure is suitable, as well as potential associated trade-offs and limitations.

Measure	Suitable for products with these characteristics	Trade-offs and limitations
Extraction and production		
Reduce losses in production	Products with impacting material production phase	Reduced production losses can come at the cost of increased energy use
Reduce material quantity in product	Any product	Risk for losing function, e.g. durability
Change material in product	Any product	Risk for burden shifting when substituting materials
Use effectively and efficiently		
Use effectively	When use-phase impacts depend on user behaviour	-
Reduce use of auxiliary materials and energy	Active* products	Reduced use-phase impacts can come at the cost of increased production impacts
Share	Durable and infrequently used products that tend to not reach their full technical lifetime	Sharing can increase car transportation for users accessing the shared stock
Extend use	Durable products	Extended use of active* products with technological development for use-phase efficiency may lead to increased overall energy or material use
Use more of technical lifetime (including reuse)	Durable products, especially passive* products and products typically discarded before being worn out	-
Increase technical lifetime	Products that tend to be used until they break down	Increased durability can come at the cost of more, or more impacting, materials
Shift to multiple use	Single-use products	Multiple use comes at the cost of increased impact from production and maintenance, e.g. washing between uses
Maintain, repair, remanufacture	Durable products	- Maintenance can increase transportation - Design for disassembly can increase material use
Repurpose	When functionality remains in a product that can no longer be used for its original purpose	Limited by market for repurposed product
Post-use		
Recycle material	Products with significant impacts from material production, except those used in a dissipative manner or consumed directly	- Impacts from recycling need to be smaller than impacts from primary production - Risk for recirculation of hazardous substances

* Active products use energy and/or materials in the use phase, whereas passive products do not.

An example of the findings for extraction and production is to *reduce losses in production*. Based on the library of assessment studies, this measure was found to be suitable for products with an impacting material production phase, although reduced production losses can in some cases come at the cost of increased energy use. When it comes to using a product effectively and efficiently, an example is to *share* products between several users, thus presumably achieving use-phase efficiency by intensifying the use of the products. In this case, the analysis revealed that sharing is suitable for durable and infrequently used products that tend to not reach their full technical lifetime, such as clothing and computers. This is because *sharing* can intensify the use and therefore lead to that more of the functionality of the product is used before it is discarded. A trade-off was identified as well, i.e. that sharing can increase car transportation if the users of the shared stock have to use inefficient transportation to access it. Another example, this time of extended use of products, is to *increase their technical lifetime*, e.g. by improving their durability. Where *sharing* is, as mentioned, suitable for products that typically do not reach their full lifetime, *increasing the technical lifetime* is instead suitable for products or components that are normally used until they break down, such as microwave ovens and light bulbs. It was also found that increasing the durability of a product sometimes comes at the cost of using more material in the product or more impacting material. For post-use, an example is to *recycle materials*, which is suitable for products where most of the impacts come from material production. An associated trade-off is that recycling can entail a risk of recirculating hazardous substances.

The findings above were ordered according to the typology of RE measures, but the findings can be further analysed from a different perspective as well. Based on the findings for each RE measure, several key product types were identified that affect the outcome of RE measures implemented on different types of products and systems. The first key product type is **consumable products**, which can be made more resource efficient by reducing losses in production, switching to bio-based or recycled materials and by effective use (i.e. to avoid over-dimensioning of a product in relation to its intended purpose). Additionally, some consumable products can be redesigned for multiple uses, although there is then always an associated trade-off from the energy and materials required to produce a multiple-use product instead of a consumable product.

Complex products was the second key product type identified. A complex product has many components which are more or less integrated. This complexity entails a high risk for faults in individual components, which might need to be regularly replaced. It also hampers efforts to disassemble the product, which can hinder repairs as well as remanufacturing. Consequently, to extend the use of complex products it is important to design them for disassembly, so that they can be taken apart and reassembled without damaging the constituent components. Another type of complexity is when products contain many different, more or less integrated, materials. The larger the number of different materials and the more integrated they are, the greater the difficulty in separating them for recycling. However, this can also potentially be remedied by designing the product in a way that allows separation of the different constituent materials.

