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## Abstract:
This chapter provides guidelines on measures for resource efficiency (RE) for products with different characteristics. The guidelines target product chain actors, producers and their designers, users and post use actors and are useful also to policy makers and business models developers. They are based on a life-cycle based typology for RE measures, distinguishing what measures may be undertaken in different life cycle phases, extraction and production, use and post use. Product characteristics is argued to be an appropriate basis for identification of RE strategies. For the use phase, it matters whether products are durable or consumable. Durable products are further divided into those using energy and/or auxiliary material during use and those that do not. Characteristics of importance for consumable products are whether they are disposable or used in a dissipative manner. Post use measures depend primarily on material properties while measures in the production phase are largely independent of product characteristics.

Keywords: resource efficiency, guidelines, measures, product characteristics, product life cycle, design

## 1. Introduction

Circular economy (CE) is a practical change-oriented concept. That is why guidelines and handbooks, such as this book, for bringing CE about are of interest. Indeed, several guidelines for a circular and more resource efficient economy already exist. Some of these address policy makers and what they can do to promote the circular economy (CE), for example OECD (2016) and EMF (2015). Others, such as WBCSD (2017), Benton et al. (2014) and Mont et al. (2017) aspire to guide business leaders towards a circular economy. Some guidelines point to the importance of industrial sectors when analysing preconditions for CE (EMF, 2015). Analysis and action on the level of products has long been recognized as important for resource efficiency (RE) in general and CE in particular, as manifested in the multitude of existing eco-design guidelines as reviewed by Pigosso et al. (2015) and Rossi et al. (2016). Several of these specifically address design enabling circular measures, such as design for recycling (Kriwet et al., 1995), design for disassembly (Bogue & Lowe, 2007), design for maintenance (Desai & Mital, 2006) and design for remanufacturing (Ijomah et al., 2007), together often denoted design for X (Chiu & Kremer, 2011). More recently, design guidelines explicitly departing from CE have been issued (Bakker et al., 2014a; Haffmans et al., 2018).

Although the potential for RE over the life cycle of a product is largely decided in the design phase, for such potentials to be realized all the actors along the product chain must do their part; producers must manufacture the product in a resource efficient manner, users must use the product with as little energy and other auxiliary resources as possible, for as long as intended (or longer), maintain it properly and when the product is finally discarded send it to appropriate post use handling. Collection organizations, remanufacturers and recyclers must in turn do their bit. All these actors are influenced by the business contexts in which they work as well as by product policies. Guidelines for resource efficient products are thus of relevance to all actors along the product chain as well as to designers, policy makers and business managers.

This chapter aims at giving guidance to measures for RE on the level of products. It is limited to physical measures for RE, 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. The term *product* is used to denote both products, services and combinations thereof.

Prominent in the literature guiding towards CE are prioritized lists of physical measures (often denoted R-frameworks) such as reuse, repair and recycling. These depart from the waste hierarchy, the European version of which prescribes the following order of priority in waste legislation and policy: prevention, preparing for reuse, recycling, recovery and disposal (EC, 2008). In other guidelines, the granularity in descriptions of prioritized measures is increased, up to nine different measures (Potting et al., 2017). Kirchherr et al. (2017) argue that such prioritization is a vital element in the definition of CE, to provide proper guidance and not open up for green-washing. However, as pointed out by Ljunggren Söderman and André (2019), the measures outlined in the R-frameworks are idealised descriptions which do not account for real-world conditions like insufficiently exploited lifetimes, low collection rates and losses in remanufacturing, repair and recycling and their grounds for prioritisation is unclear. Measures sometimes also depend on one another. For instance, the pursuit of increasing reuse requires management of product flows which can also entail increased recycling (see for example André et al. (2019)). In such cases, it is not necessarily meaningful to make priorities between them. Blomsma and Brennan (2017) introduce the concept of *circular configurations* for several different measures working together in sequence or parallel.

