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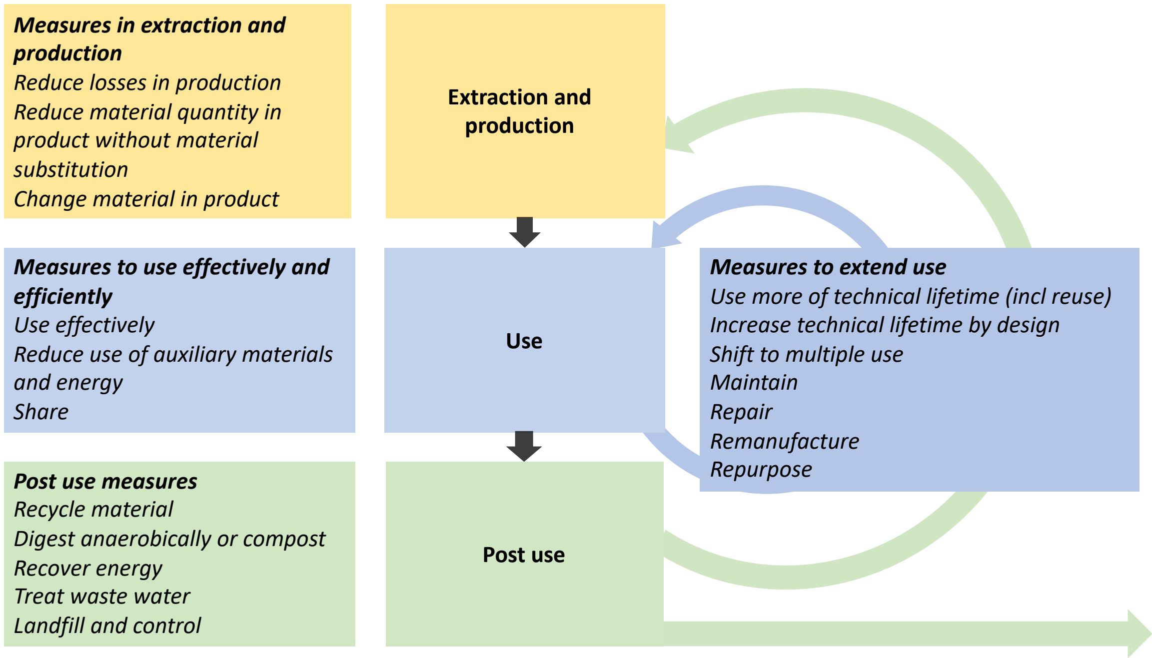

Circular economy and its impact on use of natural resources and the environment

*Chapter from the upcoming book "*Resource-Efficient and Effective Solutions – A handbook on how to develop and provide them"

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020
Report no. 2020:1

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Cover: A life-cycle based typology of physical resource efficiency measures, adapted from Böckin et al. 2019. See Figure 6 on page 9.
Gothenburg, Sweden 2020

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1 Introduction

Circular economy (CE) is about minimizing use of natural resources and generation of waste while reducing pressure on the environment and bringing about economic benefits. (For an extensive discussion on definitions of CE see Kirchherr et al., 2017). Natural resource use and environmental impact are extensively discussed in public debate and there is a common general understanding of the meaning of the concepts. However, both are multidimensional concepts and the meaning of the words to one person is not always the same as their meaning to another. And indeed, what type of environmental impact or natural resource to be concerned about is both a scientific issue and a matter of value judgement.

Luckily, there exist frameworks for natural resources and environmental impact to help structure thinking. However, there are more than one framework, and different frameworks are not always in agreement. This may be due to differences in the context in which they have been developed, such as time frame, geographical scope and administrative domain, but also to different points of departure and knowledge bases for the frameworks.

This chapter describes some of these frameworks, with the aim to give the reader a richer and more nuanced understanding of the concepts natural resource and environmental impact. Further, the idea of the product life cycle is introduced. Life cycle thinking, i.e. systems thinking with a product perspective, and life cycle assessment have been proven highly useful for identifying and assessing measures towards resource efficiency on a product level. A life cycle based typology of measures for resource efficiency is introduced, leading up to guidelines on what measures for resource efficiency are suitable for what kind of product. The chapter ends with examples of measures for resource efficiency applied to specific products – incontinence products, laptop computers and diesel engines - and life cycle assessments of those.

2 Natural resources

While the global population has doubled since the 1970s, the extraction of natural resources has more than tripled (IRP, 2019), see Figure 1. In 2017, the extraction of non-metallic minerals, biomass, fossil fuels and metals reached 92 billion tonnes and was estimated to account for up about half of total global greenhouse gas emissions (excluding impacts related to land use) and more than 90 % of biodiversity loss and water stress (ibid.). If current trends continue, the use of natural resources and their associated environmental impacts can be expected to further increase with a growing and more affluent population.

Natural resources are often referred to as encompassing precisely these four groups: non-metallic minerals, biomass, fossil fuels and metals. But, drawing on Sonderegger et al. (2017), they could in addition include renewable energy sources, water, air components, land and water surface and soil. ***Natural resources*** can be regarded as assets that occur in nature from which it is extracted to be used for human purposes in society. This instrumental view of resources as valuable for human use is for example supported by the International Resource Panel which states that “natural resources can be supplied from the natural system to be used by economies” (UNEP, 2011). European policy takes a similar stance, e.g. in the Flagship initiative for a resource-efficient Europe (EC, 2011) in which “natural resources underpin the functioning of the European and global economy and our quality of life. These resources include raw materials such as fuels, minerals and metals but also food, soil, water, air, biomass and ecosystems.”

Although the distinction is not exact, ***raw materials*** and ***energy carriers*** are natural resources that have been transformed and from which, in turn, manufactured and agricultural *goods* can be generated (ibid.). Further, raw materials can be classified as ***primary*** or ***secondary*** ones, where the former are extracted from nature while the latter are recovered from goods discarded from use in society. In the context of a more sustainable management of natural resources, recognizing and maintaining the value of secondary raw materials and goods already in the hands of humans, are a crucial point of focus.

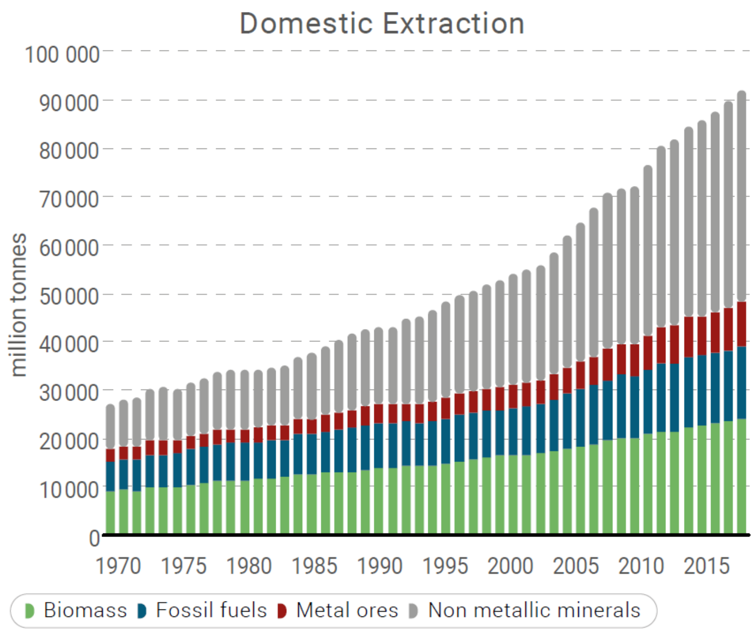

Figure 1. Global material extraction, four main material categories, 1970 - 2017, million tons. Obtained by totalling domestic material extraction for all individual nations (IRP, 2019).

Natural resources can also be categorized according to their renewability, see Figure 2. ***Non-renewables*** are exhaustible and their ***stocks*** cannot be replenished by natural cycles on human timescales. Examples include metals, non-metal minerals, fossil fuel and fossil groundwater. ***Renewables*** stem from natural ***funds*** that can return to their previous levels by natural processes. Examples include terrestrial and aquatic flora and fauna. Renewables also include ***flows*** such as solar power, wind power and land surface which are re-occurring or permanently present (OECD, 2002, Sonderegger et al., 2017).

The classification according to renewability conveys potential problems associated with using the resource. The use of non-renewable resources always reduces the stock with risk for exhaustion. Renewable resources can be used without such risks, but only if not harvested faster than their rate of replenishment, e.g. plants and animals, or if they represent flows. Raw materials and goods occupied in use in society are sometimes referred to as restorable when non-renewable and regenerative when renewable (EMF, 2013).