Another key product characteristic is which life cycle phase causes most of the total impacts. For **products where the production-phase dominates**, RE can be improved by reducing losses along the value chain or by using recycled materials, which reduces the required input of primary materials and thus avoids the impactful production of materials and/or components. Conversely, **products with significant impacts from the use-phase** are known as active products. The findings corresponding to active products will be elaborated below (as they partly coincide with the findings for durable products).

The last product type is **durable products**, which can be made more resource efficient by making their use more efficient (e.g. reducing the fuel consumption of a vehicle) or by effective use (e.g. avoiding over-dimensioning of a product in relation to its intended purpose). Furthermore, the use of durable products can be extended by for example reuse or remanufacturing, which avoids new production. Nevertheless, there are potential trade-offs when attempting to improve the RE of durable products under certain circumstances, like if the products are active. In order to go further than the brief summaries above and in Table 4, and in order to answer RQ3, the trade-offs for durable and active products will here be expanded upon.

An active product consumes energy or materials when used, which means that for example vehicles (require fuel and/or electricity) and buildings (require energy for e.g. climatization and water) share this trait. Active products can be made more resource efficient in several ways. A straightforward option is to reduce the energy or material use in the use phase. Some successful examples include switching to a lighter material in a vehicle which reduces fuel consumption (Kim and Wallington, 2013) and avoiding chemical use in a floor care service by switching to a special polishing pad (Larsson, 2009), both of which resulted in an overall reduction of life cycle impacts. However, in some cases efforts to reduce use phase impacts will not result in net environmental improvements. This is because often the reduced use-phase impacts come at a price of increased impacts in production, e.g. from using more material or switching to scarce metals. A concrete example is provided by Ingrao et al. (2016), where a building's heating needs were reduced by improving the insulation of the walls, but the environmental cost of adding an insulating layer negated the benefits from reduced heating.

Another example of this trade-off can be found in the LCA in paper II, on 3D-printing of truck engines. Some components of the engine were 3D-printed instead of conventionally produced, which allowed less material to be used and thus gave a lower weight. A lower total vehicle weight reduced fuel consumption, as can be seen in Figure 2, where S0, S1 and S2 denote three different scenarios. S0 represents conventional manufacturing and the other scenarios represent cases where parts of the engine are 3D-printed, S1 in the near future and S2 further into the future with a more mature and wide-spread 3D-printing technology. The effects of the mentioned trade-off between impacts from use phase and production can clearly be seen in Figure 2 where the greenhouse gas emissions from fuel production and combustion are decreased due to 3D-printing, while impacts from engine production are increased. One of the reasons for the increased production impacts is the use of more impacting materials, such as stainless steel instead of low-alloy steel. Another cause was the increased electricity use from 3D-printing compared to conventional manufacturing. The difference between this case and the case of buildings in the study by Ingrao et al. (2016), is that for 3D-printing of truck engines the reduction in use-phase impacts was large enough to compensate for the increased production impacts. However, this is overturned if a high-fossil electricity-mix is used, or if highly impacting materials like nickel are used to replace iron, steel or stainless steel, see Section 4.2 below.