The prioritized lists of CE measures are hence not directly applicable on a product level. Rather, what measures for resource efficiency are applicable and most effective in improving RE depends on the characteristics of the product. This has been argued in life cycle design literature, by Rose et al. (2002) and Vezzoli (2018), and in our own work (Böckin et al., 2019). The arguments are that products differ in character (for example some are durable and some disposable, some use energy during use while others just sit there, some are complex while others consist of few components or materials) and that there exist trade-offs between phases in the product life-cycle and between different types of environmental impact and resource use.

We have in previous work synthesized results from a large number of life cycle-based assessment studies of RE measures for diverse products (Böckin et al., 2019). A life-cycle based typology of RE measures was used as an analytical framework, together with a list of product characteristics of relevance for RE. The results included identification of what RE measures are suitable for products with different characteristics, using RE measures as point of entry. Trade-offs associated with different RE measures were identified along with number of key product characteristics decisive for the outcome of RE measures. In this chapter, these results are reformulated into guidelines where product characteristic is used as point of entry, guiding towards suitable measures.

## 2. A life cycle-based typology for RE measures

If, as argued, prioritization is not the most suitable basis for structuring measures for RE, some other principle must be sought. The product life cycle presents such a principle, found to be useful in many other contexts, such as eco-design (Vezzoli, 2018) and life cycle management (Sonnemann & Magni, 2015). In the typology developed by Böckin et al. (2019) RE measures are sorted according to where in the life cycle they can be undertaken: *extraction and production*, *use phase* and *post-use* (Figure 12.1). The typology draws on eco-design guidelines as described by Ceschin and Gaziulusoy (2016) and Sundin (2009), for example the Ten golden principles (Luttropp & Brohammer, 2014) and the Eco-design strategy wheel (Brezet & van Hemel, 1997). It also draws on other frameworks in the CE literature (Allwood et al., 2011; EC, 2008; EMF, 2013; Potting et al., 2017; Stahel, 2010; Stahel & Clift, 2016).

