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Resource and Environmental Impacts of Resource-Efficiency Measures Applied to Electronic Products

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Abstract
Natural resources such as ecosystems, land, water and metals underpin the functioning of economies and human well-being, and are becoming increasingly scarce due to growth in population and affluence. Metals are increasingly demanded for their specific properties as modern technology develops. The dependence on metals is of growing concern due to the environmental impacts related, for example, to energy use and local impacts from mining, as well as the scarcity risks posed by socio-economic, geological and geopolitical constraints.

Thus, there is a clear need to use metals and other natural resources more efficiently. The vision of a circular economy has been proposed as a way to do this, for example by improving durability, reusing, repairing and recycling. Such so-called resource-efficiency (RE) measures are commonly assumed to be environmentally beneficial, although the evidence is not plentiful. It is plausible that focusing on recirculating products and materials could shift burdens to other environmental impacts or life cycle stages. It has therefore been argued that a life cycle-based approach, such as in life cycle assessment (LCA), is useful to critically assess the environmental implications of RE measures. LCA aims to quantify the environmental impacts of products over their entire life cycles - from cradle to grave - assessing a wide range of impacts such as toxicity, climate change and metal resource use. For metal resource use, however, there are a number of perspectives as to what constitutes the actual environmental problem. These perspectives are represented in a variety of life cycle impact assessment methods (LCIA) which have previously been shown to give diverging results.

Electronic products are emblematic of metal resource use challenges since they deploy a broad spectrum of scarce metals. This thesis aims to provide knowledge on the potential for RE measures to reduce the environmental impacts of electronic products, by addressing the following research questions: (1) What resource-efficiency measures result in reduced potential environmental impacts and resource use – for what types of products and under what conditions? (2) How does extended use of electronic products through design for increased technical lifetime, reuse and repair affect environmental impacts, particularly metal resource use? (3) How does the application of different LCIA methods for metal resource use influence interpretations of resource-efficiency measures applied to electronic products?

This thesis builds on three appended papers which are all based on comparative assessments of resource efficiency, studied as resource use and environmental impacts per function delivered, using LCA and material flow analysis. The results indicate that extended use of electronic products through increasing technical lifetimes, reusing and repairing, is generally resource-efficient. Exceptions may occur, however, if extended use is insufficient to motivate impacts from producing more durable products or spare parts. Use extension of electronic products leads to resource efficiency in two distinct ways: through the intended use extension and by increasingly steering material flows into recycling. Further resource efficiency could be realised by combining RE measures over the entire life cycles of products.

With regards to metal resource use, the choice of LCIA method can influence the interpretation of the results of RE measures for electronic products. Therefore, it is advisable to use several complementary LCIA methods to minimise the risks of overlooking potentially important resources issues. Furthermore, better understanding and transparency of such issues is valuable in order to provide more comprehensive information to decision-makers.

Keywords
resource-efficiency, circular economy, scarce metals, metal resource use, resource depletion, life cycle assessment, electronic products

List of appended papers

Paper 1:
Böckin, D., Willskytt, S., André, H., Tillman, A-M. and Ljunggren Söderman, M. What makes resource efficiency measures environmentally beneficial? A systematic review of assessment studies. Manuscript submitted to the Journal of Cleaner Production.

All authors developed the framework and typologies used for analysis and discussed the conclusions. The first, second and third authors performed the literature search, analysed the empirical data and co-wrote the article with valuable feedback from the co-authors. The author of this thesis primarily wrote the first two sections of the article.

Paper 2:
Ljunggren Söderman, M, and André, H. Scarce metals in complex products - exploring the effects of circular economy measures. Manuscript submitted to Resources, Conservation and Recycling.

The author of this thesis conducted the material flow analysis of the three case studies with support from the first author. Both authors analysed the results and discussed the conclusions in collaboration. The first author wrote the manuscript with support from the second author.

Paper 3:
André, H., Ljunggren Söderman, M. and Nordelöf A., 2018. Resource and environmental impacts of using second-hand laptops. Manuscript.

The author of this thesis conducted the life cycle assessment and wrote the manuscript with support from the co-authors.

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Table of Contents

1. Introduction **1**
1.1 Research aim and thesis outline 3
1.2 Scope, definitions and delimitations 4
2. Methodology **5**
2.1 Life cycle assessment (LCA) 5
2.2 Material flow analysis (MFA) 6
3. Literature background **6**
3.1 Environmental impacts and assessment of electronic products 6
3.2 Methodological issues on metal resource use 8
4. Results **12**
4.1 Paper 1 12
4.2 Paper 2 15
4.3 Paper 3 17
5. Discussion **21**
5.1 What makes RE measures applied to electronic products resource-efficient? 21
5.2 A need for combinations of RE measures and enablers 22
5.3 Importance of dominant life cycle phase 22
5.4 Effects of methodological choices on the resource efficiency of RE measures 23
6. Conclusions **23**
7. Outlook for future research **25**
8. References: **27**

1. Introduction

Natural resources such as land, water, ecosystems, minerals and metals underpin the functioning of economies and human well-being. The industrial economy, which has operated in a largely linear fashion, has contributed to increased human well-being but, to a considerable extent, at the cost of natural resource degradation. This threatens to severely undermine the prosperity of future generations (Millennium Ecosystem Assessment, 2005) and is reflected in the concept of sustainable development which states that there is a need for development that provides human well-being without reducing the same opportunities for future generations (WCED, 1987). With respect to sustainable development, it is necessary to consider the future availability of the natural resources that are being used today (Rosenbaum et al., 2018).

The appropriateness of the linear economic model was questioned already by Boulding (1966), who referred to it as a “cowboy economy” which may be reasonable in economies of small size compared to their surrounding natural systems, but much less so for large ones. This would require a drastically different rationale – a “spaceship economy” seen as a closed system in which finite resources need to be recirculated. In contrast to the linear model, where value creation is coupled with resource throughput, value creation in the spaceship economy would instead be based on value preservation, i.e. minimal resource throughput.

Similarly, the Club of Rome suggested that there are limits to growth (LTG) of the economy’s resource throughput, both in resource availability and in the ecosphere’s ability to act as a sink for pollution (Meadows et al., 1972). This is a topic which has been widely debated since (Jackson & Webster, 2016). The debate has mainly concerned the availability of non-renewable resources, e.g. fossil fuels, minerals and metals, and has been formed by two different perspectives as to what type of limits or scarcity may be relevant – the opportunity cost and finite stock paradigms (Tilton, 2010). With regards to non-renewable resources, particularly metals, the opportunity cost paradigm views economic scarcity as the only relevant type of scarcity. The only limits to metal availability are posed by the opportunity cost, in other words, what other values society is willing to offer for additional metal resources. In this view, geological scarcity is considered a myth (Ayres & Peiró, 2013; Tilton, 2010). In the finite stock paradigm it is argued that geological scarcity, at least for some metals, may be a valid concern since price information may not reflect scarcity of co-produced metals and does not take account of the demand of future generations (Ayres & Peiró, 2013; Frischknecht, 2013). The LTG debate remains unsettled (Jackson & Webster, 2016), but it is increasingly understood that the current modes of the industrial economy are unsustainable, for instance as demonstrated by the transgression of planetary boundaries (Steffen et al., 2015). Resource efficiency of metals has therefore been discussed in the context of climate change, (Allwood et al., 2011) as well as in a variety of other contexts, to alleviate geological scarcity (Sverdrup et al., 2017), to ensure a conflict-free and secure supply (EC, 2014; NRC, 2008; OECD, 2013) and to reduce economic value losses (EMF, 2013; 2015). In this thesis, metals that are referred to as scarce may be so due to limited availability caused by geological (Skinner, 1979), technical, economical (Tilton, 2003) and geopolitical constraints (EC, 2014; NRC, 2008).

Many of today’s products draw upon a large diversity of scarce metals. In the electronics industry, increasing material complexity has occurred alongside the strive for ever enhancing properties and decreasing product size (Greenfield & Graedel, 2013). For example, a modern integrated circuit may comprise more than 60 elements (NRC, 2008). Rapid innovation cycles and the magnitude of consumption contribute to making waste electrical and electronic equipment (WEEE) the fastest growing waste stream globally (Widmer et al., 2005). As recycling rates of many metals are low (Graedel et al., 2011), this risks creating a situation of dispersion and future decreased availability of potentially valuable resources. Electronic products are therefore an emblematic example of the challenge of managing flows of scarce metals in a more resource-efficient manner and so are regarded as appropriate objects of study in this licentiate thesis.

In the last few years, a collection of pre-existing concepts and theories under the name of circular economy (CE) has gained widespread attention in policy, academia and industry. Although interpretations of CE vary significantly (Kirchherr et al., 2017), a common understanding seems to be that it represents an alternative to the linear industrial economy; that it may constitute a vision of how to operationalise sustainability principles in practice (Ghisellini et al., 2016; Kirchherr et al., 2017); and that influential foundations are the spaceship economy (Boulding, 1966), industrial ecology (Graedel & Allenby, 2010), the waste hierarchy (European Commission, 2008), the performance economy (Stahel, 2010; Stahel & Clift, 2016), cradle-to-cradle design (McDonough & Braungart, 2010) and product-service systems (PSS) (Mont, 2004a; Tukker, 2015). As such, the concept is composed of various strategies and tangible physical measures that may be applied in order to reduce the resource use and environmental impacts of products and services.[1]

However, there are also other ways of reducing the environmental impacts of products that are not as explicitly or commonly associated with CE, for instance by reducing losses in production. Therefore, this work includes a comprehensive typology of measures that can be applied to potentially make products more resource-efficient. Such measures are referred to as resource-efficiency (RE) measures. RE is defined in broad terms, alluding to the definitions of “natural resource”, “efficiency” and “effective” (see section 1.2, Scope, definitions and delimitations) as used in the Mistra REES programme (2018) of which this licentiate thesis is an outcome. In short, natural resources are regarded as both inputs to and outputs from the economic system, e.g. resource use and impacts on ecosystems. Consequently, the term “resource efficiency” refers to the result of a RE measure that is successfully applied to a product so that the same function is fulfilled using fewer natural resources, in terms of both resource use and environmental impacts, compared to a conventional alternative that represents business as usual.