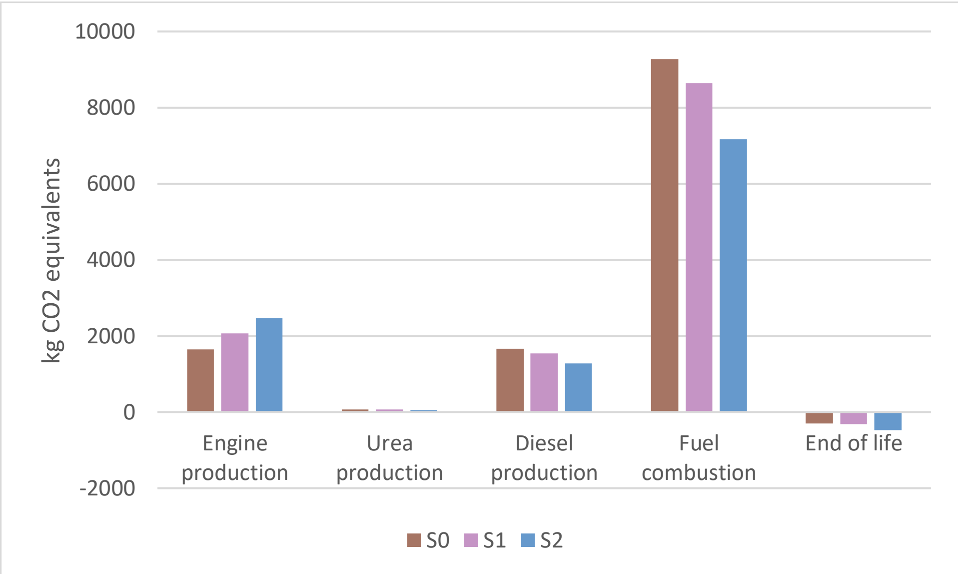

Figure 2: Emissions of greenhouse gases for the different life cycle stages of a truck engine, as represented by kg CO2-equivalents for three scenarios, S0, S1 and S2. See section 2.2, as well as paper II, Section 5.2.1.

Consequently, it can be concluded that reducing the energy or material consumption in the use phase generally gives environmental benefits, except when the required changes cost more than the benefits they generate in terms of energy or other resources. This can be the case for e.g. vehicles, buildings or any other energy or material-using product.

Another trade-off for active products depends on technological development. As mentioned, durable products can be made more resource efficient by extending their use, either by designing them for longevity or using them longer or more times, sometimes enabled by repairing, remanufacturing or repurposing. These measures generally improve the product's resource efficiency by postponing the replacement of the product, although for active products there is a trade-off to be aware of. Specifically, this trade-off comes into play when technological development takes place in a manner which at a significant pace improves the energy or material efficiency during use. Examples of products for which this trade-off can be relevant include cars (Smith and Keoleian, 2004; Spielmann and Althaus, 2007), washing machines (Ardente and Mathieux, 2014), and other household appliances (Bobba et al., 2016; Boustani et al., 2010; Domenech and Van Ewijk, 2015; Iraldo et al., 2017). A key factor is the rate at which the development happens, and the trade-off is valid during periods when the rate is higher than a certain level. This temporal aspect of the trade-off can be illustrated by the example of the EU Ecodesign directive, which included ecodesign requirements for vacuum cleaners (EC, 2013). This could be expected to trigger a period of efficiency improvements that will last until a plateau is reached. During that interval, the trade-off between energy efficiency and extended use comes into play. Consequently, any measure attempting to extend the use of vacuum cleaners would have to take this into account in order to minimise environmental impacts.

Nonetheless, there are ways of avoiding the trade-off with extended use of active products. For example, it is sometimes possible to upgrade products, to keep up with the energy efficiency standards. An example is the remanufacturing of gearboxes that could be upgraded as a part of the remanufacturing process, to match the performance of new versions (Gabhane and Kaddoura, 2017). In other cases, the trade-off can be avoided by sharing the products (see description of sharing as a RE measure in section 2.1). If new models of products are significantly more efficient because of fast-paced technological development, then a sharing scheme can expend older versions earlier by wearing them out faster. They can then be replaced by more energy efficient models while still having fulfilled their full technical lifetime and function.

To summarise, the synthesis of many assessment studies yielded a number of findings about RE measures. This allowed the identification of a number of key product types and trade-offs. For example, the results showed that there are pitfalls to avoid for durable products, which are sometimes discarded before reaching their full lifetimes, and for active products, which can sometimes become outdated in terms of energy efficiency. In these cases, the pitfalls can be avoided by e.g. upgrading or sharing the products.