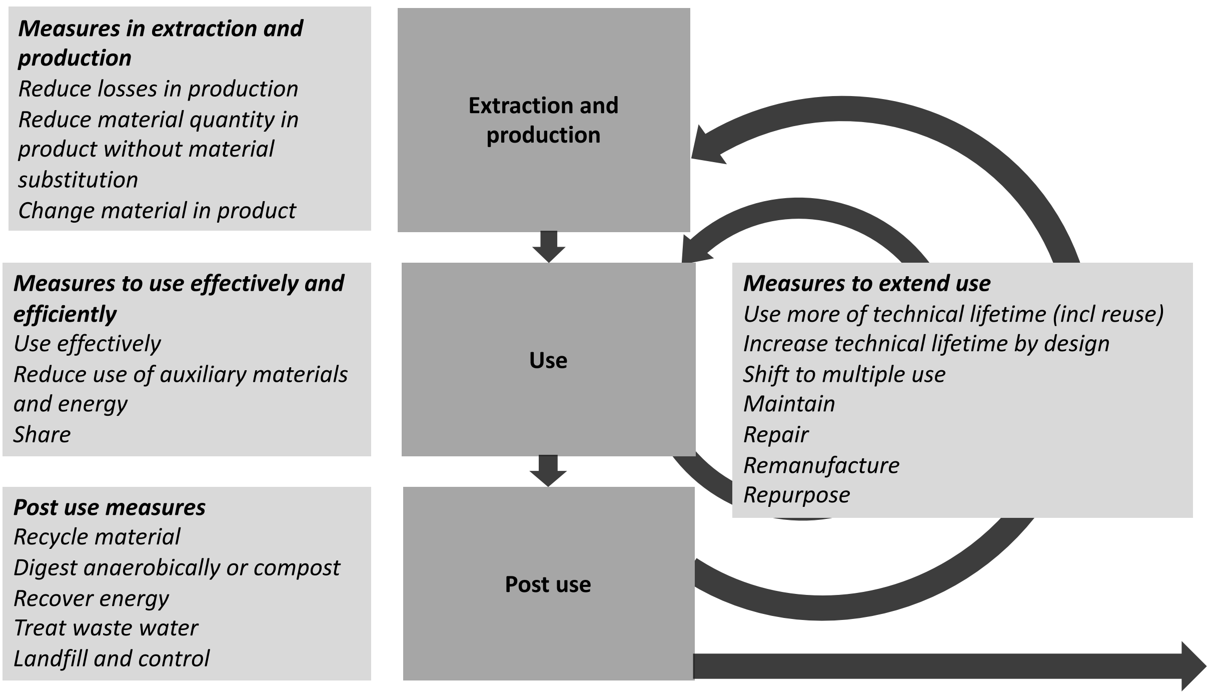


*Figure 12.1. Life-cycle based typology of physical RE measures, based on Böckin et al. (2019).*

The life cycle phase *extraction of raw materials and production* (c.f. Figure 12.1) can be made more resource efficient for all types of products through reduced use of material and energy. Process related measures such as reduced scrap rates and reduced energy use can *reduce losses*. When losses do occur, they can be valorised, internally or externally. There are also design related measures pertinent to the production phase. These include design of products to *use less material, without material substitution*. The *material used in in the product* may also be *exchanged*. Material substitution can increase RE in itself or enable other measures.

For the use phase there are two principal ways to achieve RE, either to use products more *efficiently and effectivel*y, or to *extend their use*. *Extending the use*, or prolonging the product lifetime, is where many of the loops in CE come in, such as *reuse, repair, refurbish, remanufacture and repurpose* (Potting et al., 2017).Here, some of these have been collapsed, while *maintain* has been added as well as *increase lifetime by design* and *shift to multiple use*. All the measures to extend the 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 RE in the use phase is to *use products more effectively and efficiently*. Such measures are applicable to durable and consumable products alike.

To *use effectively* means to deliver (which is relevant for a provider) or acquire (which is relevant for a customer) function according to user's needs as well as to make sure 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.

In contrast, to *use a product more efficiently* means to reduce the use of energy or auxiliary material during use. This measure is applicable to durable products which use energy or auxiliary material during use. *Sharing* products between several users, finally, is a way to get more function out of a product before it is deemed obsolete.

After use (here denoted *post-use* rather than end-of-life, which is a more common term, but with less circular connotation), r*ecycling* recovers and returns materials to use. Biodegradable materials can be *digested anaerobically* or *composted,* yielding biogas, plant nutrients and soil enhancers. *Energy recovery* recovers combustible materials into energy carriers such as heat and electricity. *Waste water treatment* handles waste collected via sewers and sometimes recovers energy and plant nutrients. *Controlled landfills* control 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 12.1.

## 3. Product characteristics of relevance of RE measures

From the above it is clear that not all measures are equally suitable to all kinds of products. The following product characteristics have been identified as key to what RE measures are relevant (Böckin et al., 2019).

Whether a product is *durable* or *consumable* directly influences what RE measures are applicable. Durable products are further divided into *active products* (e.g. buildings and vehicles) which use energy and/or auxiliary material during use and *passive products* (e.g. furniture) which do not require auxiliaries during use. For consumable products there is a difference between *disposable products* (e.g. packaging and single-use products) which remain as distinguishable items after use and *products used in a dissipative manner* (e.g. food, energy carriers, cleaning agents) which are literally consumed during use.

Many products *develop at a high pace*, technically or aesthetically or both, which affects what RE measures are suitable. In particular, for active durable products which develop towards use phase efficiency the gains of a longer product life may be outweighed by savings if replaced with a new more efficient product. This trade-off is well recognized in RE literature (see for example ISO (2002), Bakker et al. (2014b), Boustani et al. (2010), Richter et al. (2019) and Ljunggren Söderman & Andre 2019) and will be referred as *use life efficiency versus benefits of use extension*.

*Product complexity* is often discussed as a key characteristic for the effectiveness of restorative measures and recycling for example in (Ceschin & Gaziulusoy, 2016; Luttropp & Brohammer, 2014; Sundin, 2009) and (Ljunggren Söderman & André, 2019).