Applying CE measures to products is widely assumed to be resource-efficient but as yet there is limited empirical evidence of this (Bocken et al., 2017). It is plausible that a sole focus on recirculating products, components and materials may have drawbacks for other types of environmental impacts or at other life cycle stages. For such reasons, before making claims about the possible contribution of CE to sustainable development, it is crucial to critically analyse such measures from a life cycle perspective (Haupt & Zschokke, 2017; Kjaer et al., 2016; Kjaer et al., 2018) using methods such as life cycle assessment (LCA). Assessment studies of RE measures are increasingly seen in the academic literature. However, there is a lack of synthesised knowledge beyond individual cases regarding the situations in which RE measures

[1] The term “product” is hereafter used to denote both products and services, and combinations thereof, conforming to the standard for life cycle assessment (LCA) (ISO, 2006).

actually result in RE (Bocken et al., 2017; Tukker, 2015). Previous reviews of RE on a product system level have either focused on specific sectors (Ghisellini et al., 2018) or constituents of CE such as PSS (Tukker, 2015). In other words, there is limited knowledge of RE in a more general sense. It is a key hypothesis in this licentiate thesis, especially in paper 1, that product characteristics, life cycle environmental impacts and the physical nature of RE measures are interdependently decisive for RE.

Most LCAs studying the environmental impacts of RE measures applied to electronic products are limited in their scope in terms of environmental impacts and life cycle stages. Many tend to focus on climate change or energy and cover end-of-life (EoL) to a limited extent. Few studies have specifically addressed the implications on scarce metals or impacts on metal resource use in this context. LCA addresses environmental impacts categorised into three Areas of Protection (AoP): ecosystem quality, human health and natural resource use. The AoP of natural resource use is a widely discussed topic in the LCA community. There are several perspectives on what constitutes the environmental problem with specific regard to non-renewable natural resources, such as metals, minerals and fossil fuels (Steen, 2006). These perspectives are represented in a variety of largely differing life cycle impact assessment (LCIA) methods using different types of indicators. Although different terms are used to describe what these methods assess (e.g. consumption, use, depletion), they are used in the same manner and for the same purpose (Finnveden et al., 2016). This thesis discusses metals in particular in the context of the AoP of natural resource use. Since there is some debate about what actually causes *depletion*, the term "metal resource use" will be used throughout this licentiate thesis. The choice of LCIA method for assessing metal resource use has been shown to give largely differing results (e.g. (Alvarenga et al., 2016; Finnveden et al., 2016; Peters & Weil, 2016; Rigamonti et al., 2016; Rørbech et al., 2014; Van Caneghem et al., 2010)). Therefore, it is plausible that the choice of LCIA method could be influential for the interpretation of results in assessments of RE measures applied to electronic products. Furthermore, since these LCIA methods cover different aspects of resource use, it can also be argued that they complement each other (Finnveden et al., 2016).

1.1 Research aim and thesis outline

The aim of this licentiate thesis is to provide knowledge on the potential of RE measures to reduce environmental impacts of electronic products, in particular with regard to metal resource use. To fulfil this aim, the following research questions (RQs) are addressed:

(1) What resource-efficiency measures result in reduced potential environmental impacts and resource use – for what types of products and under what conditions?
(2) How does extended use of electronic products through design for increased technical lifetime, reuse and repair affect environmental impacts, particularly metal resource use?
(3) How does the application of different LCIA methods for metal resource use influence interpretations of resource-efficiency measures applied to electronic products?

The scopes of the RQs vary in terms of the RE measures, products, environmental impacts and methods studied, as illustrated in table 1. The first RQ is not delimited to electronic products nor to specific RE measures. However, the general nature of the first RQ implies that it contributes to the overarching aim of this thesis since some general findings are applicable to electronic products. This question was addressed by a systematic review of comparative RE assessment studies, predominantly LCAs and material flow analyses (MFAs). To address RQs 2 and 3, assessment studies (LCA and MFA) of RE measures based on extended use were conducted, allowing for higher resolution with regards to metal resource use and particularly relevant product characteristics. Paper 2 was conducted as a comparative assessment of losses of scarce metals when introducing RE measures that extend use through increasing technical lifetimes, repairing and reusing electronic products. Expanding on paper 2, paper 3 also studied the environmental impacts (using LCA) of one of the same RE measures, namely, reuse. This was to ensure that sufficient attention and clarity could be provided in terms of the variety of environmental impacts assessed, in particular, covering different perspectives on metal resource use (RQ3).

Table 1. Scope of research questions.

RQ	RE measure(s)	Product(s)	Environmental impact(s)	Assessment method(s)
1	Measures addressing extraction and production, use phase and post-use	A large variety, not exclusively electronic products	A large variety of environmental impacts	Review of LCAs and MFAs
2	Measures based on ***extended use****: - Use more of technical lifetime through reuse - Increase technical lifetime - Repair	Electronic products - Laptops - LED lighting - Smartphones	- Net loss of scarce metals - Metal resource use - A large variety of environmental impacts	- MFA - LCA
3	Use more of technical lifetime through reuse as main example	Electronic products - Laptops as main example	Metal resource use	- Life cycle assessment using several LCIA methods for metal resource use

* According to the developed typology, RE measures addressing the use phase can be divided into measures that make use more effective and efficient as well as measures based on extended use. Measures based on extended use are: using more of the technical lifetime (e.g. through reusing), increasing the technical lifetime, shifting to multiple use, maintaining, repairing, remanufacturing and repurposing. For more descriptions of the typology, see appended paper 1.

Chapter 2 describes the fundamentals of the methods used for assessing RE in the three appended papers. **Chapter 3** presents a literature review providing background and motivation for RQs 2 and 3. **Chapter 4** summarises the most important results from appended papers 1, 2 and 3. **Chapter 5** attempts to synthesise the findings from the papers. **Chapter 6** summarises the conclusions. **Chapter 7** outlines topics for future research, combining the results, discussion and conclusions with methodological foundations.

1.2 Scope, definitions and delimitations

This thesis concerns RE on a product level. RE is defined by alluding to the following definitions.

"Natural resources are renewable and non-renewable resources which can be extracted from the natural system to the technosphere; manufactured resources, which are man-made physical objects in the technosphere, originating from renewable and non-renewable resources in the natural system; ecosystem services provided by the natural system, including provisioning services, regulating services, cultural services, and underlying supporting services" and it is acknowledged that natural resources "underpin the functioning of the economy and the quality of life" (Mistra REES, 2018).

Efficient means "maximum ratio of an output to the corresponding input" (ISO, 1992).

Effective means “successful in solving one or more needs of targeted and relevant actors” (Mistra REES, 2018).

Consequently, “resource efficiency” is realised if the same function is fulfilled using fewer natural resources, in terms of both resource use and environmental impacts. Although it is acknowledged in LCA that resource use is an environmental impact, the particular focus on metal resource use, as well as the use of material flow analysis, makes it appropriate to explicitly refer to both resource use and environmental impacts.

“Electronic products” is a broad category and all cases are delimited to specific electronic products. Some results and conclusions for these specific cases may be generalised to electronic products but this needs to be done cautiously. The term “information and communication technologies” (ICT) is a subcategory of electronic products. In this thesis, ICT refers to computers, laptops and smartphones collectively, but not other products such as servers that are normally included in this term.

As stated in the introduction, a life cycle-based approach has been argued to be necessary and purposive for critical assessment of RE and CE. It may, however, be limited in indicating the global or societal relevance of efficiency gains (Allwood et al., 2011). Life cycle-based approaches are generally temporally static, which may limit the consideration of relevance of processes which may change over time. Furthermore, criticism has been directed towards RE as a means for sustainability, predominantly because of rebound effects (Hobson, 2013). One such example is Jevon’s paradox, which states that efficiency gains may lead to lower prices and therefore spur increased demand (Alcott, 2005). On a macro-level, such effects have been suggested as likely causes for the absence of any decoupling of climate change and metal use from economic growth, giving rise to the term “myth of decoupling” (Jackson, 2011). Although theoretically possible, rebound effects are seldom accounted for in life cycle-based approaches. Considering how to account for rebound effects could be a valuable topic of future research in the RE and CE discourse. Although briefly discussed in papers 1 and 3, rebound effects are not explicitly considered in this licentiate thesis. Hence, it is assumed that RE on a product level is conducive to approaching a more environmentally sustainable society.

2. Methodology

As indicated by table 1, LCA and material flow analysis are in this thesis central to the assessment of resource and environmental impacts of RE measures. Given the purpose of this research, using these methods was deemed suitable as it allows for the comparison of resource and environmental impacts caused by different product systems that provide the same function.