4.2 Learnings from a single assessment study

As shown by the examples in Section 4.1, a synthesis of many assessment studies can yield learnings about RE measures, over sectors and different products. In this section, focus will instead be on a single assessment study, to investigate what lessons can be learned, not only for the specific case but also regarding what learnings are relevant for other cases. In line with RQ4, the prospective LCA on 3D-printing of a truck engine in paper II will be the subject of analysis. The study quantified the environmental impacts of 3D-printing the metal components of a truck engine, compared to manufacturing the engine conventionally. The results were aggregated in three different ways, using three different weighting methods, namely EI99, EPS and EDIP (Goedkoop and Spriensma, 2000; Steen, 2015; Wenzel et al., 1997). As a result of their differences, the weighting methods emphasise different parts of the Life Cycle Inventory (see section 2.2). An example is that EPS takes both present and future generations into account in the valuation of abiotic resources and thus the impacts of resource consumption are emphasised. The use of three different weighting methods thus gave a richer insight into the nuances of the environmental impacts of the product system. The results showed that the redesign for 3D-printing enabled a lower weight for the engine and hence the vehicle, which in turn reduced fuel consumption over the lifetime of the truck. Although the 3D-printing process entailed increased impacts, these were outweighed by the benefits from reduced fuel consumption why a net decrease was achieved in fossil resource depletion, global warming potential and human health effects. However, this was only valid when using a low-fossil electricity source and when it was possible to print using low-alloy materials. Additionally, a prerequisite was the possibility to print large components, whereas presently there is a limit to the size of components that can be printed (although this limit is being expanded continuously (Gutowski et al., 2017)). The study thus enabled the identification of a number of important factors to consider for future technological development of additive manufacturing, both for resource efficiency in general, as well as specifically for applying the technology within the automotive industry.

The first factor relates to material choice. The number of different materials that can be used for 3D-printing is limited, and commonly used materials include stainless steel, nickel-alloys and titanium-alloys. A risk that was identified in the study was that implementation of 3D-printing could lead to the substitution of low-impact materials, such as low-alloy steel, to materials with a higher impact from production, like nickel-alloys. For example, a cylinder head is conventionally manufactured from cast iron and hence a switch to 3D-printing would necessitate a substitution to one of the materials available for 3D-printing. Were nickel-alloys to be used for this part, this would dramatically increase the overall environmental impacts, because of the substantial impacts from extraction and production of nickel-alloys compared to cast iron (see the first row of Table 5, where the numbers were generated by averaging the results of the three weighting methods, EDIP, EI99 and EPS and comparing to the reference scenario, S0). The same is true for titanium-alloys, which is also a common material for metal 3D-printing, or even for substitution of low-alloy steel with stainless steel (see the second row in Table 5). The consequent recommendation was thus to, whenever possible, avoid substituting current materials with materials that have a significantly higher impact on resource use and the environment, for example changing from iron or steel to nickel-alloys. In line with this it can be recommended to develop AM technology to be able to use low-alloy steel for printing, which is not currently possible but would generally enable material choices with lower environmental impact. These recommendations are valid for any implementation of 3D-printing both in the automotive industry and other manufacturing industries.

Table 5: Sensitivity analysis for three different parameters of relevance for AM, detailing how the parameter was altered and the consequent change in results due to the change in the parameter. S0 is the reference scenario (conventional manufacturing). S2 is the scenario representing the future state of technological development of 3D-printing. The results are normalised to S0 and then averaged over the changes in EDIP, EI99 and EPS results.

Parameter	**Tested change**	**Resulting increase in impacts (in S2)**
Nickel alloy printing	Printing the cylinder head from nickel instead of cast iron	+86 %
Stainless steel content	Printing the majority of steel parts in stainless steel instead of low-alloy steel	+14 %
Electricity mix for LBM	Using a US electricity mix for LBM printing instead of a SE mix	+37 %

A second factor that was identified as important was the electricity mix used for 3D-printing. Because 3D-printing uses a large amount of electricity to melt and build components, the total environmental impacts are to a large degree determined by the electricity source. In the study in paper II, the manufacturing was assumed to take place in Sweden, with a Swedish low-fossil electricity mix. Even with low-fossil electricity there were significant impacts from the 3D-printing process. Table 5 shows that if a high-fossil US electricity mix is used instead, total impacts would increase by 37% (for the future scenario S2). This reversed the benefits achieved from lower component weights and thus lower fuel consumption in the truck. Hence, there are potential environmental improvements to be made using 3D printing for automotive components, but only if a clean electricity source is used. This is similar to electrification of vehicles, which is also environmentally beneficial only when using clean electricity (Nordelöf et al., 2014).