## 4. Guidelines – what measures suit what kind of product?

In the following we present what measures are suitable (and sometimes even possible) to apply, depending on product characteristics. Sections 4.1 and 4.2 pertain to the *use phase* for durable and consumable products, respectively, each with sub-characteristics of relevance for RE measures. Section 4.3 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*, discussed in section 4.4, there is no clear relation between product characteristics and what RE measures are more suitable. As mentioned, the guidelines build on Böckin et al. (2019), in which references to the assessment studies underpinning them may be found.

### 4.1. Durable products - use for longer, use more effectively and efficiently, share

Table 12.1 shows what measures related to the use phase can be applied to durable products, depending on their characteristics. The table also provides examples of products exhibiting the respective characteristics, concrete examples of the measure and potential trade-offs. As many products have more than one characteristic relevant to RE measures, examples appear in several entries.

As shown, *all durable products* can be *used more effectively*. That implies to provide, or use, products with appropriate, i.e. needed, function, but not more than that. There are no identified trade-offs between different life cycle stages or different types of environmental impact associated with effective use.

More effective use of products challenges profound features of our modern economic system and its consumption culture. For instance, specification above needs (such as cars able to run way faster than what speed-limits allow) is often used as a sales argument by providers and a corresponding status marker by customers.

Most *durable products* can also be given a longer life, through restorative measures such as *maintenance, repair and remanufacturing*. For these measures there are some trade-offs. They usually require transport, either of staff delivering the service, or of the product, to a workshop or similar. In addition, spare-parts need to be produced and transported. There is a risk that associated environmental impact outweighs the benefits of use extension. In addition, designing products to be maintained, repaired or remanufactured may come at the price of more (or more impacting) material being used. For condition monitoring, equipment such as sensors is used, which cause environmental impact. For active durable products the use life efficiency versus benefits of use extension may come into play.

A*ctive durable products* may also be *used more efficiently*, *using less energy, water or other auxiliaries during use*. Use phase efficiency can be enabled by design, but also depends on user behaviour. User dependency may sometimes be designed out, such as showers not allowing more than a certain water flow and lights turning off when no one is in the room. Efficiency during use often comes at the price of more material and components, or more sophisticated ones, being invested in the product. This goes for electrified vehicles (EVs) where more energy is used for production of EV drive trains than for those of internal combustion engines (Nordelöf et al., 2014). A similar trend can be observed for buildings, where more energy is embodied in materials in low energy buildings compared to conventional ones (Mirabella et al. (2018).

Investment in new features is however not always necessary for more efficient use, which may then seem like the obvious thing to do, not only to save natural resources but also to reduce cost. And yet, much equipment is kept idling, in industries, offices and homes at additional cost and to little use. In many cases different cost structures would help create incentives for RE, for example if operational costs are made visible to users rather than hidden among fixed costs or over-heads.

Some *durable products* are *typically used for their full technical lifetime*. They are then not repairable when deemed obsolete and will not lend themselves to resale. In such cases the user cannot do much, but the producer can. Such products can be *designed to last longer* and to be easier to maintain, repair and upgrade. There are some potential trade-offs associated with design for durability and repairability. More durable products may require more and/or higher quality material and for active products the use life efficiency versus benefits of use extension comes into play. There is also a risk that products with a modular design are needlessly upgraded (Agrawal et al., 2016).

In other cases, *products that are not worn out* are *discarded*. This is common for example for clothes, furniture and electronics. In such cases *more of the technical lifetime can be used*, by the same user or through passing it on via second-hand sales. A potential trade-off is if second hand sales requires much transportation. For passive products there are no other associated trade-offs, whereas for active products it may be better to replace the product if use efficiency is considerably better in newer products.