2.1 Life cycle assessment (LCA)

LCA is a methodology that aims to systematically account for all the relevant environmental impacts of a product or process occurring from the cradle (resource extraction from ecosphere to technosphere) to the grave (final disposal) (ISO, 2006). It principally consists of three phases: goal and scope definition, inventory and impact assessment along with continuous interpretation and, if needed, iteration. Why and for whom the study is being conducted are stated in the goal and scope definition phase. System boundaries for the specific product system in terms of life cycle phases, environmental impact categories, temporal and geographical aspects are also presented in this phase. The functional unit which constitutes the basis for comparison, is also specified here. The inventory analysis constructs a model of the technical system including all environmentally relevant flows going in and out of the processes within the system boundary that altogether are required to fulfil the functional unit. The impact assessment collects the environmentally relevant flows of the inventory analysis and translates them into environmental impacts of different types. Environmental impacts are categorised into three AoP: ecosystem quality, human health and natural resource use (Baumann & Tillman, 2004). An LCA was conducted as part of paper 3 and many of the reviewed comparative assessment studies of paper 1 were LCAs (table 1). Furthermore, paper 3 studied issues of relevance to the AoP of natural resource use, namely alternative impact assessment methods for metal resource use (table 1).

2.2 Material flow analysis (MFA)

MFA is a method used to quantify flows and stocks in a specified system. This can be done, for example, on global, national, process or product system levels. Analyses may concern aggregated material flows such as products or multi-material flows, or alternatively a smaller number of substances, commonly referred to as substance flow analysis (SFA). Central to both MFA and SFA is mass balance of inputs and outputs over each sub-process of a system and the application of transfer coefficients through which they relate. Results are typically presented in Sankey diagrams where direction and magnitudes of flows are represented by arrows of varying thickness. Using such methods may be conducive, for instance, to identifying material flow patterns (Brunner & Rechberger, 2004). A version of MFA as described by Brunner and Rechberger (2004) was used in paper 2 to establish the net losses of scarce metals from alternative product systems providing the same functional unit (table 1).

3. Literature background

The literature review provides the background to and motivation for RQ2 and RQ3. Section 3.1 gives an overview of the existing knowledge regarding relevant environmental impacts, processes, components, data quality and methodological choices of computers, laptops and smartphones (ICT). Section 3.2 gives an overview of the methodological discussions regarding metal resource use in LCA as well as earlier comparisons of LCIA methods for metal resource use. It should also be noted that paper 1 (section 4.1), which consists of a literature review of RE measures and products in a general sense, can be regarded as providing additional literature background for RQ2 and RQ3 while simultaneously addressing RQ1. The literature review concludes with a short summary specifying how identified knowledge gaps were considered in the thesis.

3.1 Environmental impacts and assessment of electronic products

This section is delimited to computers, laptops and smartphones, collectively referred to as ICT.

The environmental impacts of ICT use have been widely studied through the use of LCA. Reviews of such studies by Arushanyan (2013) and Andrae and Andersen (2010), however, observe that representation of use patterns and methodological choices, such as functional unit, inventory approaches and system boundaries cause LCA results to diverge significantly. Arushanyan et al. (2014) note that it is common to include only a few impact categories, predominantly climate change or energy use, which could conceal important information.

Manufacturing and use are generally the most environmentally burdensome life cycle phases for ICT; which of these is most burdensome depends on aspects such as product size, lifespan, intensity of use and background electricity (Arushanyan et al., 2014; Teehan & Kandlikar, 2012). To a large extent, environmental impacts from manufacturing are caused by printed circuit boards (Choi et al., 2006; Deng et al., 2011; Duan et al., 2009; Eugster et al., 2007) and, in particular, by integrated circuits (ICs) mounted on them (Andrae & Andersen, 2010; Arushanyan et al., 2014; Eugster et al., 2007; Williams et al., 2002). ICs are used, for instance, as processors or memory. The production of ICs is often shown to be environmentally burdensome due to process energy-intensity, cleanroom conditions, production of high-purity silicon and chemicals and use of perfluorinated compounds (Boyd, 2012; Liu et al., 2011). Mining of precious metals, especially gold, can also cause considerable impacts due to energy-intensive extraction (Deng et al., 2011; Eugster et al., 2007) and toxic emissions (Moberg et al., 2014). EoL is a reportedly less covered life cycle stage in LCAs of ICT (Arushanyan, 2013). Given that some ICT are treated in informal recycling pathways where hazardous material handling is inadequate, certain impacts may be underestimated, which calls for more realistic modelling of EoL (Arushanyan et al., 2014). The low EoL coverage could also be related to the predominant focus on climate change and energy use in LCAs of ICT, for which EoL has been shown to have fairly negligible impacts (Arushanyan et al., 2014). Eugster et al. (2007) concluded that proper EoL treatment of computers can have noteworthy positive impacts as it may displace primary material and energy production. However, for computers, this is mainly relevant for resource use and human toxicity and less so for impacts related to ecosystem quality such as climate change.

Access to representative data is a challenge in environmental assessment of ICT use due to the complexity of products and processes, rapid technological innovation cycles, intellectual property rights and uncertain EoL pathways. However, the material use of some computer components is indicated to be quite constant over time due to a balance between material efficiency and increased levels of functionality (Kasulaitis et al., 2015a). Exceptions may be design shifts, such as choice of casing materials where magnesium alloy has to a large extent replaced earlier use of plastics (Kahtat et al., 2011; Kasulaitis et al., 2015b), or transitions from hard-disk drives to solid-state drives (Buchert et al., 2012). ICs are an important source of results variation in LCAs of ICT both due to real variability and modelling uncertainty (Teehan & Kandlikar, 2012). Energy use and climate change impacts have decreased per level of functionality, e.g. computational power, due to process efficiencies (Boyd, 2012). Modelling of ICs is plagued by uncertainties concerning the use of chemicals (Boyd, 2012; Plepys, 2004a; 2004b; Williams et al., 2002) and difficulties involved with measuring semiconductor area, which is the relevant parameter for ICs' environmental impacts (Kasulaitis et al., 2015b; Liu et al., 2011; Proske et al., 2016; Teehan & Kandlikar, 2012). Because of the complexities involved and the amount of data necessary, many LCAs of ICT depend on large databases such as Ecoinvent (Hischier et al., 2007; Wernet, 2016), but the Ecoinvent data was collected about 15 years ago and has been argued to be outdated (Proske et al., 2016). Further, the low coverage of EoL, which has been mentioned previously, could also be related to unavailability and uncertainty of data regarding EoL pathways (Arushanyan et al., 2014).

In order to reduce the environmental impacts of ICT, measures that extend the use of products and components are of interest. So far, studies that have investigated the effects of ICT use extension, e.g. through reuse and repair, have rarely been based on real-world cases, which could potentially conceal important aspects. Moreover, they have predominantly focused on the trade-off between use extension and supposed energy efficiency (Bakker et al., 2014; Quariguasi-Frota-Neto & Bloemhof, 2012; Sahni et al., 2010; Schischke et al., 2003; Williams & Sasaki, 2003). However, the conclusions of these studies regarding this trade-off point in different directions, since results depend largely on assumptions and methodological choices. Methodologically, the rapid technological change of ICT poses some difficult questions. The choice of functional unit is especially important in comparative assessment studies. It may be argued that newer technology generations possess higher levels of functionality, suggesting that functional units could suitably be based on computational power. On the other hand, functionality is largely a matter of individual preferences and most applications do not require the latest functionality improvements within relevant timeframes (Schischke et al., 2003), implying that access to an ICT product for a specific time period could be an appropriate functional unit. A related methodological issue is displacement. This is a concept that should reflect the potential for recirculated products or materials to displace new production. It has been argued that, for example, reused products are unlikely to fully displace new production of corresponding counterparts (Cooper & Gutowski, 2017; Zink & Geyer, 2017; Zink et al., 2014). Accounting for displacement is challenging, however, since displacement rates are difficult to estimate.

3.2 Methodological issues on metal resource use

Since metal resources are of specific interest in this thesis, especially for RQ3, an overview of some methodological discussions regarding their assessment in LCA now follows. The first issue relates to allocation of multi-output processes and the second to impact assessment.

As metal extraction from ore is often a multi-output process, this gives rise to the question of appropriate allocation method, i.e. whether to allocate the environmental burdens by mass or economic revenue (Althaus & Classen, 2004; Ekvall & Tillman, 1997). Scarce metals are seldom mined for themselves but as by-products of a carrier metal (Ayres & Peiró, 2013). An argument for revenue-based economic allocation is that extraction is driven by economic interests (Althaus & Classen, 2004; Ekvall & Tillman, 1997). This is the chosen and consistently applied method in the Ecoinvent database for all system processes including multi-output production of metals (Classen et al., 2009; Wernet, 2016). As a consequence of economic allocation, however, relevant elementary flows to such processes are not in balance (Weidema, 2017). Carrier metals tend to carry the burdens of by-product metals to a greater extent than if allocating by mass, even though refined by-product metals can be expensive. This is due to lower value at the point of allocation, i.e. of by-product metal containing residues compared to the value of raw carrier metals. In terms of LCA results, multi-output process allocation may influence results so that certain products are allocated the use of metals that are not in the products studied and, vice versa, that the products studied are not allocated the use of metals contained in the products. For instance, this has some relevance to the interpretation of the results in paper 3.