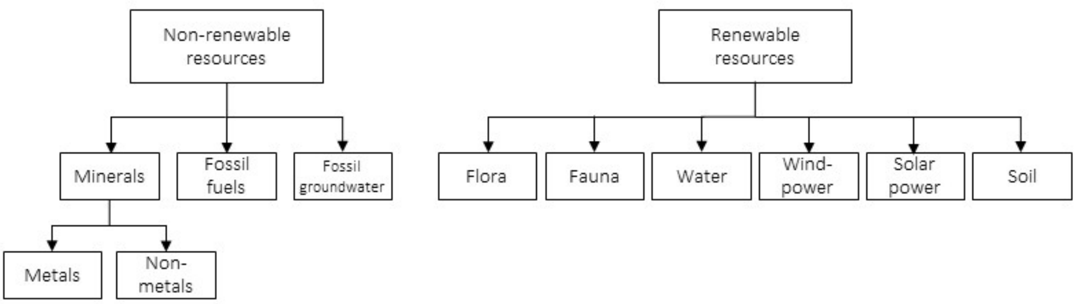

Figure 2. Non-renewable and renewable resources

Another common classification of natural resources is based on their origin. ***Biotic resources*** are living and organic material, such as plants and animals. ***Abiotic resources*** are non-living and non-organic, for example metals, minerals, land area, fresh water, air and sunlight. Fossil fuels are sometimes classified as abiotic, sometimes as biotic. Although often treated as such, the classifications according to renewability and origin are not interchangeable. For example, fresh water as well as kinetic water energy are abiotic, but renewable, and can be harvested without depleting the stock. Another example is land area, which is abiotic but cannot be depleted. Thus, the distinction between biotic and abiotic resources does not suggest the types of challenges related to their availability.

The terms ***resource base***, ***reserve*** and ***resource*** have specific meanings in the context of mineral natural resource availability (Tilton 2003). The resource base covers all of the mineral in the earth's crust. The reserve covers the part that is identified and economic to extract. The resource is the reserve plus the minerals that are economic but not yet discovered or are expected to be economic in the foreseeable future. Thus, neither reserves nor resources are fixed stocks that reflect the remaining availability of minerals (ibid.). Consequently, estimates of life expectancies of minerals and metals rely on entities that are dynamic and may shift with mineral prices and costs for extraction.

An alternative perspective on the significant value that natural resources provide is the so-called ecosystem services (see Figure 3). These "benefits people obtain from ecosystems" are classified into four types of services: ***provisioning services*** such as provision of food, wood and fibre, fresh water and genetic resources, ***regulating services*** such as climate regulation, flood regulation and water purification, ***cultural services*** such as recreation and ***supporting services*** such as photosynthesis, nutrient cycling and soil formation (Millennium Ecosystem Assessment, 2005). It has been suggested that nature is resilient to produce ecosystem services, as long as the impact of human activities stays within the safe operating space of planetary boundaries (Rockström et al., 2009). Four out of nine planetary boundaries are already estimated as overstepped: climate change, loss of biosphere integrity (biodiversity loss), land-system change and altered biogeochemical cycles (phosphorus and nitrogen) (Steffen et al., 2015). No planetary boundary is defined for natural resources as such, but they are important components of others.

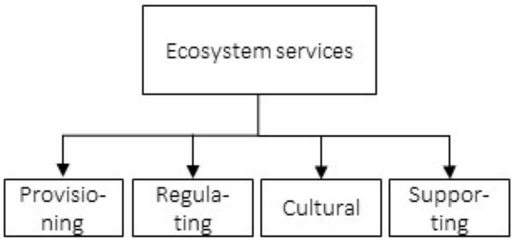

Figure 3. Ecosystem services.

In sum, establishing a concise and widely applicable and agreed definition on natural resources is notoriously difficult. As shown, definitions can be done on different grounds, for different purposes and with different views on their value.

On a final note, resource is a broadly used term with other meanings in e.g. economics, biology, business management and computer science. It can refer to such various factors as natural resources, human resources, financial resources, knowledge and time. As a consequence, terminology related to natural resources should be selected carefully and preferably further specified for the purpose at hand.

2.1 Critical resources and scarce resources – what's the difference?

Natural resources are being assessed in different contexts, using different methods. For instance, in life cycle assessment (LCA), availability of natural resources is one of three areas of protection, together with ecosystem quality and human health (Sonderegger et al., 2017). LCA is done with respect to impact on these three areas of protection, according to longstanding consensus documents (ISO 14040, 1997; ISO 14040, 2006). Nevertheless, an exact definition of what is to be protected when it comes to natural resources is yet to be formulated. Consequently, there are a number of different methods in LCA that serve to assess the impact category resource depletion, ultimately rooted in different perspectives on what constitutes the most relevant constraint for humans, for instance, geological availability, energy, monetary cost for extraction or environmental impact associated with extraction.

More recently, the term ***critical material*** has become an important topic in policy contexts. For instance, the EU has identified materials as critical if there is a high probability of supply disruption and if disruptions could have severe negative impacts on the region's economy, competitiveness and jobs (EC, 2014, 2017). Such supply disruptions could occur, for example, due to dependency on imports from politically unstable countries. Criticality assessment is hence a different kind of assessment of resources than what may be found in LCA.

Despite being rooted in essentially different contexts, the terms "resource depletion" and "criticality" are sometimes used interchangeably in the scientific literature, policy and industry. Further, some argue that also geopolitical issues should be accounted for in LCA since they may also limit resource availability for humans. We therefore think it is appropriate to contrast the two types of assessment to illustrate their main differences.

Criticality assessment aims to identify or rank resources for which a temporary (often geopolitically induced) supply disruption might occur and to which a particular organization (for example a region, nation or a company) is vulnerable. Predominantly, the temporal perspective is short term. Resource depletion, as assessed in LCA, on the other hand, aims to rank resources according to some mechanism that can be suspected to reduce long term resource availability.

3 Environmental impact

Environmental impact, what is that then? These days most people will probably first come to think about climate change or perhaps plastics littering of the oceans or extinction of species. Some decades ago, other kinds of environmental impact were high on the agenda, impacts such as the ozone hole, acidification and effects of toxins in the environment, for example reduced breeding rates of predator birds. Obviously environmental impact can mean many different things, and the fact that it is multidimensional is a key feature of the concept. This section will give examples of frameworks for different types of environmental impact.

Another key feature of environmental impact is the long chains of effects where one environmental load (e.g. an emission of a pollutant from the technosphere) leads to one or several primary effects, which in turn have one or several secondary effects, and so one, as shown in Figure 4. Further, several different effects on one level may contribute to effects on the next level. There are also feed-back mechanisms involved.

As an example, consider global warming. Several greenhouse gases (carbon dioxide, methane, nitrous oxide and fluorinated gases) emitted into the atmosphere stay there for a long time and absorb infrared radiation, disturbing the balance between inflow and outflow of energy to the earth. This increase in radiative forcing can be taken as the primary effect. In turn, it causes increased global surface temperatures (secondary effect). The increased temperature causes a whole series of tertiary effects, such as ice-melting, sea-level rise, acidification of the oceans, and changed weather patterns including a higher frequency of extreme weather conditions. In turn, these impact human societies, interacting with other stressors. Among such impacts are effects on poverty and livelihoods, increased migration with compromised human security and impacts on human health (IPCC, 2014).

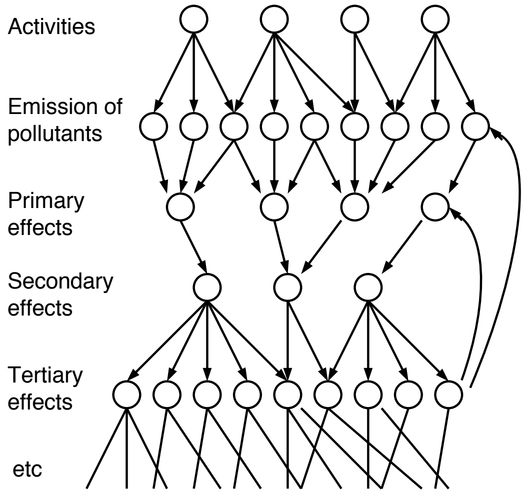

Figure 4. Cause-effect chains of environmental impacts (Baumann and Tillman, 2004)

What is considered an environmental impact also depends on what we consider the impacted ***environment*** to be. The natural environment, such as the ecosystems and the climate system, is always included in the concept the environment. But are we, as human, part of the environment and should impact on us, on our health and on society at large, such as the societal impacts projected by IPCC, be understood as environmental impact? Similarly, is resource use or resource depletion to be regarded as an environmental impact? A third, similar question is whether impact on man-made structures, such as corrosion caused by acidification, should be regarded as an environmental impact?