Durable *products that are typically not worn out* and are *used infrequently* can also be *shared*. This is another way of getting more function out of products before they are discarded. Examples include car-pools, clothing libraries and shared tools. In some cases, the function of products can even be used by several users simultaneously, such as ride sharing. Sharing can only be environmentally beneficial if the total function delivered by each product on average is higher than if the products are owned by individuals. For example, for clothing libraries, the number of times garments are worn must be higher than if they are privately owned. Further, if shared stock is accessed by car transportation, the benefits of sharing may be negated (Mont, 2004; Roos et al., 2015).

Lastly, in cases where *part of the function of a durable product remains* at the point of discarding, the life of the product or its components may be extended though *repurposing* for a different application. An example would be the reuse of automotive batteries for energy storage in stationary installations (Tong et al., 2017). Also for this measure the use life efficiency versus benefits of use extension comes into play.

Table 12.1. 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 using 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<br><br>Repair after wear, malfunction or failure<br><br>Remanufacture: restore product to functional state as good as new (or better) | – Maintenance, repair and reman can increase transportation<br>– Products designed for disassembly may use more material<br>–Benefits of longer use vs impact from sensors<br>For active products with technological development towards use-phase efficiency:<br>– 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<br><br>– Reduced use phase impact vs impact from sensors in cases when required |
| **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<br>For active products with technological development towards use-phase efficiency:<br>– 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<br>For active products with technological development towards use-phase efficiency:<br>– 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:<br>– No identified trade-offs<br>For active products with technological development towards use-phase efficiency:<br>– Use-phase efficiency vs benefits of use extension |

## 4.2. Consumable products – use effectively or shift to multiple use

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.

As mentioned in section 3, we distinguish consumable products used in a dissipative manner from disposable products. As seen in Table 12.2, products *used in a dissipative manner* can be *used more effectivel*y. Losses during use can be avoided and only needed function and amount provided (or used). Often, when products used in a dissipative manner are used effectively (e.g. water and energy used in a building), this correlates with efficient use of an active durable products (the building through which energy and water flow).

An interesting example relevant to some products used in a dissipative manner is when improved functionality leads to RE on a system level. Examples include detergents allowing lower washing temperature and fuel additives increasing engine efficiency.

There are few trade-offs associated with using consumable products more effectively. An exception may be when sensors are required, in which case there is a potential risk that the environmental impact from sensors overrides the benefits of the effective use. Also, when more potent chemicals are used for system efficiency they may pose a higher environmental risk.

Design and marketing play roles for effective use. Large packaging sizes, or offers of two items for the price of one, risk lead to losses during use. Smart dispensing, on the other hand, enables effective use. An example is the soap foam delivered by certain dispensers, more or less forcing use of less soap per cleaning.

Turning to *disposable products*, they may also be *used more effectively*. There are no associated trade-offs, except possibly when sensors are required.

*Disposable products* may also be redesigned *for multiple-use,* and users can choose to purchase such products. Examples include refillable bottles, rechargeable batteries and reusable machine components such as filters. The trade-off is that producing a multiple-use product usually requires more resources and causes more environmental impact, per item, than producing a disposable alternative. The multiple-use product must then be used enough times for the "investment" to break even. In addition, all multiple-use products require maintenance between uses, such as washing or recharging, to which transportation is sometimes needed.

We often equal disposables to packaging and disposable consumer goods. However, it is worth noting that many durable devices contain disposable components which are replaced regularly, for example toner cassettes in printers, batteries in electronic devices and the many components replaced in a vehicle during its life. Also heavy industrial machinery contain components which are replaced regularly. Many such components may be turned into multiple-use products or be designed to last longer. (However, if design for durability is a possibility, perhaps they should be seen as durable components in even more durable products rather than as disposables. The line between disposable and durable components is indeed blurry, but we do not expect this fuzziness to reduce the value of the guidelines.)

Table 12.2. 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 using 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:<br><br>– Reduced use phase impact vs production of sensors in cases when required<br><br>– 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 using use (e.g. smart dispensing), use for intended purpose | No identified trade-offs except:<br><br>– 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 |

## 4.3 Post-use measures depend on type of material

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. Discussed in this section is handling of products which have actually been used, often termed post consumption waste, whereas handling of production waste is seen as an aspect of production efficiency, discussed in section 4.4.