There is no consensus in LCIA on what is to be protected under the AoP of natural resource use, especially with regards to non-renewable resources such as metals, minerals and fossil fuels (Sonderegger et al., 2017). The following section is delimited to these types of natural resources. Although it is not always explicit in the discussion about the AoP of non-renewable resources, there are relevant parallels with the LTG debate (Drielsma et al., 2015; Jackson & Webster, 2016; Tilton, 2010) and its underlying paradigms of opportunity cost and finite stock. Differing views relate to the perceived importance of whether to include non-renewable resource use as an impact category in LCA and, if so, how to assess it.

The majority of LCIA methods for assessing non-renewable resource use are based on their instrumental values to humans (Sonderegger et al., 2017). As provisioning of such instrumental values mainly depends on socio-economic factors it has been questioned whether non-renewable resource use should be part of environmental LCA (Drielsma et al., 2016). For example, it may be argued that scarcity is reflected and mitigated by resource market prices. If such resources become too expensive, substitutes will be used instead. Such reasoning may be connected to the opportunity cost paradigm where the only relevant limit to non-renewable resource use is what other values society is willing to offer for additional resources (Drielsma et al., 2015; Tilton, 2010). On the other hand, there are also several arguments for the inclusion of non-renewable resource use in LCA. Firstly, market price information has been argued to be a poor indicator of availability of co-produced metals (Ayres & Peiró, 2013). Also, it lacks the intergenerational equity perspective of sustainable development since future demands are usually not reflected (Frischknecht, 2013). Sonderegger et al. (2017) claim that changes in the environment's ability to provide non-renewable resources is clearly an environmental concern. Rather, these arguments may be connected to the finite stock paradigm. In this view, the earth is considered to be a materially closed system, making non-renewable resources finite, some of which can be regarded as geochemically scarce (Skinner, 1979). With regards to the entropy law, non-renewable resources may be depleted from forms in which they are available to humans (Daly, 1992). For metals in particular, it is argued that the potential for substitution is limited, given that they often exhibit specific properties (Ayres & Peiró, 2013).

Finnveden (2005) suggests that competition is also a relevant limitation to the non-renewable resource availability for humans. In line with such reasoning, there have been attempts to integrate aspects of the criticality concept into LCA or life cycle sustainability assessment (Gemechu et al., 2016; Mancini et al., 2018; Mancini et al., 2015; Sonnemann et al., 2015). Criticality can be assessed using several available methodologies (e.g. (EC, 2014; Graedel et al., 2012; Knoeri et al., 2013; Miehe et al., 2016; NRC, 2008)) but commonly includes aspects such as supply risk and the socio-economic importance of specific resources in the shorter term and relates to a defined entity such as a nation, an industrial sector or company. As yet, criticality is not included in commonly applied LCIA methods (Sonnemann et al., 2015). It should also be noted that dimensions of criticality, such as socio-economic importance, go beyond the traditional environmental LCA scope.

As outlined above, there are different views on the need to assess non-renewable resource use in LCA. Furthermore, LCIA methods that aim to assess non-renewable resource use depart from differing perceptions of what poses its limits or what the environmental problem consists of (Steen, 2006). Such perceptions involve:

1) assuming that mining costs will be a limiting factor
2) assuming that collecting metals or other substances from low-grade sources is mainly an issue of energy
3) assuming that scarcity is a major threat

4) assuming that environmental impacts from mining and processing of mineral resources are the main problem. (Steen, 2006)

Furthermore, there are several ways of categorising indicator types used in LCIA methods to assess impacts related to non-renewable resource use. There are four principal types, categorised as follows (Sonderegger et al., 2017; Steen, 2006):

1) exergy or solar energy required for extraction
2) the relation of use-to-resource (different resource classes may be applied, e.g. average crustal concentration, reserve base or economic reserves)
3) increased future environmental impacts or costs of mining and material production due to decreasing ore grades
4) aggregated mass or energy consumed.[2]

Possible linkages between problem perceptions and indicator types are outlined in table 2.

Table 2. Possible linkages between problem perceptions and indicator types of LCIA methods

Problem perception / Indicator type	*Assuming that mining cost will be a limiting factor*	*Assuming that collecting metals or other substances from low-grade sources is mainly an issue of energy*	*Assuming that scarcity is a major threat*	*Assuming that environmental impacts from mining and processing of mineral resources are the main problem*
Exergy or solar energy required for extraction	x	x		
Relation of use-to-resource			x	
Increased future environmental impacts or costs of mining and material production due to decreasing ore grades	x			x

A key aspect of these methods is the type of data that is used to derive characterisation factors. Some methods use different classes of resources, e.g. average crustal concentrations, reserve base or economic reserves. Respectively, the last two represent resources that have reasonable potential to become economically and technologically viable as well as known resources that are economically exploitable at the point of determination (Van Oers et al., 2002). Others use different types of deposit data, e.g. exergy required to produce metals depending on ore grade or the rate at which ore grades decrease as a result of extraction. According to Drielsma et al. (2015), LCIA methods that refer to average crustal concentrations adhere to the finite stock paradigm, while methods that refer to some form of reserves adhere to the opportunity cost paradigm. The latter can be argued to relate to impacts on resource availability rather than resource depletion (Drielsma et al., 2015). Drielsma et al. (2015) therefore argue that some

[2] This indicator type has low support as an LCIA method (Steen, 2006) and is therefore not further discussed.

LCIA methods assess an actual AoP that is different from what they intend to assess, e.g. impacts on availability as opposed to depletion.

A number of studies have applied and compared LCIA methods for metal resource use (Alvarenga et al., 2016; Finnveden et al., 2016; Peters & Weil, 2016; Rigamonti et al., 2016; Rørbech et al., 2014; Van Caneghem et al., 2010). The results of such studies show a divergence between LCIA methods in terms of what metals are regarded as the most important. Rørbech et al. (2014) performed a quantitative comparison of LCIA methods. They suggested that choice of LCIA method should be based on wide resource coverage in order to increase the chances of comparability to other studies, coverage of relevant resources for the product systems studied and reflection of environmental concerns relevant to the intended audience. Peters and Weil (2016) compared LCIA methods for lithium-ion batteries and found that some metals, although not contained in the product, contributed significantly in some methods because of how allocation in co-production had been done (as previously discussed). They also pointed out similarities in the contribution patterns of reserve-based methods and a method based on exergy demand, which was argued to support the relevance of such indicators (Peters & Weil, 2016). Finnveden et al. (2016) compared the use of exergy-based approaches to other methods. Mostly based on its theoretical foundations rather than comparison with other LCIA methods, they concluded that exergy is an appropriate indicator of resource use because exergy is *used* as opposed to *dispersed* (as material resources are) and could be argued to constitute the ultimate limit to resource availability (Finnveden et al., 2016). Rigamonti et al. (2016) compared alternative LCIA methods for resource use to account for the benefits of recycling WEEE. Some metals were observed to be important in specific indicator types: silver in reserve-based methods and copper in methods based on the increased future environmental impacts of mining as a result of decreasing ore grades.

In summary, although environmental impacts of ICT have been widely studied, this literature overview points to some knowledge gaps that could be valuable to address. This relates both to the impacts and assessment of ICT use, as well as ICT use extension. Firstly, few LCAs of ICT use address metal resource use issues and sufficiently cover EoL. Additionally, in LCAs of ICT it may be advisable to use the most up-to-date inventory data possible given the rapid pace of technological development. Such issues were considered in the LCA conducted on laptops (paper 3). Secondly, few comparative assessment studies on ICT use extension are based on real-world business cases, which means that potentially important aspects may be overlooked. Also, these studies mostly focus on energy use and climate change, neglecting other impact categories. Thirdly, while some comparative studies of LCIA methods for non-renewable resource use have been carried out, there is still room for more in-depth analysis of which aspects of the methods underlie the observed divergence in results. Furthermore, there are no comparative LCAs of RE measures that deploy complementary LCIA methods on non-renewable resource use, which may be of particular value for electronic products given their metal diversity. The second and third knowledge gaps motivate RQ2 and RQ3, which constitute the main scientific contributions of this thesis. As stated at the beginning of the literature review, paper 1 both addresses RQ1 and serves to provide a general literature background on comparative assessment studies of resource efficiency.

4. Results

The results section summarises the appended papers and presents the key findings.

4.1 Paper 1

Paper 1 dealt with the first RQ of this licentiate thesis: what resource-efficiency measures result in reduced potential environmental impacts and resource use – for what types of products and under what conditions? It aimed to address the lack of synthesised knowledge on general circumstances for RE (Bocken et al., 2017; Tukker, 2015). The paper departed from the hypothesis that product characteristics, the life cycle environmental impacts of products and the physical nature of RE measures are interdependently decisive for RE, and that analysis of these factors in combination may generate findings which may be overlooked when using strict sectoral scopes. Compared to previous work with similar aims, it had a wide scope in terms of product types spanning several sectors, environmental impacts and RE measures pertaining to several relevant discourses e.g. eco-design, cleaner production, PSS and CE. Given the purpose and wide scope of paper 1, this part of the licentiate thesis does not exclusively focus on electronic products although many findings are applicable to them.

The paper's aim was fulfilled by reviewing comparative life cycle-based assessment studies, predominantly LCAs and MFAs, using an analytical framework consisting of three parts: (1) a typology of RE measures applicable to a product (see left column of table 3); (2) a typology of relevant product characteristics e.g. number of components or materials, ability to be disassembled, frequency and intensity of use and whether products require energy during use; and (3) a tool to describe assessment studies of RE measures in a comprehensive and comparative manner, noting, for example, the goal of the study, functional unit, system boundaries, indicators and key assumptions.