There is of course no simple answer to such a question. Different frameworks give different answers to such questions, and will be discussed in the following.

On a global level, the planetary boundaries approach aims to define a safe operating space for human activities. The framework provides a science-based analysis of the risk that human perturbation will destabilize the earth system on a planetary scale (Rockström et al., 2009, Steffen et al., 2015). Nine planetary boundaries have been defined, as listed in Table 2.1.

On national levels, there are environmental policy frameworks. In Sweden, the over-arching goal for environmental policy is, to “hand over to the next generation a society in which the major environmental problems have been solved, without increasing environmental and health problems outside Sweden’s borders” (SEPA, 2019). Sixteen environmental quality goals express what state of the environment the policy aims at, in order to reach the over-arching goal (Table 2.1)

On a product level, LCA is a widely used tool for assessing environmental impact, from “cradle-to-grave”. In LCA, inflows of natural resources to the product life cycle and outflows of pollutants to the environment are quantified and then translated into indicators for environmental impact. This takes place in two steps, first to mid-point impact categories, which may be further aggregated into impact on the three end-points (or areas of protection) human health, ecological consequences and availability of resources. One of the latest recommended lists for midpoint impact categories is shown in Table 2.1 (Hauschild and Huijbregts, 2015).

The table is constructed to identify impact categories for which there is a high level of correspondence between the three frameworks and impact categories where there is less, or no, correspondence. This is discussed in the following, together with brief descriptions of the different impacts.

Table 1. Planetary boundaries (Steffen et al., 2015), Swedish environmental quality goals (SEPA, 2019) and mid-point environmental impact indicators in LCA recommended by ILCD (as cited in Hauschild and Huijbregts, 2015).

Level of correspondence between impact categories	Planetary boundaries	Swedish environmental quality goals	Mid-point indicators in LCA as recommended by ILCD
High level of correspondence	Climate change	Reduced climate impact	Climate change
	Stratospheric ozone depletion	A protective ozone layer	Stratospheric ozone depletion
	Biogeochemical flows (nitrogen and phosphorus cycles)	Zero eutrophication	Eutrophication
	Novel entities (chemical pollution)	A non-toxic environment	Ecotoxicity
			Human toxicity
Some correspondence	Atmospheric aerosol loading	Clean air	Photochemical ozone formation
			Particulate matter formation
	Ocean acidification	Natural acidification only	Acidification
	Biospheric integrity (biodiversity loss)	A rich diversity of plant and animal life	Land use
	Land system change	A balanced marine environment, flourishing coastal areas and archipelagos	Land use
		Thriving wetlands	
		Sustainable forests	
		A varied agricultural landscape	
		A magnificent mountain landscape	
	Freshwater use	Good-quality groundwater	Water use
		Flourishing lakes and streams	
No correspondence		A good built environment	
		A safe radiation environment	
			Abiotic resource use

All three frameworks bring up the environmental impacts caused by emissions which occur on a global level, ***climate change*** (already briefly described) and ***depletion of stratospheric ozone***. The ozone layer in the upper atmosphere, the stratosphere, screens out most of the dangerous ultra-violet radiation from the sun. Ozone depletion refers to thinning of the layer due to chlorinated and brominated substances (e.g. CFCs and HCFCs). Also nitrous oxide (N_2O) contributes to ozone depletion (Hauschild and Huijbregts, 2015). Ozone depleting substances are being phased out after international agreement and the ozone hole over Antarctica is now slowly repairing itself (Steffen et al., 2015).

The three frameworks are similar also in that they include ***eutrophication***, which is an effect of nutrients, mainly nitrogen and phosphorus compounds emitted to water, or emitted to air and then deposited on land and in water ecosystems. Effects include algal blooms and following oxygen depletion in freshwater and marine environments and changing composition of species in terrestrial systems. The effects of nutrients vary with receiving environment and geographical location, but flows of nitrogen and phosphorus is one the planetary boundaries grossly transgressed (Steffen et al., 2015).

The planetary boundary novel entities include chemicals and engineered materials or organisms. The boundary is about toxic effects, but also about other not anticipated risks, such as the ozone depletion which followed from the release of CFCs. The increase in number of chemical substances and materials put on the market is in itself seen as a risk. Also in environmental policy and in LCA, ***toxic effects*** of chemicals in the environment and on humans are seen as impacts of concern.

Swedish environmental policy has a goal about ***clean air*** due to the health effects of air pollutants but also because they cause corrosion of man-made objects. Particles, nitrogen oxides and organic compounds cause health effects in themselves, but also contribute to the formation of ground-level ozone (which, in contrast to stratospheric ozone, damage human health). In LCA, impact from particles on human health and ground-level ozone (photochemical oxidant formation) is accounted for separately, and not only health impacts but also damage to crops and forestry is accounted for.

The planetary boundaries are not so much concerned with health effects when it comes to air quality. The boundary for atmospheric aerosol loading is not set because aerosols damage health, even if they do, but because they affect monsoon rains. Particles in the atmosphere from combustion processes and traffic decrease the solar radiation at the surface of the earth, which risks leading to substantially drier monsoons in South Asia.

Similarly, for acidification, Swedish environmental policy and LCA agree on seeing the impact of ***acidifying*** substances (mainly emissions to air of nitrogen and sulphur oxides from combustion and ammonia from agriculture) on land and water ecosystems as a significant environmental impact. The planetary boundary for ocean acidification is about a different environmental cause-effect chain. It is set because increased levels of carbon dioxide in the air increases up-take of carbon dioxide into sea water which then becomes more acidic. Among the effects are that calcium carbonate can no longer be formed by marine organisms such as corals and some plankton, or is even dissolved from them.

Loss of biodiversity is a major global challenge and is another planetary boundary which is grossly transgressed. A rich biodiversity is also among the Swedish environmental goals. In LCA, which has a product focus rather than a regional (country) or global perspective it has been methodologically difficult to come up with useful indicators for impact on biodiversity. It is however recognised in LCA literature that different land use practices impact biodiversity and indicators have been suggested.

When it comes to ***land use and impact from it***, there are many different ways to slice the dice, and naturally they vary with level of geographical granularity. As seen in Table 2.1, in the Swedish environmental goals there are several goals related to different kinds of land use, which is only natural in a national context. Also for ***water use*** the level of granularity in descriptions vary and is higher in the national context. The ***built environment*** and ***radiation environment*** are only considered in the Swedish national goals and ***use of abiotic resources*** only in LCA.

4 Product life cycles

A systems perspective is necessary for strategies and action for resource efficiency and environmental improvement. When strategies and action concern products, the product life cycle is a very useful way to delimit the system. A product life cycle stretches from "cradle-to-grave" and includes extraction of natural resources, production of raw materials, manufacturing of materials and components, assembly, distribution, use and any handling after use such as waste management. In a circular economy waste handling is avoided (or at least minimized) and used products are reused or recycled. Between all activities in the life cycle there is also transportation, which is included in the product life cycle. A life cycle perspective is useful not only for physical products, but also to services, to the extent that a physical basis for the service exists (which it usually does), and also for combinations of products and services. The word product is hence in the following used to denote both products and services, alone or in combination.

The most elaborate use of the product life cycle perspective is in life cycle assessment. LCA not only identifies all the different activities in a product life cycle and puts them into relation with one another, it also quantifies the flows of raw materials, volumes of transport work, energy and auxiliary material used during use and flows associated with the post use phase and relate them to the function of the product. Further, use of natural resources and impact in the environment are quantified (see e.g. Baumann and Tillman, 2004, ISO 14040, 2006). However, there are other, less strenuous uses of the life cycle perspective. One is the mere life cycle thinking, the consideration of life cycle implications of activities and products but without the number crunching, another life cycle management, the managerial practices and organizational arrangements in a product chain expressing such life cycle thinking (Baumann and Tillman, 2004).

The strength of the life cycle perspective is that it allows identification and estimation (quantitative or not) of the implication of actions, up-stream and down-stream along the product chain, and across different types of impact on the environment, including use of natural resources. Trade-off between types of environmental impact and shifting of environmental burden between life cycle phases can be identified (and in LCA quantified). The life cycle perspective allows for identification of key actions and key actors in the system, and it allows individual actors in the chain to better understand their role.