What post use measures are suitable depends less on whether products are durable or consumable, and more on their material content (see Table 12.3). The material in most products can be *recycled*, products consisting of biodegradable material can be *digested anaerobically* or *composted* and products consisting of combustible materials can be *incinerated to recover energy*. Some dissipatively used products will end up in sewers and *waste water treatment* plants. Finally, there will always be waste which cannot be handled in any other way than *landfilling* which should be done in a *controlled* manner.

In all post use handling, sorting and separation into well defined material fractions is decisive for the quality of the output. Waste can be sorted while still consisting of distinguishable used products, at the source or after collection. Even so, many, if not most, products consist of more than one type of material, which means that additional separation is often required. For this reason, complexity and level of integration of materials are important for the efficiency of post use measures.

As shown in table 12.3, the material in *most product*s 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 and to material diversity and complexity of products. It can be noted that the measures for product use extension interplay with recycling, since not all products collected for reuse will be reusable. They will then be sent to recycling together with parts replaced during maintenance, repair and remanufacturing.

*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 it is primarily regarded as a soil enhancer (Salomon, 2016). Since only biodegradable material can be composted or digested anaerobically careful sorting of waste fractions is necessary. If products consist of a mixture of degradable and non-degradable materials, the non-degradables should preferably be removed after treatment.

Similarly, only *combustible materials* can be *incinerated,* even though, in practice, many non-combustible materials go into incinerators, where they yield ashes and/or slag. Energy is usually recovered. Air emissions emanate either directly from the incinerated material (such as carbon dioxide and metals) or can be formed during incineration (such as nitrogen oxides and dioxins). In modern large-scale incinerators air emissions are controlled, resulting in solid phase residues which together with ashes and slag are deposited in landfills, sometimes after metals and other materials have been retrieved for recycling.

*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. WWTP clean water before release, while producing useful flows, including biogas, heat and sludge containing plant nutrients. The use of sewage sludge in agriculture is however contested in many countries due to contamination with chemicals and risk for dispersion of pathogens.

*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 stores non-renewable materials, making them available for potential future resource extraction.

Common to all post use processes which recover energy or material resources is that they will improve RE 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. Recycling, incineration and biological treatment lead to less material ending up in landfill deposition, with associated environmental impact.

Table 12.3. 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<br>– Risk of keeping hazardous substances in circulation |
| **Biodegradable products** | **Digest anaerobically** | Biogas<br>Digestate (complete fertilizer and soil enhancer) | – Impacts from digestion need to be smaller than avoided impact from alternative production of its products<br>– Risk of keeping hazardous substances in circulation |
| **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)<br>– 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<br>Heat<br>Sludge containing plant nutrients | - Impacts from digestion need to be smaller than avoided impact from alternative production of its products<br>– Risk for introduction of hazardous substances in the food chain<br>– Risk for dispersion of pathogens |
| **All products** and/or residues from other post-use processes | **Landfill and control** | Not relevant | Not relevant |

## 4.4. All products can be produced more efficiently

In the life cycle phase raw material extraction and production, there is little correlation between product characteristics and means for RE. Even so, *reducing losses in production* through energy and material efficiency is an obvious means to increase RE of products. There are several ways to achieve such efficiency (Table 12.4). Scrap rates and other material losses may be reduced, the energy efficiency improved and by-product energy and material flows utilised, internally through process integration or externally through recycling of pre-consumption waste or other forms of industrial symbiosis. These are just examples from the vast literature on cleaner production. The only identified potential trade-off is when it takes energy (or other resources) to reduce material losses, or to recover scrap and by-product streams.

Also related to production is when less material is used in products. *Reduction of material content, without substituting material*, can be done for most products, but often at the price of reduced functionality, such as durability. There are also light-weight structures with high functionality, such as truss structures.