Using this framework, 58 assessment studies including 118 cases of RE measures were analysed. Some general conclusions could be drawn from this analysis (table 3), indicating for which product characteristics RE measures might be suitable as well as potential trade-offs. Note that the analysis did not aim for a ranking of optimal RE measures.

Table 3: The characteristics for which each measure in the typology 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 of losing function, e.g. durability
Change material in product	Any product	Risk of 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 of recirculation of hazardous substances

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

The following section elaborates on some of these findings. Firstly, some findings relate to which life cycle phase that dominates environmental impacts. This considerably determines what type of RE measure that may lead to resource efficiency. Production and use-phase measures are especially important for products dominated by extraction and production. If material production is responsible for significant impacts, recycling is often effective since this decreases the need for primary material production. For products with significant impacts from the use phase, measures for efficient and effective use tend to reduce environmental impacts notably. There is, however, a well-known and common trade-off between use extension and energy efficiency improvements for products that require energy during the use phase. If the use phase dominates life cycle impacts and newer products are significantly more energy-efficient, replacement may be more beneficial than use extension. For products that do not require energy during use, use extension is generally beneficial but exceptions may exist if, for example, substantial transportation is required.

Secondly, durability was found to be an important characteristic for those RE measures that address the use phase (table 3). Durable products can be made more resource-efficient by using them more efficiently and effectively or by extending their use. The results of such measures are influenced by the rate of technological development as many durable products such as laptops and smartphones tend to be discarded before they reach the end of their technical lifetimes, for instance because their functionality is being judged in relation to that of newer products. In such cases, their use may be extended by a different user through reuse. Sharing may also be suitable for durable and infrequently used products as this may allow them to provide more functionality before they become outdated. However, sharing is not beneficial for products that are disposed of more quickly because of use and that tend to be used for their entire lifetimes. For example, sharing cars without reducing the total distance travelled merely speeds up replacement rates without reducing the net use. Another factor that may render sharing schemes less resource-efficient is if fossil-fuel based transportation is required to access a shared stock of products, e.g. tools or clothes (Mont, 2004b; Roos et al., 2015).

Complexity of products is also important for RE, for instance if they comprise many components or materials. In complex products some components may cause premature discarding of entire products. In such cases, measures that extend use are applicable. The efficacy of such measures depends on the extended use and the impacts from the additional efforts required, for instance the degree of component replacement and environmental impacts from production of spare components (Ljunggren Söderman & André, 2018; Quariguasi-Frota-Neto & Bloemhof, 2012). On the other hand, complexity may hinder component replacement as it often entails difficulty in disassembling and reassembling. In such cases, design for disassembly or modular design may facilitate and enable such measures. In the case of a modular smartphone, this could facilitate maintenance and repair and thereby keep the majority of components in use for longer while replacing components which, for various reasons, may have a shorter lifetime (Proske et al., 2016). This was shown to reduce all environmental impacts except metal resource use. Since the modularity itself required increased use of connectors (Proske et al., 2016), the gains from modularity were not sufficient to motivate the modular design in terms of metal resource use. Complex and durable products that are obsolete in their original function can also be repurposed in applications where residual functionality may come into use.

With regards to materially complex products, changing materials may be interesting in order to alleviate the environmental impacts of those that are particularly burdensome. For example, scarce metals may be substituted by more abundant or available ones. However, substitution of metals to alleviate scarcity may not be beneficial even in terms of metal resource use and may also come at the cost of increased energy use. Substituting cobalt in lithium-ion batteries was shown to deteriorate the energy efficiency and thus shift burdens to other environmental impacts (Reuter, 2016). The use of copper for production of graphene-based transparent electrodes contributed more to metal resource use than the indium it was supposed to substitute (Arvidsson et al., 2016). Furthermore, depending on the future technological development of graphene production, it could also require more energy-intensive production (Arvidsson et al., 2016). Since scarce metals often provide specific properties in products it was noted that it is difficult to draw general conclusions on the circumstances for environmentally beneficial substitution.

It was also argued that consumable products are undeservingly overlooked in the CE discourse, since there are also several ways of improving the RE of consumables. Single-use products can be redesigned for multiple use (Willskytt & Tillman, 2018) and the impacts of dissipative products, such as detergents, can be reduced by minimising production losses. Effective use can also have significant importance. For example, food waste can be reduced by not purchasing more than necessary.

Finally, it was noted that in many cases several RE measures could be successfully combined, as specifically demonstrated by Willskytt and Tillman (2018). Another point on the need for combinations of RE measures related to the observation that measures based on extended use do not mean that recycling is unnecessary. On the contrary, the existence of efficient recycling is important as implementations of such measures are prone to losses and quality degradation. Rapid technological development, in particular, can notably limit the feasibility of use extension as old components may not be compatible with new product generations, for example in remanufacturing.

To conclude, the feasibility of analysing RE in general terms suggested that strict sectoral scopes may be uncalled for. By understanding the interdependencies of product characteristics, the life cycle environmental impact patterns of products and RE measures, it can be observed that there are similarities between vastly different products in terms of which solutions are successful (indicated by the general product characteristics in table 3). While some of the findings were already well known for specific circumstances, paper 1 presented the first comprehensive analysis of the CE and RE literature to cover such a wide range of product types, environmental impacts and RE measures. This allowed for elaboration, questioning and confirmation of previous findings and identification of general patterns.

4.2 Paper 2

Paper 2 addressed the second RQ of this thesis: how does extended use of electronic products through design for increased technical lifetime, reuse and repair affect environmental impacts, particularly metal resource use? It set out to map the effects of a few selected RE measures on scarce metal flows. For this purpose, three comparative case studies were set up, all studying some form of RE measure based on extending the use of electronic products: increasing the technical lifetime of LED lighting, reusing laptops (thereby using more of the technical lifetime according to the typology presented in paper 1) and repairing smartphones. Like paper 1, it departed from the hypothesis that potential for RE depends to a large extent on relevant product characteristics. However, in contrast to the wide scope of paper 1, it focused in more detail on the characteristics related to product complexity, e.g. material diversity, number of components and rate of technological development. In summary, paper 2 aimed to generate knowledge on the effects on scarce metal flows resulting from electronic product use extension.

The aim was fulfilled through the use of MFA to calculate net losses of scarce metals in alternative product systems providing the same function: conventional and supposedly resource-efficient ones. In this paper, RE was accordingly considered to be realised by reducing net losses of scarce metals. The studies were based on real business cases. The LED lighting case was based on a result-oriented PSS where the provider sells the result of office lighting as opposed to selling lighting products. The other two cases were based on resale and repair companies. In the CE discourse, such companies may be referred to as gap-exploiters since their business models are *"…based on the recognition and commercial exploitation of a product lifetime value gap in the life of another firm's product…"* (Den Hollander and Bakker, 2016).

In the LED lighting case, the result-based PSS business model changes some incentives that are relevant for resource efficiency of scarce metals. Since the company in this case delivers the result of office lighting, they are incentivised to minimise full lifetime costs by using as long-lasting equipment as possible to fulfil the function they deliver. In contrast to conventional users, who are assumed to prioritise low up-front installation costs and thereby purchase lower quality products, this company designs their LED office lighting system for longevity, so as to minimise costs in the long run. This involves using more LED lights driven by a lower current in order to minimise thermal stress and degradation, modular LED lamp design to maximise component lifetimes, an automatic sensoring system so that lights are only turned on when needed and efficient collection into recycling. The results demonstrated the success of such measures in terms of RE of scarce metals. Despite having more LED lights used per lamp, these measures lowered the net losses of scarce metals per hour of office lighting compared to the conventional alternative of normal product sales. However, an important aspect of this case is whether the long-life system will actually be used for long enough to be beneficial or will be replaced earlier, for example due to energy efficiency in newer product generations.

In the case of smartphone repairs, the rate at which components are replaced was found to be imperative for the outcomes in terms of RE for individual scarce metals. The repair case was based on data from a repair company on how frequently they replace different components to enable product use extension. For example, smartphone screens were replaced by new screens in almost all repairs. As such, actual use extension needed to be almost as long as the product lifetimes of new smartphones for the repair to break even with regards to scarce metals in screens. Given the rapid technological development of smartphones, it was deemed unlikely that repaired smartphones would be used for such duration. Thus, it was found that the use of scarce metals in screens was likely to be higher in the repair product system than in the conventional alternative of using new smartphones. However, with regards to scarce metals in components that are less frequently replaced, repair was indicated to reduce net metal losses and thereby be resource-efficient. For instance, one in five repairs required a new loudspeaker. For scarce metals in loudspeakers such as neodymium to benefit from repair, use extension would thus need to be merely a fifth of a new smartphone lifetime. Repairing smartphones was therefore indicated to be beneficial in terms of some scarce metals but at the cost of others.

For laptops, the RE measure studied was to use more of the technical lifetime through reuse. The reuse company sources and resells high-quality laptops. The majority of laptops are resold after testing and data erasure. The remaining ones are sent for recycling. In this case, assuming that metal contents are constant, there are no break-even points in terms of scarce metal RE, as no spare parts are required to enable product use extension. However, there can be exceptions if newer laptops have lower contents of specific scarce metals. This was demonstrated in an alternative scenario representing the currently on-going design shift from hard-disk drives to solid-state drives – the former contains permanent magnets while the latter does not. Accordingly, newer laptops were assumed to have lower contents of scarce metals in permanent magnets compared to reused laptops, which were assumed to still be equipped with hard-disk drives. Since other applications of permanent magnets remained, the design shift implied different degrees of content reduction for three different metals. For metals whose content was only somewhat reduced by this design shift, reuse was found to still be preferable to the new production alternative. For metals that can be drastically reduced by design shifts, in this case dysprosium, the product system using new laptops could actually be more resource-efficient than the product system involving reuse. Since a portion of laptops cannot be reused, the reuse product system requires a larger number of laptops in the first use phase to fulfil the same functional unit over the whole system. A larger amount of dysprosium is therefore required in the reuse product system. Since dysprosium is lost from functional use in subsequent recycling, net losses of dysprosium are consequently larger.