Examples of product life cycles are given in the case studies in section 2.6. Flow diagram are shown for three different product life cycles, incontinence products, reuse and recycling of laptops and productions of a diesel engine with conventional manufacturing and 3D-printing. The cases illustrate burden shifting between life cycle stages and trade-offs between types of environmental impact as a result of resource efficiency measures. They also provide examples key aspects to consider when implementing specific measures and the laptop case point to the interdependence between the measures reuse and recycling.

There are many applications for life cycle life cycle thinking and LCA, e.g. as support for decision making, in policy, design and purchasing and for underpinning communication about the environmental performance of products, such as in eco-labelling. The learning about product systems and identification of improvement possibilities is a very important application. When it comes to design, a general opinion is that environmental aspects should be considered as early as possible in the design process, when there is still room for changes to the design. On the other hand little is known about the product early in the design process, making life cycle thinking, and even more so quantitative environmental assessment, difficult (see Figure 5). This is generally referred to as the design paradox.

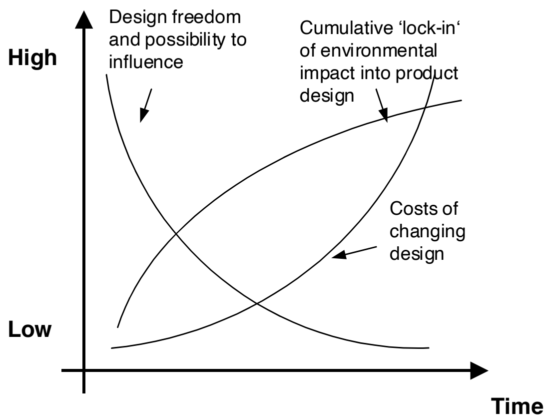

Figure 5. Conditions for ecodesign change during the product development process (Baumann and Tillman, 2004)

5 Life cycle based measures for resource efficiency

Products differ in character. Some are durable and some are disposable, some use energy during use while others just sit there, some are complex while others consist of few components or materials. What can be done to improve their resource efficiency differs accordingly (Vezzoli, 2018) Böckin et al., 2019), why guidelines for resource efficiency need to be based on the characteristics of products. This is in contrast lists which set priorities between resource efficiency measures irrespective of product characteristics, such as the waste hierarchy and more elaborate R-frameworks for CE (e.g. Potting et al., 2017).

This section presents guidelines developed within Mistra REES for what physical measures for resource efficiency can be taken for different kinds of products (Böckin et al., 2019, Tillman et al. forthcoming). In the guidelines, resource efficiency is defined as fulfilling the same function causing less use of natural resources and environmental impact. The guidelines are limited to physical measures for resource efficiency, while recognizing the importance of policy and/or business drivers. The argument is that for CE to deliver on its promises for RE, all policy, business and design actions for CE must eventually lead to reduced material flows. They are relevant to all actors along the product chain, producers, users and end-of-life actors as well as to designers, policy makers and business managers.

5.1 A life cycle based typology of measures for resource efficiency

There are many different measures which can be taken to improve the resource efficiency (including environmental performance) of products and services. Figure 6 presents a typology of all the various measures for resource efficiency which are applicable on a product level. The typology, developed within Mistra REES (Böckin et al., 2019) follows the logic of the product life cycle. The measures are divided according to the life-cycle phases where they can be implemented, extraction and production, the use phase and the post-use phase.

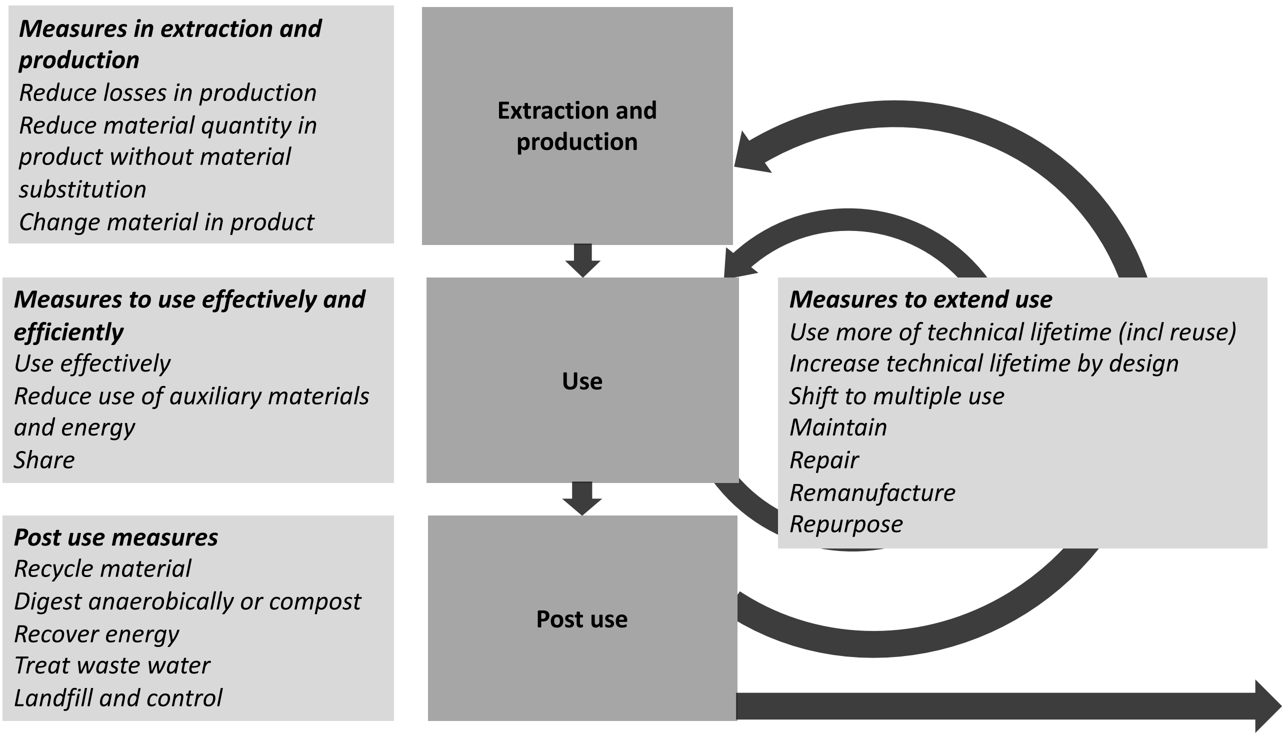

Figure 6. Life-cycle based typology of physical RE measures. (Böckin et al., 2019)

The resource efficiency of the life-cycle phases ***extraction of raw materials and production*** can be improved for all types of products by reducing the use of material and energy in production processes. Measures related to production processes, such as smart production planning and reducing scrap rates and energy use can ***reduce losses***. In cases when losses do occur, they can be valorised, either internally or externally (the former often called process integration and the latter sometimes called industrial symbiosis).

Also related to the production phase, there are design-related measures that can be undertaken, such as designing products to ***use less material (without material substitution)***. It is often also possible to ***change the material used in the product***, to a more environmentally preferable alternative. Examples include substituting primary materials with recycled materials, changing from fossil-based to bio-based materials and to substitute hazardous or scarce constituents. Material substitution can increase resource efficiency in itself or enable other measures (e.g. by increasing technical lifetime through increased durability).

In the ***use phase***, there are two main means of achieving resource efficiency, either to use products more efficiently and effectively, or to extend their use. ***Extending the use***, or prolonging the product lifetime, is where many of the loops featured prominently in CE literature come in, such as reuse, repair, refurbish, remanufacture and repurpose (Potting et al., 2017). These loops go under many names in literature, and here some have been combined into ***use more of technical lifetime (including reuse), repair, remanufacture*** and ***repurpose*** and some added, ***increase lifetime by design, shift to multiple use*** and ***maintain***. All the measures for extended use are applicable only to durable products, except shift to multiple use, which refers to consumable products being made durable.

The other principal avenue to use-phase efficiency is to ***use products more effectively and efficiently***. Such measures are applicable to durable and consumable products alike. To ***use effectively*** means to either deliver or acquire function according to user's needs (the former is relevant for providers while the latter is relevant for customers). Another way to use effectively is to make sure that losses are avoided and that the product is used for its intended purpose. An example would be packaging designed to be fully emptied and users actually emptying them. Use effectively also includes improving product functionality to enable system efficiency, such as detergents allowing for lower washing temperatures.