More commonly, light-weighting is achieved through *changing the material composition* of products. Materials can also be substituted with more environmentally benign materials. 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. There is always a risk for trade-offs between types of environmental impact when substituting materials. Examples include trade-offs between climate impact and impact from land use when substituting fossil-based materials with bio-based and between material scarcity and climate change when substituting scarce materials with energy-intensive nanomaterials. Furthermore, since change of material is often a precondition for other measures there is a trade-off between the benefits of such measures and the impact of the new material.

If the intention of changing to a biodegradable material is to solve a littering problem, it should be noted that "biodegradable" according to some standards means biodegradable under industrial conditions (70°C) (Napper & Thompson, 2019).

Table 12.4. 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<br>– Increase energy efficiency in production<br>– 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<br>– 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:<br>- Bio-based material<br>- Bio-degradable material<br>- Recycled material<br>– Substitute/decrease share of:<br>- Scarce materials<br>- Hazardous constituents | – Risk for burden-shifting when substituting material<br><br>– 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 |

## 5. Needs for new knowledge

These guidelines are based on product characteristics rather than priorities between measures, with the intention of being practically useful. Intended users include actors along product chains, producers and their designers, users and post use actors. We also believe the guidelines are meaningful to those forming policies for RE and those shaping circular business models. But CE is still in a formative phase, and more research can contribute to even more clear guidelines in the future. A few research needs are:

On a practical level, there is opportunity to create a design tool for RE based on these guidelines. More theoretically it would be of interest to compare such a tool to existing eco-design tools and try to understand what CE adds that is new.

More systematic investigation of how different RE measures relate to one another is needed, in particular how they play out under industrial conditions. Although these guidelines have been based on a comprehensive review of existing assessment studies of CE cases (Böckin et al. 2019) many of these were hypothetical. More studies of existing industrial CE cases is expected to more fully reveal the complexity of CE.

Other topics which require more attention are the consequences for RE of on-going trends towards increasing product complexity and how complex products can be designed not to hinder CE.

Finally, this work has made the need for a life cycle management perspective in CE research obvious. Different actors along product chains have different spheres of influence and are able to implement different measures. Questions about "who can do what and what would be their incentives" call for answers.

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## References

Agrawal, V. V., Atasu, A., & Ülkü, S. (2016). Modular Upgradability in Consumer Electronics: Economic and Environmental Implications. *Journal of Industrial Ecology, 20*(5), 1018-1024. doi:10.1111/jiec.12360

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling, 55*(3), 362-381. doi:10.1016/j.resconrec.2010.11.002

André, H., Ljunggren Soderman, M., & Nordelof, A. (2019). Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. *Waste Manag, 88*, 268-279. doi:10.1016/j.wasman.2019.03.050

Bakker, C., den Hollander, M., Van Hinte, E., & ZljLstra, Y. (2014a). *Products that last: Product design for circular buisness models*: TU Delft Library.

Bakker, C., Wang, F., Huisman, J., & den Hollander, M. (2014b). Products that go round: exploring product life extension through design. *Journal of Cleaner Production, 69*, 10-16. doi:10.1016/j.jclepro.2014.01.028

Benton, D., Hazell, J., & Hill, J. (2014). *The guide to the circular economy: Capturing value and managing material risk* Oxford: Do Sustainability.

Blomsma, F., & Brennan, G. (2017). The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *Journal of Industrial Ecology, 21*(3), 603-614. doi:10.1111/jiec.12603

Böckin, D., Willskytt, S., André, H., Tillman, A.-M., & Ljunggren Söderman, M. (2019). Learning from synthesising assessment studies - How product characteristics can guide measures for resource efficiency. *Paper under review*.

Bogue, R., & Lowe, G. (2007). Design for disassembly: a critical twenty-first century discipline. *Assembly Automation, 27*(4), 285-289. doi:10.1108/01445150710827069

Boustani, A., Sahni, S., Graves, C., & Gutowski, T. G. (2010). *Appliance Remanufacturing and Life Cycle Energy and Economic Savings*. Paper presented at the Paper presented at the 2010 IEEE International Symposium on Sustainable Systems & Technology (ISSST), May 17-19, 2010, Arlington, VA.