In all three cases it was observed that RE was achieved in two principal ways: through the intended use extension and through directing obsolete products and components into recycling. Both PSS providers and gap-exploiters were indicated to exhibit this feature. PSS providers who retain ownership of equipment usually take responsibility for efficiently sending products that can no longer be used to recycling. This implies a higher collection rate than would be the case with normal product sales as collection rates from users are generally lower. Analogously, not all products handled by gap-exploiters can be resold or repaired. These too are sent to recycling, resulting in higher overall collection rates compared to conventional product systems. Naturally, increased collection does not matter for metals that are not functionally recycled in EoL treatment. Resource efficiency of such metals is achieved solely by extending the use of products in which they are contained. For metals that are functionally recycled in EoL, this increased collection rate, however, leads to additional reduction of losses, i.e. RE gains. In fact, product use extension is not as important for such metals. In some cases, especially where collection rates from users are low, this feature of increased recycling is just as capable of leading to RE of scarce metals as product use extension. Thereby, it terms of reducing scarce metal losses, the prioritisation of measures as proposed by CE (EMF, 2013) could not be verified to be generally applicable to complex products.

In sum, it was found that extending the use of electronic products was indeed resource-efficient in terms of scarce metal use, but this was not without exceptions. For RE of individual scarce metals, extended use must be sufficient to motivate the additional scarce metal use required to produce a more durable product or a spare part. Moreover, it was discussed that actors along products' life cycles – material and component suppliers, original equipment manufacturers (OEMs), users, gap-exploiters and recyclers – have different potentials for and ways of affecting resource efficiency. For a product to be resource-efficient, each actor along the product life-cycle chain must utilise its potential for contributing to RE, otherwise losses will inevitably occur. For instance, if users do not utilise full technical lifetimes, it does not matter how durable products are. In terms of RE, gap-exploiters usually address and depend on the existence of low-hanging fruit, e.g. underutilised product lifetimes of laptops or fragile smartphone screens. In other words, it is easy and seemingly resource-efficient to address resource-inefficient features. However, there are additional potentials for improvement in other parts of the life cycle that could also be beneficial but that are not as easy to address. The same RE gains could also be realised by other actors; for instance users could use more of technical lifetimes and OEMs or component manufacturers could design more durable products and components. Given the losses that occur in each recirculating use extension (e.g. reuse or repair), it is plausible that this could be even more resource-efficient.

4.3 Paper 3

Paper 3 concerned the second and third RQs of this thesis:
(2) how does extended use of electronic products through design for increased technical lifetime, reuse and repair affect environmental impacts, particularly metal resource use?
(3) how does the application of different LCIA methods for metal resource use influence interpretations of resource-efficiency measures applied to electronic products?
The aim was firstly to generate knowledge on how use extension, specifically reuse, of electronic products compares to new production in terms of environmental impacts (RQ2). Secondly, it aimed to generate knowledge on how different problem perceptions and related indicators influence what metal resources are shown to be important in laptops and, moreover, how such factors influence the interpretation of supposed benefits of reuse (RQ3). Thus, several LCIA methods for metal resource use were applied in parallel to study such effects.

In this case, the reuse of laptops is mediated by a company that resells high-quality used professional-grade laptops through the principal activities of collection, testing, data erasure, resale and redistribution. While 70% can be resold, the rest are sent to recycling (figure 1). Second-hand laptops were deemed functionally equivalent to new ones given their high-quality and warranties, and the argument by Schischke et al. (2003) that, to a large extent, the functionality of computers is a subjective matter and most applications do not require the latest functionality improvements. As such, reuse was assumed to extend product life to six years in total. In the new production alternative, a three-year lifetime was assumed. The use phase itself would not affect the comparison and was excluded. In EoL, system expansion was applied to account for the benefits of recycling, i.e. it was assumed that the metals and energy recovered displaced primary metal production and other energy production.

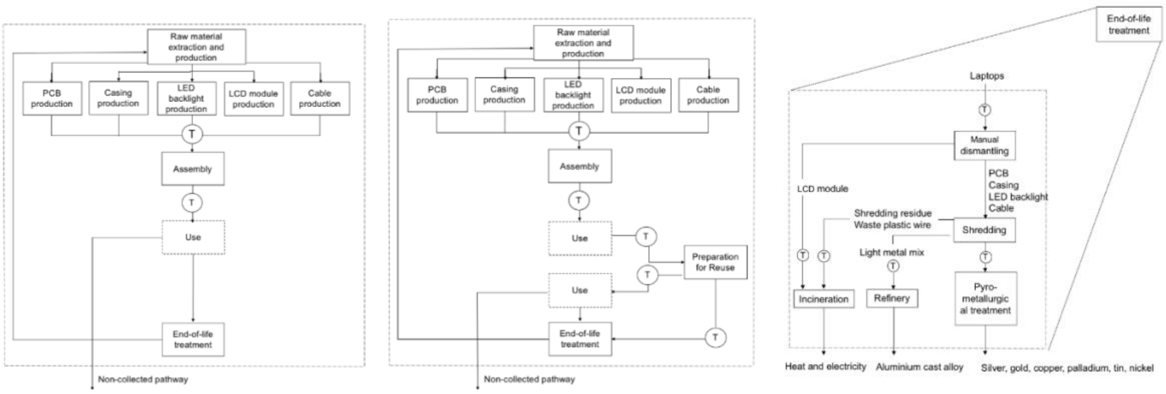

Figure 1. Flowcharts of new production (left), second-hand (middle), and EoL treatment (right).

The environmental impact categories, e.g. climate change and human toxicity, were chosen from the International Reference Life Cycle Data Handbook recommendation (European Commission, 2012; Wolf et al., 2010). In addition, the following LCIA methods for metal resource use, representing different problem perceptions and indicator approaches (section 3.2), were used:

- Cumulative exergy demand (CExD) of metal resources, based on the chemical exergy consumed by a product or process (Bösch et al., 2006)
- Abiotic depletion potential developed by Centrum voor Milieuwetenschappen Leiden (CML), based on the relation of use-to-resource (specifically, extraction rate to three resource classes used as approximations of what might be ultimately extractable), ultimate reserves (UR), reserve base (RB), and economic reserves (ER) (Van Oers et al., 2002)
- Ecological scarcity method (EcoSc), based on the present situation in relation to environmental protection policy, with maintaining current extraction levels as the interim environmental target for metal resource use (Frischknecht, 2013)
- ReCiPe midpoint (Goedkoop M., 2009), based on estimates of increased economic costs for future resource extraction taking decreasing ore grades into account
- Environmental Priority Strategies (EPS) (Steen, 1999a; 1999b), based on current and future generations' willingness-to-pay (WTP) for sustainably produced resources, i.e. from dilute sources such as common bedrock or seawater.

As discussed in section 3.2, a central aspect of these methods is what type of data they use to derive characterisation factors. CML-UR and EPS use average crustal concentrations, CML-ER, CML-RB and EcoSc use reserves (either economic reserves or reserve base) and CExD and ReCiPe use deposit ore grades.

The results showed that the use of second-hand laptops through a resale and refurbishment company has the potential to reduce environmental impacts when compared to buying new ones and that the additional efforts required are for the most part negligible despite long transportation requirements. However, it is important to note that these results cannot be assumed to apply to reuse in general as they focus on high-grade laptops with a long second-use phase and efficient transportation to and from users as well as to recycling.

As observed in paper 2, reuse of laptops reduces environmental impacts in two principal ways: through the intended use extension and by steering material flows, i.e. laptops that cannot be reused, into recycling. Use extension consistently reduces the cradle-to-gate impacts of all components and assembly by 29% in all impact categories, as a consequence of the reusability rate and the doubled lifetime of the second-hand laptops. Since component production was generally dominant for most impacts, with, for example, transportation and preparation for reuse being less important, this use extension has a major influence on the comparison. The increased share of recycling was found to be especially important for the impacts to which primary production of functionally recycled metals contribute considerably. Such impacts were human toxicity, and also metal resource use, depending on which LCIA method is applied (figure 2 and explained below). However, EoL has limited effects for the majority of environmental impacts since most emissions stem from energy-intensive component production as opposed to primary material production. Thus, impacts such as climate change are mainly reduced due to use extension.