Conversely, ***using a product more efficiently*** means to reduce the use of energy or auxiliary material during use. This measure is applicable to durable products that require energy or auxiliary material during use, like vehicles, buildings, machinery and household appliances. Lastly, ***sharing*** is a way to get more function out of a product before it is deemed obsolete, by having several users share it. When use is intensified in this way, more function is delivered per item during its life, while product lifetime, if measured as calendar time, is often reduced.

Lastly, we get to the measures that can be undertaken after use, here denoted ***post-use*** rather than end-of-life, which is a more common term but with less circular connotation. ***Recycling*** recovers and returns materials to use. Biodegradable materials and products can be ***digested anaerobically*** or ***composted,*** yielding products such as biogas, recovered plant nutrients and soil enhancers. ***Energy recovery*** converts the energy stored in combustible materials into energy carriers like heat and electricity. Waste products collected via sewers is handled by waste water treatment, which sometimes delivers useful flows of energy and plant nutrients. ***Controlled landfills*** are constructed for controlling emissions to air and water from disposed waste. Material and energy recovered post-use are commonly used in applications where quality requirements are lower than in the disposed products, as indicated by the flow leaving the product life cycle in Figure 6.

5.2 Life cycle based guidelines for resource efficiency

This section presents guidelines for what resource efficiency measures are suitable (and sometimes even possible) to apply to a product, depending on product characteristics (Tillman et al., forthcoming). The guidelines are sorted according to product characteristics and life cycle phases where the resource efficiency measures can be undertaken. The first part covers the use phase and is separated into measures for durable and consumable products, each with sub-characteristics of relevance for resource efficiency measures. The second part is about post-use, for which the distinction between durable and consumable products is less relevant. Instead, the material content influences what measures can be taken. For extraction and production, presented in the last part, there is no clear relation between product characteristics and what resource efficiency measures are more suitable.

Table 2.2 shows what measures related to the use phase can be applied to durable products, depending on their characteristics and provides examples of products exhibiting the respective characteristics, concrete examples of the measure and potential trade-offs. Since many products have more than one characteristic relevant to resource efficiency measures, several of the example products appear in more than one entry.

Several measures that are valid for ***all durable products, irrespective of other product characteristics; use effectively*** and ***maintain, repair, remanufacture***. Use effectively implies to provide, or use, products with appropriate, i.e. needed, function, but not more than that. Maintain, repair, remanufacture are restorative measures and could potentially generate trade-offs. These activities usually require transport, either of staff delivering the service, or of the product, to a workshop or similar, with associated environmental impact which risk outweigh the benefits of use extension. Also, designing products to be maintained, repaired or remanufactured may come at the price of more (or more impacting) material being used.

If the ***durable is an active product***, which means that it uses energy or auxiliary materials during use, efficiency measures to ***reduce use of auxiliary materials and energy during use*** are suitable. It should be noted that for active durable products which develop towards use phase efficiency the gains of applying restorative measures such as maintain, repair or remanufacture, may be outweighed by the savings obtained in the use-phase if an old inefficient product is replaced with a new more efficient one. As can be seen in the table, this trade-off is valid for many of the other extend product life measures. Additional trade-offs connected to reduce auxiliary materials and energy during use is that efficiency during use often comes at the price of more material and components, or more sophisticated ones, being invested in the product.

For ***durable products which are typically used for their full technical life time*** resource efficiency can be improved through ***increasing their technical lifetime by design***. A potential trade-off connected to this measure is that more, or more impacting, materials is sometimes used to achieve increased durability. For ***durable products that are typically discarded before being worn out***, ***using more of technical lifetime, which includes reuse,*** is central. One way to accomplished reuse is through second hand sales, which may involve transportation out-weighing the benefits of reuse.

Durable products, that are typically discarded before being worn out and that are ***infrequently used***, are suitable for ***sharing*** among different users. However, one should be aware of that sharing can increase transportation for users accessing the shared stock. Lastly, ***durable products for which function partly remains when no longer usable for original purpose*** can be used for another purpose (***repurposing***). This means that the product is reused in a function other than the original one, e.g. reuse of automotive batteries for stationary energy storage.

Table 1. For durable products with different sub-characteristics - suitable use phase measures, examples of measures and potential environmental trade-offs.

Product characteristic	Example products	Suitable/possible measure	Example measures	Potential environmental trade-offs
Durable products, irrespective of other characteristics	Machines, buildings, vehicles, furniture, household appliances, electronics; components thereof; clothes	Use effectively	Deliver/acquire only needed function, use for intended purpose, avoid losses during use, increase functionality to improve system efficiency. E.g. specification to needs, turn off equipment when not in use, eco-driving	No identified trade-offs
		Maintain, repair, remanufacture	• Maintain: inspect, maintain and protect before failure • Repair after wear, malfunction or failure • Remanufacture: restore product to functional state as good as new (or better)	• Maintenance, repair and reman can increase transportation • Products designed for disassembly may use more material • Benefits of longer use vs impact from sensors For active products with technological development towards use-phase efficiency: • Use-phase efficiency vs benefits of use extension
Durable products, active	Machines, buildings vehicles; household appliances, electronics; active components thereof; (for vehicles also passive components)	Reduce use of auxiliary materials and energy during use (use efficiently)	Energy efficient machines, vehicles, electronics etc, energy and water-efficient buildings and household appliances	• Reduced use phase impact vs increased production phase impact • Reduced use phase impact vs impact from sensors in cases when required

Product characteristic	Example products	Suitable/possible measure	Example measures	Potential environmental trade-offs
Durable products, typically used for full technical life-time	Vehicles, machines, household appliances and their components, furniture	Increase technical lifetime by design	Products and components designed to last longer	• Durability vs amount (or impact) of materials For active products with technological development towards use-phase efficiency: • Use-phase efficiency vs benefits of use extension
Durable products, typically discarded before being worn out	Furniture, household appliances electronics, clothes	Use more of technical lifetime, including reuse	Use for longer by the same user and/or second-hand sales	• Second-hand sales risks inducing transportation out-weighing benefits of reuse For active products with technological development towards use-phase efficiency: • Use-phase efficiency vs benefits of use extension
Durable products, typically discarded before being worn out and infrequently used	Vehicles, washing machines, tools, clothes	Share	Use regularly by several users, e.g. clothes-library, rented tools, communal washing machines	Sharing can increase transportation for users accessing the shared stock
Durable products for which function partly remains when no longer usable for original purpose	Automotive batteries, electronics	Repurpose	Reuse in a function other than the original one. E.g. reuse of automotive batteries for stationary energy storage	For passive products: • No identified trade-offs For active products with technological development towards use-phase efficiency: • Use-phase efficiency vs benefits of use extension

For consumable products fewer options relate to the use phase. And yet, these may be very important, since a fair share of our consumption consists of consumable products. Two sub-characteristics are identified as decisive for what measures are suitable and/or possible. *Disposable products* (e.g. packaging and single-use products) remain as distinguishable items after use whereas *products used in a dissipative manner* (e.g. food, energy carriers, cleaning agents) are literally consumed during use.

As can be seen in Table 2.3, for ***dissipatively used consumable products*** the measure ***use effectively*** is suitable. This means to deliver or acquire only needed function, avoid losses during use, use the product for its intended purpose, and increase functionality to improve system efficiency. If sensors are required to enable this measure, there is a risk of increasing the environmental impact due to their production. For ***disposable consumable products***, such as tissues, packaging, hygiene products and disposable components in durable equipment, there are two alternative suitable measures. Similar to other products they can be ***used effectively***. For disposables it is also possible to ***shift to multiple use products***, which is a matter of design for a provider, but a matter of purchase for a user. There are trade-offs between the benefits of multiple use and increased impact from production and maintenance (often including cleaning and transportation).

Regardless of efforts to make products last longer and to use them effectively and efficiently, there will always be a point when they reach their end of life. Waste treatment will always be needed, but waste can be turned into new resources, in line with the circular economy. What post use measures are suitable depends less on whether products are durable or consumable, and more on their material content (see Table 2.4).

Most products can be ***recycled*** if collected, provided suitable recycling technology is in place. An exception is dissipatively used products, such as food and energy carriers, which will no longer exist as distinguishable items after consumption and will not lend themselves to material recycling. With few exceptions, material quality is down-graded during recycling. This is due to limitations in sorting, to material diversity and complexity of products and to limitations in recycling processes.

Table 2. For consumable products with different sub-characteristics - suitable use phase measures, example measures and potential environmental trade-offs.