In general, if directly replacing conventional manufacturing with 3D-printing, impacts will increase. However, for mobile products that require energy, a net decrease in environmental impact can be achieved by redesigning components for lower weight, which consequently lowers fuel consumption.

The automotive industry is a straightforward example, as is the aerospace industry, where benefits from lightweighting can be vast (Mami et al., 2017).

Yet another potential benefit from 3D-printing which is mentioned in literature, is to print spare parts on-demand. This was only discussed qualitatively in paper II, but spare-part printing can have the effect of reducing the need for keeping stocks of spare parts in storage. Furthermore, spare parts are often produced in small numbers, and with conventional manufacturing it can be prohibitively expensive. With AM, the spare parts can be printed on-demand, thus significantly reducing the associated production costs (Jamshidinia et al., 2015). In turn, spare part printing can improve remanufacturing and repairing possibilities, hence enabling a prolonged life of products. These benefits can be achieved both within the automotive industry and most other industries, as long as the product or its components can be 3D-printed.

To summarise, although only 3D-printing of components for one specific product was studied, several results and identified key factors were found valid for a wider set of product types, as summarised in Table 6. Either they were valid for the automotive or other industries, or they were valid for products that share similar traits with active and mobile products, for example that they use energy or materials in their use phases.

Table 6: Summary of conclusions and recommendations from the LCA of additive manufacturing of a truck engine

General conclusions and recommendations for implementation of AM	Valid for
Avoid substituting current materials with materials with a higher impact on resource use and the environment	Any application
Redesign components for lower weight, thus e.g. lowering fuel consumption	Mobile products whose use-phase energy use depends on the product’s weight, e.g. in the automotive or aerospace industries
Use as clean an electricity mix as possible for printing	Any application
Develop the technology to be able to use low-alloy steel for printing	AM in general
Develop the technology to be able to print larger components	AM in general
Spare-part printing can enable prolonged life of products	Any product that benefits from repairing

5 CONCLUSIONS

The results of this thesis were divided into two parts, one presenting learnings from a synthesis of many assessment studies and the second presenting learnings from a single assessment study on additive manufacturing of truck engines.

By synthesising many assessment studies on RE measures, a number of trade-offs and key characteristics were identified (as summarised in Table 4), thus showing that syntheses can produce useful knowledge regarding how the outcome of RE measures depend on product system characteristics. Some key product types were identified as particularly relevant for the outcome of RE measures. These included consumable products, complex products, products that have a dominant production phase and lastly durable products. Several trade-offs were identified. Of these, two trade-offs relating to active products were chosen for further discussion. The first one was a general finding for all active products (and was supported by the results of paper II), that efforts to reduce impacts in the use phase could lead to increased impacts from production, e.g. from adding material such as insulation to walls. The second trade-off is for active products where technological development rapidly improves the product's energy efficiency. During this period of improved energy efficiency, life cycle energy savings can be made from replacing older products with newer versions rather than extending the use of older products, which is in line with findings in previous research.

The second part of the results drew from the assessment study that was carried out on 3D-printing of a truck engine. This study produced conclusions that were useful also for the future RE potential of AM more in general. Some of the key conclusions were that additive manufacturing can improve the RE for engines by allowing components to be redesigned for lower weight. Such redesigns can generally provide reductions in fuel consumption for mobile products, e.g. in the automotive and aerospace industries. In this case, however, net environmental and RE improvements were only achieved when using low-fossil electricity and when technological development was assumed to allow for the use of low-alloy materials for printing as well as for printing large components. More in general, for realising the RE potential of metal 3D-printing in any application, it is important to use a clean electricity source and to choose feedstock materials with the least amount of impact (often by a lower degree of alloying).