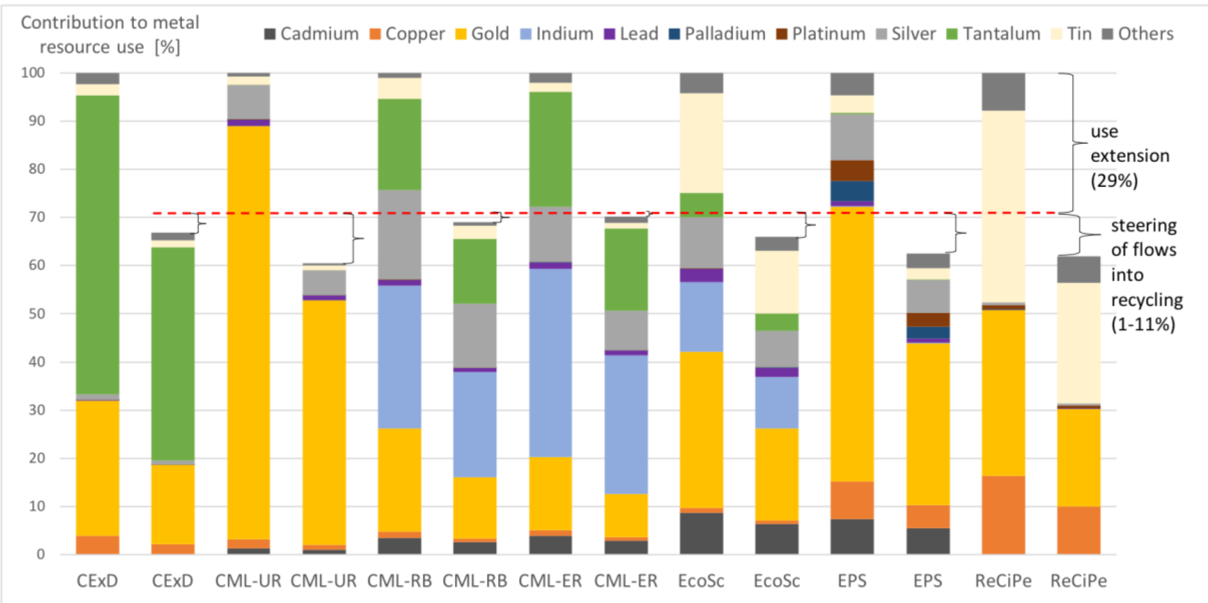

Figure 2. Metal resource use impacts: the reuse alternative compared to the new laptop alternative [%] with five impact assessment methods of which one has three versions. Metals with >1.5% contribution with at least two methods or >4% with at least one method are displayed individually. Others include 20 metals such as aluminium, iron, nickel and rare earth elements (REE).

Figure 2 demonstrates that the results in terms of metal resource use depend on the LCIA method used, most notably in terms of which metals are highlighted as important. This in turn affects the importance of increased recycling in the reuse alternative (1-11%, figure 2 and explained below) and thereby the degree of total reduction of metal resource use. The metals that were highlighted as important varied in the methods due to the different perceptions of what constitutes the environmental problem, related choices of indicators and data, as well as the metals' geological characteristics. For example, gold is shown to be important in all methods but especially so in ones that refer to average crustal concentrations, i.e. CML-UR and EPS. Gold is rare in average crustal concentrations but has deposits with significantly higher concentrations (Ayres & Peiró, 2013). These deposits imply that gold is economically extractable to a larger extent than the average concentration would imply. Since economic extractability implies the existence of reserves, gold has a lesser importance in reserve-based methods (CML-RB, CML-ER and EcoSc). However, reserve-based methods tend to give greater weight to by-product metals, such as indium (figure 2) with quite ordinary average crustal concentrations and even distribution, i.e., without deposits of higher concentrations. Their reserves may thus be underestimated since they have not been specifically explored for. This could imply that their impacts are overestimated in reserve-based methods (Drielsma et al., 2015). The results may also differ depending on the data of the methods used. For example, the main difference between CML-RB and EcoSc is that the latter uses more recent reserve and extraction data. Since extraction of tantalum has decreased between these data collection points (Sverdrup et al., 2017), tantalum has a noticeably lower contribution in EcoSc.

The total reduction of metal resource use from using second-hand laptops depends on which individual metals are important in each method and, in particular, whether or not these important metals are modelled to be functionally recycled in WEEE treatment. Methods that give greater weight to metals that are functionally recycled (CML-UR, EPS and ReCiPe) result in a larger reduction of impacts due to the increased recycling in the reuse alternative. In comparison, the merits of recycling are not as considerable in reserve-based methods which characterise some metals without functional recycling as being important (e.g. indium and tantalum). Consequently, total reductions of metal resource use are not as significant with these methods and are almost exclusively attributed to use extension. According to most LCIA methods, however, the focus on precious metals and copper in current WEEE recycling seems justified since this notably mitigates metal resource use (figure 2).

It can be further observed that some metals (gold, copper and tin) have visible contributions in all methods (figure 2). It can therefore be concluded that they are of relevance for different issues with metal resource use. It is unlikely that these metals will be missed if only one LCIA method is used on ICT. This is however a risk for the other metals, which contribute notably in merely one or a few methods. It is therefore valuable to use complementary methods to avoid missing relevant metal resource use impacts.

Another interesting result was an effect of the revenue-based economic allocation of co-produced metals, as implemented consistently in the multi-metal production processes used from Ecoinvent. This allocation choice implies that zinc carries substantial shares of the environmental burdens of its by-products, including the majority of their impacts in terms of metal resource use. It was thereby observed that the indium contributions to metal resource use were not caused by the laptop's major indium use, in indium-tin-oxide of the liquid crystal display, but instead by the use of zinc in various components.

5. Discussion

This section discusses some synthesised insights derived from looking at all three appended papers in conjunction.

5.1 What makes RE measures applied to electronic products resource-efficient?

Some of the product characteristics discussed generally in paper 1 were explored further in papers 2 and 3. Characteristics related to product complexity, e.g. material diversity, number of components and rate of technological change, were especially relevant for electronic products.

Material diversity is perhaps most notably relevant in terms of its effects on the feasibility of recycling. It is often argued that material diversity poses challenges to recycling systems since a high diversity increases the efforts needed to separate materials. In paper 1, recycling was intentionally left outside the main focus. While papers 2 and 3 demonstrated noticeable RE gains for metals with functional recycling, it also showed that many scarce metals are not functionally recycled in current WEEE recycling. Nevertheless, paper 3 demonstrated that noteworthy metal resource use impacts may be reduced through the recovery of metals such as gold and copper in WEEE recycling. Additional aspects with regards to metal diversity and RE are discussed in section 5.4.

In paper 1, a rapid rate of technological change or fashion was a characteristic argued to render products suitable for sharing, especially for products such as clothes and laptops that are usually discarded before reaching the end of their technical lifetimes. In this way, each product is able to deliver more functionality before it becomes outdated. However, laptops are currently used in ways that make viability of sharing solutions questionable (e.g. storage of personal information and settings). In addition, the diffusion of sharing solutions has been argued to be inhibited by the fact that users tend to value ownership and easy access to products (Tukker, 2015; Tukker & Tischner, 2006). As discussed in paper 2, the rate of technological change can also be regarded as a dimension of product complexity that may affect the appropriateness of RE measures. For metals whose contents can be radically reduced through design shifts, RE may be greater in conventional product systems compared to alternative ones involving, for example, reuse. This is analogous to the common trade-off between use extension and energy efficiency (paper 1).

Paper 1 argued that the more components there are in a product, the larger is the risk that one component will break before the others, potentially causing obsolescence of the entire product. If such components can easily be replaced, e.g. through design for disassembly, product use can be extended. In an assessment study of a modular smartphone reviewed in paper 1, there were, however, ambiguous results in this respect. The connectors that were required between modules made rather large contributions to some environmental impacts (further discussed below in section 5.4). Paper 2 demonstrated a successful example of how a modular design facilitated disassembly and thereby enabled replacement of components that are known to otherwise limit the lifetimes of entire LED lamps. This allowed the lifetimes of LED lights which contain numerous scarce metals to be fully utilised. Paper 2 also illustrated an example of where increased design for disassembly could be useful. Smartphone screens were observed to be a dominant reason why smartphones need repairs. According to the company in this case, it is most often only the glass that is broken while the liquid crystal display containing the scarce metals remains functional. However, the difficulties involved with separating these subcomponents make entire screens obsolete (Jarbin, 2016). As shown in paper 2, such a high degree of screen replacement most likely makes smartphone repairs a resource-inefficient solution for scarce metals in screens. In general, design for easy disassembly seems to make electronic products more resource-efficient as long as such designs do not add substantial environmental burdens.

5.2 A need for combinations of RE measures and enablers

A common observation emphasised in all three appended articles is that several RE measures may be performed in conjunction or along the life cycle. Single RE measures have limited potentials for achieving substantial reductions of environmental impacts. In particular, it can be argued that so-called gap-exploiters, such as resale and repair companies, reduce impacts of the linear economy while simultaneously depending on its resource-inefficient features such as fragility of smartphone screens or underutilised lifetimes. Because of this, such companies alone have limited potential for making electronic product use more resource-efficient. For further improvements towards a more resource-efficient and circular economy, additional measures, such as more durable design, material substitutions and more efficient recycling adapted to their metal diversity, are probably required. On a similar note, papers 2 and 3 indicated that reuse and repair do not redirect material flows from recycling but rather the opposite, which perhaps is counterintuitive. From a life cycle perspective, a key characteristic of such measures is that they steer higher shares of material flows into recycling. From recyclers' perspectives, such measures may delay the recycling of some products while also collecting some that would not have been recycled otherwise.