Sub product characteristic	Example products	Suitable/possible measure	Example measure	Potential environmental trade-offs
Consumable products used in dissipative manner	Food, fuels, water, electricity, cleaning agents	Use effectively	Deliver/acquire only needed function, avoid losses during use (e.g. smart dispensing), use for intended purpose, increase functionality to improve system efficiency (e.g. detergents allowing lower washing temperature and fuel additive increasing engine efficiency)	No identified trade-offs except: • Reduced use phase impact vs production of sensors in cases when required • Chemicals with higher functionality vs risk of more hazardous constituents
Disposable products	Single-use items, e.g. tissues, packaging, hygiene products. Disposable components in durable products, e.g. ink- cartridges, single-use batteries, disposable machine components	Use effectively	Deliver/acquire only needed function, avoid losses during use (e.g. smart dispensing), use for intended purpose	No identified trade-offs except: • Reduced use phase impact vs production of sensors in cases when required
		Shift to multiple use product	Reusable e.g. washable, rechargeable and refillable products	• Benefits from multiple use vs increased impact from production and maintenance/cleaning, including transportation

Biodegradable products can be ***digested anaerobically*** or ***composted***. Anaerobic digestion yields biogas and a digestate containing nitrogen, phosphorous, potassium and organic matter which can be used as a fertilizer. In contrast, compost has a low nitrogen content and is primarily a soil enhancer. Combustible products can be ***incinerated***, even though, in practice, many noncombustible materials go into incinerators, where they yield ashes and/or slag. Energy is usually recovered. Dissipatively used products that end up in sewage will be treated in ***waste water treatment*** plants (WWTP). Examples include tissue, detergents and human excretions emanating from food.

Landfill deposition, finally, is not a circular solution, but one that always will be needed to handle residues which cannot be handled in any other way. In ***controlled landfills*** emissions are reduced through collection and treatment of landfill gas and leaching water. Fossil-based materials stored in landfills will not be released as carbon dioxide (as they would if incinerated) and deposition of bio- based material will even create a carbon sink. Landfills also store non-renewable materials, making them available for potential future resource extraction.

Common to all post use processes which recover energy and/or material resources is that they will improve resource efficiency only as long as their impacts are smaller than impacts from alternative production of the recovered resource. Processes which recover material resources risk recirculate any hazardous substances contained in their inflow, keeping them the technosphere.

Table 3. All products – post use measures including potential environmental trade-offs

Product characteristic	Suitable/possible measure	Useful output	Potential environmental trade-offs
All products except consumables used in a dissipative manner. Relevant in particular for products with significant impacts from material production	Recycle material	• Recycled material	• Impacts from recycling need to be smaller than impacts from alternative material production • Risk of keeping hazardous substances in circulation
Biodegradable products	Digest anaerobically	• Biogas • Digestate (complete fertilizer and soil enhancer)	• Impacts from digestion need to be smaller than avoided impact from alternative production of its products • Risk of keeping hazardous substances in circulation

Product characteristic	Suitable/possible measure	Useful output	Potential environmental trade-offs
Biodegradable products	Compost	• Soil enhancer	• Impacts from composting need to be smaller than avoided impact from alternative production of its products (e.g. soil enhancers) • Risk of keeping hazardous substances in circulation
Combustible products	Incinerate with energy recovery	• Heat and/or electricity	• Impacts from incineration need to be smaller than avoided impact from alternative production of its products
Dissipatively used products, collected as waste in sewers	Treat waste water	• Biogas • Heat • Sludge containing plant nutrients	• Impacts from digestion need to be smaller than avoided impact from alternative production of its products • Risk for introduction of hazardous substances in the food chain • Risk for dispersion of pathogens
All products and/or residues from other post-use processes	Landfill and control	• Small relevance	• Landfill impacts vs sink for carbon, materials and hazardous substances

Measures in the extraction and production phase do not depend on product characteristics, but are relevant for all products (Table 2.5). ***Reducing losses in production*** of both material resources and energy can be applied in all types of production. This could involve reducing scrap rates and other material losses, improve the energy efficiency and utilise by-product energy and material flows, both internally through process integration or externally through recycling of pre-consumption waste. ***Reduction of material content***, ***without substituting material***, can be done for most products, but often at the price of reduced functionality, such as durability.

Lastly***, changing the material composition*** of products to more environmentally benign materials is way to improve the resource efficiency. Examples include substitution of fossil-based material with bio-based, use of biodegradable material in products that risk ending up as litter, increased share of recycled material, substitution of hazardous constituents and substitution of materials based on scarce raw materials. However, there is always a risk for trade-offs between types of environmental impact when substituting materials.

Table 4. All products - measures in extraction and production, including example measures and potential environmental trade-offs

Suitable/possible measure	Example measures	Potential environmental trade-offs
Reduce losses in production (including valorising by-product streams)	• Reduce scrap rates and other material losses in production • Increase energy efficiency in production • Valorise by-product energy and material flows, internally (process integration) or externally (industrial symbiosis)	• Reduced losses of material in production vs energy use for avoiding losses
Reduce material quantity in product without material substitution	• Thinner layers of specific materials • Non-massive designs, e.g. truss and shell structures	• Risk for losing function, e.g. durability

Change material in product	• Change to/increase share of:
	  • Bio-based material
	  • Bio-degradable material
	  • Recycled material
	• Substitute/decrease share of:
	  • Scarce materials
	  • Hazardous constituents
		• Risk for burden-shifting when substituting material
		• Change material is often a precondition for other measures, e.g. use phase efficiency or increased life time. Potential trade-off between the benefits of the enabled measure and impact of the new material

6 Cases studies

This section presents three case studies of measures applied to actual product systems, of very different nature. Their impact on resource efficiency was assessed with life cycle assessment. All three case studies were carried out in collaboration with industrial companies participating in the Mistra REES programme.

The first case study is on ***incontinence products***. An interesting observation in this case was that ***several different measures for resource efficiency*** were possible for such a ***disposable product***. It is also interesting to note that most, if not all, of the identified measures were possible to implement independently of one another. The LCA study revealed a very clear trade-off between types of environmental impact, impact from land use and climate change, when the share of bio-based material was increased.

The second case is on ***reuse and recycling of complex durable products***, ***laptop computers***. It was done in collaboration with a remanufacturing company which acquires used high-grade and professional-use laptops from companies and resells to new customers. The study is a life cycle assessment of an existing industrial circular economy case. In contrast to the incontinence case, this case clearly pointed to the interdependence between measures for resource efficiency, i.e. reuse and recycling. Reuse of laptops increases resource efficiency, but so does the recycling of those laptops collected for reuse, but which cannot be reused. The study also revealed that recycling of computers reduces some types of environmental impact, e.g. human toxicity, which mainly emanates from primary metal extraction, but does not do much to reduce global warming, since greenhouse gas emissions mostly occur further downstream in the product chain, during production of electronic components.

The third case concerns ***production technology*** for a ***durable active component***, 3D-printing of a diesel engine. The study is a prospective LCA, where future environmental potential and risk of an ***emerging technology*** were assessed. The study illustrates the common trade-off between reducing impacts in different life cycle phases for active products. 3D-printing enables lighter components and hence lower fuel consumption of the truck, at the cost of increased impacts from production. It also shows the importance of considering technological development and of estimating the environmental potential of technologies expected to be widely adopted in the future.

Case study 1 – Measures for resource efficiency for a consumable – incontinence products

There is much focus in the discussion about circular economy on durable products, which are to be maintained, repaired, reused and shared. However, many of the products we use are consumable, such as food, fuels, cleaning agents, packaging and hygiene products. These products must be made resource efficient as well. For this reason, a case study of a consumable product, incontinence products was carried out (Willskytt and Tillman, 2019). The life cycle-based typology of measures for resource efficiency described in Figure 7. was used to identify possible measures for incontinence products. Even though the study was limited to such measures as could be implemented without any further technology development and hence within a short time perspective many different things can be done to increase resource efficiency for this type of consumable product. They were:

- Recycling of waste generated in production, which was compared to incineration (this activity is denoted as manufacturing waste recycling in the flowchart in Figure 7)
- Increasing the share of bio-based material in the product by replacing part of the super-absorbing, fossil-based material (SAP) with wood-based absorption material (fluff pulp) (thus affecting the volumes of pulp production and production of fossil-based components in Figure 7)
- Shifting to a partly reusable product system. A wholly reusable incontinence product was not considered feasible under current conditions, but a product system with a reusable pant which holds an absorbing, disposable insert in place already exists on the market. This was compared to a completely disposable product (see Figure 8). This measure thus adresses the use-phase of the products lifecycle.
- More effective use of products through customization to user's needs. In practice, this means to measure the degree of incontinence and the size of patients and use this together with information on the patients' general health status to generate recommendations for which size and absorption capacity of products individual patients actually need. This measure was thus also addressing the use-phase.