In summary, the findings show that useful knowledge on RE measures could be produced from synthesising many assessment studies as well as from carrying out a single assessment study. Moreover, both paper I and paper II gave insights into the role of active products for the outcome of RE measures, and paper II indicated the environmental and resource implications of using metal 3D-printing for truck engines. As seen in the findings from the synthesis study in paper I and the assessment study in paper II, the devil is often in the details, like the product characteristics in each particular case. A bottom-up approach is here shown to provide a way of dealing with such details, and since they are often lost in top down studies, bottom-up studies are shown to be necessary complements.

6 FUTURE RESEARCH

The review in paper I covered a wide range of physical measures aimed at decreasing resource flows and environmental impacts of a product system, such as reducing losses or remanufacturing. However, there are several ways of achieving these physical measures, e.g. by adopting new business models, by implementing new policies or by utilising new design methods. Hence, it is important to be able to assess whether a new business model, policy or design will actually result in RE improvements in terms of reductions in physical flows of material and energy. Environmental and resource assessments of new business models have been selected as the main subject for the research following this thesis.

In order to assess the consequences of implementing a new business model, estimations have to be made regarding how it will affect the physical flows, preferably by quantifying the cause and effect relationships. Previous attempts at finding the effects of business models on physical flows can be found in literature, and most use scenario-based approaches rather than formulating models of cause and effect relationships. An example is a study by Mont (2004) on the case of sharing and leasing of tools and garden equipment. The assessment was made by formulating different scenarios together with the involved stakeholders, to attempt to find the ones with the least environmental burden. Finding such a scenario can reveal barriers and opportunities related to sharing systems, but it is not guaranteed that the scenario will be realised if the business model is actually implemented. In a study by Chun and Lee (2016) on leasing of water purifiers, scenarios were formulated based on assumptions on maintenance patterns and user behaviour, which as they point out introduces uncertainties in the assessment. Furthermore, Amaya et al. (2014) assess the environmental consequences of bike sharing and also note the difficulties in taking user behaviour into account. They also formulate scenarios and make assumptions based on data from the specific case site. This site specific data makes it more difficult to generalise the learnings for other contexts because different conditions might affect the outcome differently. Diener et al. (2015), on the other hand, used expert interviews to estimate the changes in material flow that could result from introducing a PSS business model for truck components. Conservative estimates were consistently used in their study, as a way of increasing the robustness of the results. Aside from these single assessment studies, Tukker (2015) carried out a review of studies on PSS. He concludes that environmental benefits are not guaranteed and depend on factors such as less careful user behaviour when products are leased or rented. In summary, it is difficult to assess how physical flows change due to changes in the business model, which in turn makes recommendations difficult. Furthermore, as indicated in section 1, there is a lack of synthesised knowledge about the environmental impact of business models for RE outside the field PSS. In order to fill these gaps, the overall aim of the research following this thesis is to identify cause-and-effect relationships between changes in business models and changes in physical flows. If this proves unfeasible, then the aim is to at least conceive a strategy for formulating informative scenarios that can guide decision-making for the implementation of business models for RE.

In the research work following this thesis, the aim will in practice be pursued via two initial avenues. The first approach is to synthesise the findings of several studies that have been conducted within the Mistra-REES consortium. The studies have developed or investigated business models for leasing, functional sales and increased recycling within the automotive industry as well as for charging infrastructure for electric trucks. The common theme is changes in business models with potential for RE improvements in the automotive industry. The mentioned studies will be complemented by studies from literature, and together they will be synthesised building on theory and literature on business model design and particularly circular business models. This is expected to be a first step in establishing possible causal links between changes in business models and changes in RE. A second avenue for identifying how changes in business models affect physical flows is to carry out studies of different specific cases. This would enable a detailed investigation of some potential business models and their effects on the RE of products. A possible example would be to expand on the research presented in paper II. Specifically, something that was only briefly discussed in that paper could be further investigated, namely on-demand 3D-printing of spare parts, which can have interesting after-market effects (Jamshidinia et al., 2015).

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