Furthermore, considering the worthwhile, but arguably limited, potential of isolated RE measures, electronic product use extension may be further enabled by new business models. As illustrated by the result-based PSS for office lighting (paper 2), business models can be of significant importance for RE through the incentives they induce. Leasing is another business model that is often mentioned as a possible enabler of product and component use extension. Of particular relevance to metal resource use, it has been argued to potentially enable more efficient management of scarce metals (Ayres & Peiró, 2013; Sverdrup et al., 2017). However, it has also been argued that leasing is prone to more careless user behaviour (Tukker, 2004; 2015). To balance such intricate choices, it may be fruitful to study further the effects of incentives induced by business models on physical flows. If laptops are not affected to a great extent by the mode of user behaviour, leasing is likely to be a suitable enabler for extending use and increased control of scarce metals. Furthermore, while modular upgradability is often mentioned as an enabler for use extension, it may have the rebound effect of speeding up replacement rates of easily replaceable components (Agrawal et al., 2016). To conclude, it may be valuable for future research to investigate the effects of combinations of design, business models and policy and to find ways to adequately account for rebound effects.

5.3 Importance of dominant life cycle phase

The importance of which life cycle phase dominates impacts was found to be crucial both in papers 1 and 3. For instance, paper 1 found that products with significant impacts from extraction and production generally benefit from reduced losses and efficient recycling since this decreases the need for primary material production. Paper 3 elaborated on this general finding, observing that the benefits from recycling laptops varied substantially between environmental impacts. While the majority of toxic emissions were attributed to metal production, emissions of greenhouse gases were dominated by the production of advanced and complex components. Recycling therefore reduced toxicity impacts substantially while having small effects on climate change. Therefore, in order to find suitable RE measures it is not always enough to state that certain products are environmentally burdensome in particular life cycle stages. Rather, it is necessary to specify which environmental impacts of products are of higher priority to reduce, and to look for hotspots and suitable RE measures accordingly.

5.4 Effects of methodological choices on the resource efficiency of RE measures

Methodological choices such as allocation and LCIA methods can have noteworthy influence on the outcomes and interpretations of RE measures. In the case of smartphones (reviewed in paper 1), the increased use of connectors required to enable modular design contained gold (Proske et al., 2016), which has a particularly high characterisation factor in the LCIA method used, i.e. CML-UR (paper 3). As a result, modular design was not beneficial in this respect, although it enabled significant product use extension compared to a non-modular smartphone. However, it is plausible that it might have been beneficial using other LCIA methods. Likewise, in the case of indium substitution, the copper used in graphene production resulted in higher metal resource use than indium using EPS as the LCIA method (Arvidsson et al., 2016). The results would probably change if LCIA methods capturing other metal resource use issues were used instead. In particular, methods based on use-to-reserves would likely alter the results, since this is the perspective in which indium is most notably scarce. This reinforces the conclusions of paper 3, emphasising the utility of using several complementary LCIA methods in parallel in order to get a more comprehensive view of the various aspects linked to metal resource use of RE measures. Furthermore, the choice of allocation method may have a decisive influence on which RE measures appear successful in mitigating metal resource use. With revenue-based economic allocation, implying that zinc is responsible to a large extent for the resource use impacts of indium, it could be argued that it is not indium that needs to be substituted or functionally recycled from liquid crystal displays, but rather zinc from various components. Hence, since metal resource use can be a result of allocation as opposed to the contents of the product at hand, it is necessary to investigate what causes such results. Otherwise, LCA results could be misinterpreted and point to unfitting RE measures.

6. Conclusions

This licentiate thesis has studied the environmental effects of RE measures applied to electronic products, particularly in relation to metal resource use. The work has indicated that RE measures have the potential to reduce the environmental impacts of electronic products as intended, but there are exceptions and, furthermore, results may depend on specific circumstances and methodological aspects.

Firstly, with regards to RQ1, paper 1 demonstrated that it was possible to draw generic conclusions about RE based on the interplay between product characteristics, life cycle environmental impact patterns and RE measures. Based on such factors it was possible to link suitable RE measures to distinct product characteristics. While some of the findings had been presented before for specific products and circumstances, paper 1 was the first comprehensive analysis of the CE and RE literature to demonstrate such patterns collectively. Product characteristics such as complexity, durability, use intensity and the limiting factor for product lifetime (e.g. number of times a product is used, rapid technological development or fashion) were found to be highly relevant for the suitability of RE measures. For example, sharing products that are disposed of more quickly because of use, and that are usually used for their entire lifetimes, provides no significant RE gains as this merely leads to the products being disposed of more quickly. In addressing RQ1, product characteristics related to product complexity, such as material diversity, number of components and rate of technological development, were identified as particularly relevant for the RE of electronic products. Consequently, these characteristics were relevant for RQs 2 and 3.

With regard to RQ2, paper 2 found that measures based on extended use of electronic products are generally resource-efficient in terms of reduced net losses of scarce metals, although not without exceptions. RE outcomes from applying measures such as repairing and increasing technical lifetime depend partly on the extended use and partly on the degree of component replacement or additional scarce metal use required to achieve improved durability. If components are frequently replaced, e.g. screens in smartphone repairs, there is a risk that extended use is insufficient, thereby decreasing the RE of metals in replaced components.

A key conclusion regarding RQ2 observed in papers 2 and 3 is that RE measures that extend the use of products generally contribute to RE in two distinct ways – through the intended use extension and by directing flows into recycling. For laptops, the merits of use extension are generally the most significant due to the large embedded impacts from energy-intensive component production as opposed to primary production of the metals that are functionally recycled at EoL. However, increased recycling can make a particular contribution to reducing impacts such as toxicity and metal resource use (depending on the chosen LCIA method), since primary production of recycled metals, which is dominant for these impacts, is thus displaced.

Of particular relevance to RQ2, papers 2 and 3 showed that single measures in isolation have limited potential for RE. Gap-exploiters, in particular, address and depend on resource-inefficient features such as fragile products or underutilised product lifetimes. Although providing worthwhile improvements, RE measures performed by gap-exploiters can be argued to depart from resource-inefficient reference alternatives. Thus, other RE measures could successfully be performed in conjunction in order to reduce environmental impacts further. In paper 1 it was observed that RE measures are often performed in combination but there are only a few examples of subsequent measures along products' life cycles before recycling. In this respect, it can be noted that the potential for use extension of products and components is limited by the pace of technological innovation, for instance due to incompatibility of previously used components with newer product generations. Given the benefits and limits of the cases of use extension studied, investigating the effects of business models as enablers of further use extension has been argued as a potentially valuable topic of future research.

With regards to RQ3, it has been demonstrated that methodological choices in life cycle assessment can be highly relevant for the interpretation of RE measures applied to electronic products. In paper 3, the choice of LCIA method largely influenced the metals that were highlighted as being important in laptops. Moreover, it also influenced the degree of total reduction of metal resource use. LCIA methods that gave high value to metals that were modelled to be functionally recycled resulted in a more significant total reduction of metal resource use than other methods. Some metals were shown to be important according to all methods and others according to one or a few methods. Some possible explanations for such patterns were given with respect to the methods' indicator types and choice of data as well as the geological characteristics of the metals. These observations suggest that it is advisable to use several complementary LCIA methods and to have a good understanding of their methodological approaches to be able to draw relevant conclusions on metal resource use in assessments of RE measures applied to electronic products.

7. Outlook for future research

Differing views of non-renewable resource scarcity are prevalent in the LTG debate and the discussion on LCIA of metal resource use, and may also underlie various interpretations of the CE. As well as being firmly rooted in industrial ecology, Ghisellini et al. (2016) claim that CE has roots within environmental economics (which is a subfield of neoclassical economics) and ecological economics. Neoclassical economics is commonly associated with the opportunity cost paradigm (Tilton, 2010) and ecological economics with the finite stock paradigm (Daly & Farley, 2011). Considering these diverse roots, it is not clear what CE is supposed to imply in terms of the use of non-renewable resources such as metals. Nor is it clear what LCIA methods actually assess. It has been argued by Drielsma et al. (2015) that many LCIA methods for metal resource use confuse their actually assessed AoP with the AoP they intend to assess, e.g. impacts on availability as opposed to depletion. Adding to this, it has been argued that criticality is relevant to the AoP of non-renewable resources. Like metal resource use, criticality can also be assessed in a number of ways. To contribute to better understanding of metal resource use, it could be valuable in future work to review the foundations of a spectrum of resource assessment methods applicable to metals, e.g. in terms of (implicit or explicit) ethical foundations, temporal and spatial perspectives and assumptions on physical constraints and substitutability. In addition, analysis of such factors could contribute to classifying methods into the paradigms of opportunity cost and finite stock. Relevant methods to include could be gathered from LCA, criticality methodologies as well as neoclassical, environmental and ecological economics. The value of such research may be indicated by comparing paper 3 and a study conducted by (Mancini et al., 2018) who compared parallel resource criticality methods to the production of a computer. Their results were radically different, showing dominant contributions from metals that were all negligible in paper 3: magnesium, iron, gallium and REE. Integrating criticality aspects into LCIA of metal resource use is thus indicated to amplify the already diverging results.

Depending on the direction of future discussions on assessments of metal resource use, the suggested review could contribute in different ways. If discussions lean towards recommending the use of one single method the review could reveal and clarify which resource aspects are assessed by such a method and compare it to others. This development seems likely considering the recommendation of CML-UR in the Product Environmental Footprint guidance (EC, 2018). If, instead, future discussions concerning metal resource use suggest the use of complementary methods, or weighting of various resource issues, greater transparency and explicitness of these issues may guide such developments. The value of the review outlined could lie in identifying which metal resource issues are essential constituents of such, perhaps more comprehensive, resource assessments. Furthermore, the knowledge could be practically applied to case studies of RE measures where there are trade-offs between different types of metal resources, e.g. repairs where use of some metals in core components may be extended at the cost of other metals required for spare parts. This could provide more nuanced assessments with respect to metal resource use of the effects of RE measures.

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