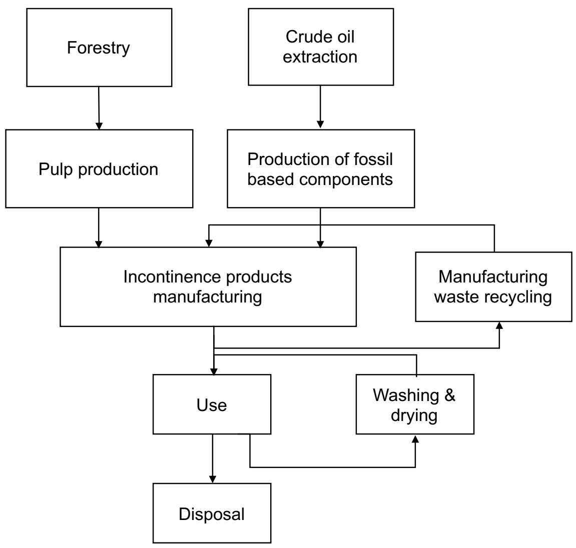

Figure 7. Simplified flowchart of the incontinence product´s life cycle.

Figure 8. The all-in-one disposable incontinence product that was compared with a partly reusable product system (reusable pant plus disposable insert)

The LCA study showed that customization of products to patients' needs leads to at least 20% lower environmental impact, with no trade-offs between different types of environmental impact. The reason for the large improvements was that a vast majority of patients in the sample use products with two levels too high absorption capacity as well as one size too large products, which thus meant that products with less materials content could be recommended after the measurements.

The partly reusable product system (reusable pant plus disposable insert) decreased climate impact by more than 50% compared to a corresponding disposable product. Washing and drying of the pants did not contribute significantly to environmental impact (merely 1 %), even though many previous studies comparing single-use and multiple-use health care products have shown that washing of the products may outweigh the benefits from multiple-use product. In this case study, the washable pants were assumed to be used as many times as designed for (20 times) and the washing was energy efficient using electricity produced with only a small share of low fossil energy.

To evaluate the robustness of this result, a sensitivity analysis investigated how different loads in the washing machine and electricity mix influenced the result. The results showed that it was only, as an extreme worst case, when it was assumed that the pants were washed and dried as the only garment in the machines, the impacts increased significantly and changed the ranking order between the single-use and partly reusable product.

Surprisingly, when the electricity production mix was changed in another sensitivity test, from an essentially fossil-free Swedish mix to electricity based on 100% lignite, the global warming potential of the system did not increase substantially. This was due to the high energy efficiency of the machines. Thus, energy efficient maintenance systems are a requirement for a resource efficient multiple-use product. It is also important to use the multiple-use product enough times to outweigh the impacts from its production, which is usually more resource intensive than producing a single use product.

As expected, an increased share of bio-based material in the products led to reduced climate impact, but at the price of increased land use. This example showed the risk of burden-shifting between environmental impact categories when changing the material of products. Recycling of scrap and waste material from production reduced environmental impact by around 5% and demonstrate that all measures that lead to reduce resource use are important for resource efficiency.

Lastly, an important observation from the study was that most of the measures can be used in combination. This means that there exists considerable potential to increase the resource efficiency of incontinence products in a short time perspective. Although not shown in the study, the implication is that there are also many ways to make other consumable products more resource efficient.

Case study 2 – Measures for resource efficiency for a complex product – reuse and recycling of laptop computers

Laptop computers and other types of electronic equipment is one of the fastest growing waste streams globally. Production of electronic equipment is intensive in terms of energy and material resources. For instance, to produce just a computer chip may require up to 60 different elements (NRC, 2008) and requires highly advanced production processes. Recycling systems are currently only capable of recycling a few of the metals that compose laptops, which implies that there are considerable metal losses. Furthermore, laptops tend to be discarded while they are still functional, which implies that there are considerable losses of potentially usable function.

Both these types of losses imply that environmental impact and resource use could be substantially reduced if laptops were provisioned in a more circular way. If laptops were used for longer, not as many would have to be produced. If at the end of their functional lives more metals were recycled, not as much primary metal production would be needed. Fortunately, laptops have quite a second-hand value. This makes it possible for companies to make a business case out of collecting unwanted laptops, erasing information and redistributing them to new users in "as new" condition.

In this study, the environmental effects of using second-hand laptops provisioned by a Swedish reuse company was compared to using newly produced laptops using life cycle assessment (André et al., 2019) (see Figure 9). The company acquires used high-grade professional-use laptops from companies and resell them to new users in the public sector and companies and to private users, in Europe and Asia. About 70% of the laptops acquired can be resold while the rest is sent to recycling.

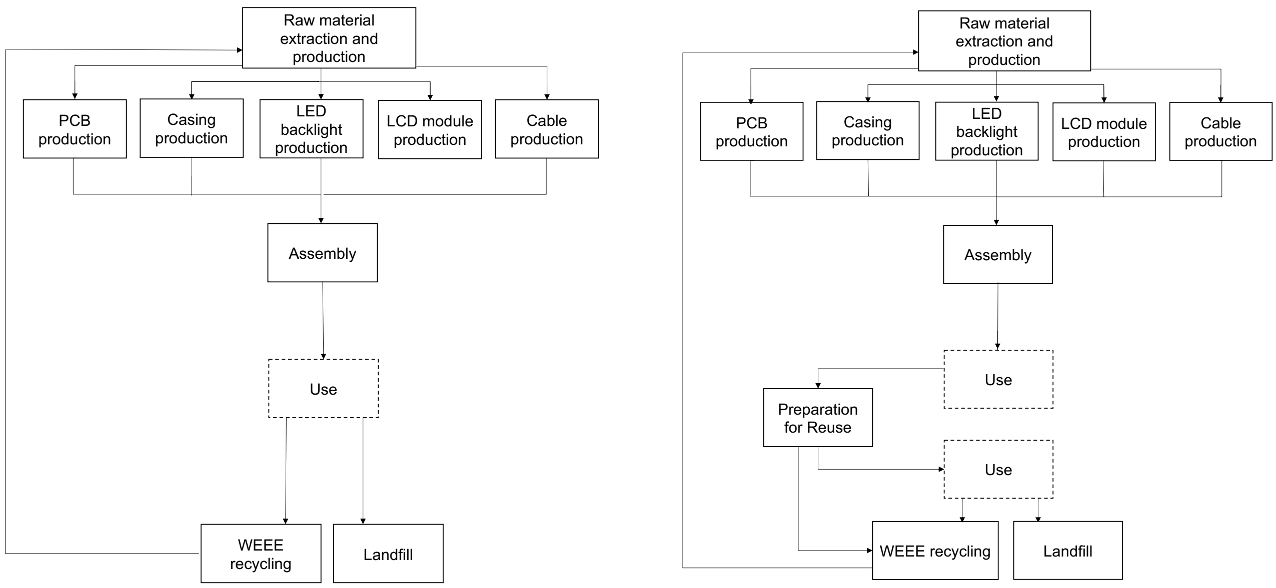

Figure 9. Flow charts for using new (left) and second hand laptops (right).

The results revealed that provisioning of second-hand laptops through such a reuse company contributes to resource efficiency in two principal ways. Firstly, as expected, environmental impacts are reduced because the laptops are used for longer, which reduces the need for producing new ones. Secondly, and less expected, environmental impact was further reduced since those laptops which are in insufficient condition for reuse get sent to proper recycling. This is because the company has well organized channels to recycling facilities, whereas had the laptops been collected for recycling directly from users a smaller share would have reached well-functioning recycling systems. Furthermore, the study showed that the efforts required to enable use extension, for instance long-distance transportation, were environmentally negligible compared to the benefits.

In summary, the environmental improvement enabled by the reuse company can be understood in terms of two features: use extension and steering of laptop flows into recycling. Use extension contributes the most to the total reduction and reduces all types of environmental impact equally. The merits of the second feature however vary depending on the environmental impact category.

The types of impacts which are reduced by metal recycling to a larger extent than others are those to which primary production of the metals contribute significantly. For instance, recycling reduces human toxicity impacts to a larger extent than climate change impacts. This is because the most impacting processes in terms of human toxicity are in the primary production of recyclable metals such as gold, silver and copper. On the contrary, most contributions to climate change are caused by the energy and material intensive production of highly advanced components such as the microchips. In comparison to production of such components, production of recyclable metals in the laptop contribute much less to climate change.

Since recycling can displace the need for primary production of metals it can avoid emissions that are toxic to humans. Recycling cannot however offset much of a laptop's climate emissions since these are caused by advanced component production rather than primary production of metals. Thereby, recycling plays a larger role for reducing human toxicity impacts than climate change.

Since electronics such as computers contains so many different elements (most of them metals), the assessment of resource depletion was done in some detail in the LCA study. Among the expectations on an LCA study is that it should prioritize between different resources and answer questions such as "Which metal is most important to recycle?" and "Which metal is most important to reduce the use of?" However, the existing methods for assessing depletion of abiotic resources in LCA are not in agreement. This is because they depart from different perspectives on what constitutes the actual problem (see section 2.2.1). Essentially, the differences revolve around what is assumed to constitute the limit to resource availability for humans, for instance, geological availability, energy, environmental impact of extraction or monetary cost of extraction. Depending on impact assessment method, which may be based on either one of these perspectives, the study pointed to different metals as contributing the most to resource depletion. However, most impact assessment methods highlight gold as the resource of most concern in terms of resource depletion for laptops.

Case study 3 – Measures for resource efficiency in production – 3D-printing of a diesel engine

3D-printing, also called *Additive Manufacturing (AM)*, is a collective term for techniques for constructing three-dimensional objects, usually by binding material together until a desired shape and size is achieved based on 3D-model data. AM is recognised as an emerging technology, which means that it is in the early stages of maturing and spreading and can potentially play a large role in the future (Gebler et al., 2014). 3D-printing has received attention because it is expected to revolutionise many different industries, by e.g. enabling the on-demand production of specialised and complex parts. The technology can have far-reaching effects in terms of resource use and environmental impacts. Assessment of future potential benefits, and risks, can help steer the development in a desired direction.

This was the idea behind an LCA-study investigating metal 3D-printing of light truck engines (Böckin and Tillman, 2019), done in collaboration with a truck manufacturer. The specific type of 3D-printing considered was Powder Bed Fusion (also known as Selective Laser Melting, Laser Beam Melting and Laser Sintering), one of the most common techniques for metal AM (Wohler's Associates, 2016).

Powder Bed Fusion was compared to conventional manufacturing, and in order to capture the future potential of the technology, three scenarios were formulated. The first was chosen to represent the conventional way of manufacturing a truck engine (scenario S0), and the other two scenarios were chosen to represent 3D-printing of the engine. Scenario S1 represents the state of the technology as it is today, with limitations regarding what materials and sizes of components can be printed. Finally, scenario S2 represents a future case where AM has developed roughly a decade into the future, with the possibility of printing even the largest engine components and to use a wider range of materials.

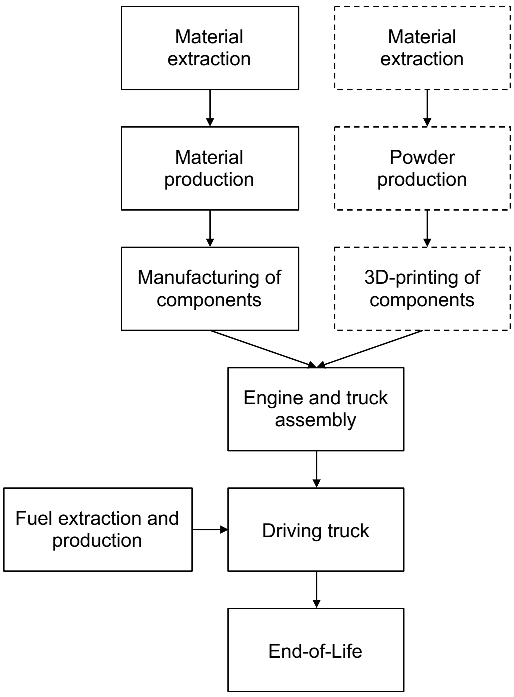

Figure 10. Simplified life cycle of a truck engine. The left part of the flow chart shows conventional manufacturing, the right part 3D printing. In S0 only conventional manufacturing is used, in S1 select components are 3D-printed and in S2 a majority of the components.

LCA was used to quantify the environmental impacts associated with the different stages of the life cycle in each scenario (see Figure 10). Some ways that AM improves environmental performance compared to conventional manufacturing is the design freedom that it enables. Products can in general be redesigned for e.g. less material, lower weight, fewer components or added functionality. For trucks and other vehicles e.g. weight reduction potential is important

The study revealed weight reduction to be decisive for the outcome, and because larger components can be printed in the future scenario S2, a greater total weight reduction of the engine can be achieved (roughly 22%, compared to 6% for scenario S1 representing current technology).

The results showed that 3D-printing of engines does have the potential to reduce environmental impacts from vehicles in the future, even when using consistently conservative estimates and assumptions. As shown by Figure 11, the emissions of greenhouse gases from engine production are higher for 3D-printing (in S1 and S2) than for conventional manufacturing (in S0). However, the impacts from tailpipe emissions and fuel production are decreased, because of the lower vehicle weights (especially in S2). This leads to a potential future net decrease of climate impacts of 15% for AM compared to conventional manufacturing.

It is important to note that in scenario S1, representing current technology, net impacts were only reduced by 3%, and that the future potential comes with some important caveats. Because of the energy intensity of the 3D-printing process, a clean electricity mix is necessary or the production impacts would outweigh the benefits of reduced fuel consumption. Additionally, what materials lend themselves to 3D-printing can be restricted by limitations in AM technology. Materials need to be chosen carefully to avoid negative environmental effects from e.g. substituting low-alloy steel with high-alloy steel or even nickel-alloys.

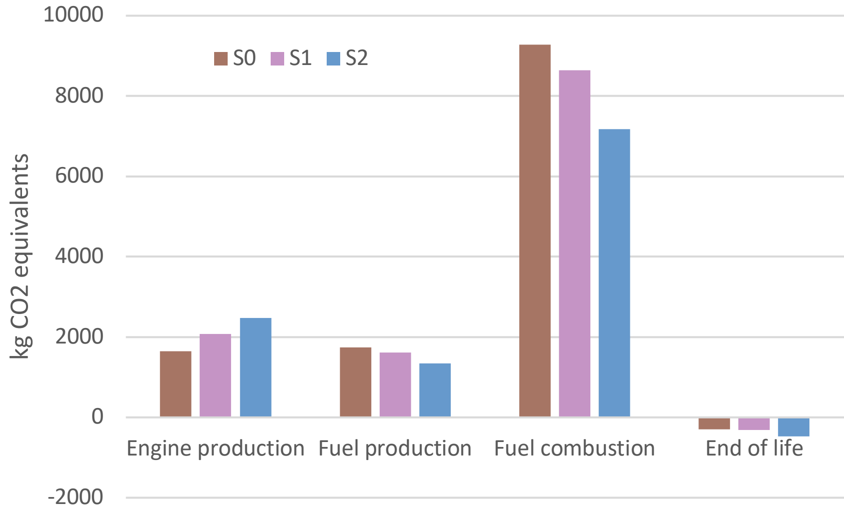

Figure 11. Emissions of greenhouse gases for the different life cycle stages of the engine, as represented by kg CO2-equivalents per functional unit for each scenario S0, S1 and S2, from Böckin and Tillman (2019). The total reduction of greenhouse gas emissions compared to S0 is 3 % for S1 and 15 % for S2.

In summary, the study illustrates two crucial points. First is the trade-off between reducing impacts in different life cycle phases for active products. AM enabled lighter components which gave lower fuel consumption, but in turn the impacts from production were increased.

The second point regards the importance of considering technological development and of estimating the environmental potential of technologies expected to be widely adopted in the future. Omitting future developments in the case study would have given an unfavourable comparison for AM, at the risk of missing out on the future potential of the technology. Conversely, the results indicate limited benefits from implementing AM at the current state of technology, why wide adoption today would be premature. Studies like the one presented here can aid in guiding such development, for example by identifying the need for printing larger components, of low-impact materials and at a lower energy consumption or with clean electricity.

7 Acknowledgements

This research was supported by the Mistra REES (Resource-Efficient and Effective Solutions) programme, funded by Mistra (The Swedish Foundation for Strategic Environmental Research) and Chalmers Area of Advance Production.

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