Brezet, H., & van Hemel, C. (1997). *Ecodesign: a promising approach to sustainable production and consumption*. Paris, France: UNEP.

Ceschin, F., & Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies, 47*, 118-163. doi:10.1016/j.destud.2016.09.002

Chiu, M. C., & Kremer, G. E. O. (2011). Investigation of the applicability of Design for X tools during design concept evolution: a literature review. *International Journal of Product Development, 13*(2). doi:10.1504/ijpd.2011.038869

Desai, A., & Mital, A. (2006). Design for maintenance: basic concepts and review of literature. *International Journal of Product Development, 3*(1), 77-121.

EC. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 november 2008 on waste and repealing certain directives. *Official Journal of European Union*(L 312(3)).

EMF. (2013). *Towards the Circular Economy. Economic and business rationale for an accelerated transition.* Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

EMF. (2015). *Delivering the Circular Economy. A toolkit for policy makers.* Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/publications/delivering-the-circular-economy-a-toolkit-for-policymakers

Haffmans, S., van Gelder, M., Van Hinte, E., & Zijlstra, Y. (2018). *Products that Flow: Circular Business Models and Design Strategies for Fast-Moving Consumer Goods*: BIS PUBLISHERS.

Ijomah, W. L., McMahon, C. A., Hammond, G. P., & Newman, S. T. (2007). Development of design for remanufacturing guidelines to support sustainable manufacturing. *Robotics and Computer-Integrated Manufacturing, 23*(6), 712-719. doi:10.1016/j.rcim.2007.02.017

ISO. (2002). *ISO/TR 14042:2002 Technical Report. Environmental Management – Integrating Environmental Aspects into Product Design and Development*. Geneva, Switzerland. International Organization for Standardization.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221-232. doi:10.1016/j.resconrec.2017.09.005

Kriwet, A., Zussman, E., & Seliger, G. (1995). Systematic integration of design-for-recycling into product design. *International journal of production economics, 38*(1), 15-22.

Ljunggren Söderman, M., & André, H. (2019). Scarce metals in complex products - exploring the effects of circular economy measures. *Paper under review*.

Luttropp, C., & Brohammer, G. (2014). *EcoDesign Roadmap* (1 ed.). Lund: Studentlitteratur.

Mirabella, N., Röck, M., Ruschi Mendes Saade, M., Spirinckx, C., Bosmans, M., Allacker, K., & Passer, A. (2018). Strategies to Improve the Energy Performance of Buildings: A Review of Their Life Cycle Impact. *Buildings, 8*(8). doi:10.3390/buildings8080105

Mont, O. (2004). Reducing Life-Cycle Environmental Impacts through Systems of Joint Use. *Greener Management International, Spring 2004*(45), 63-77.

Mont, O., Plepys, A., Whalen, K., & Nussholz, J. (2017). *Business model innovation for a Circular Economy: Drivers and barriers for the Swedish industry – the voice of REES companies.*: Mistra REES.

Napper, I. E., & Thompson, R. C. (2019). Environmental Deterioration of Biodegradable, Oxo-biodegradable, Compostable, and Conventional Plastic Carrier Bags in the Sea, Soil, and Open-Air Over a 3-Year Period. *Environ Sci Technol, 53*(9), 4775-4783. doi:10.1021/acs.est.8b06984

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment, 19*(11), 1866-1890. doi:10.1007/s11367-014-0788-0

OECD. (2016). *Policy Guidance on Resource Efficiency*. Paris. Organisation for Economic Co-operation and Development. https://www.oecd.org/environment/waste/Resource-Efficiency-G7-2016-Policy-Highlights-web.pdf

Pigosso, D. C. A., McAloone, T. C., & Rozenfeld, H. (2015). Characterization of the State-of-the-art and Identification of Main Trends for Ecodeisgn Tools and Methods: Classifying Three Decades of Research and Implementation. *Journal of Indian Institute of Science, 95*(4), 405-427.

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring Innovation in the Product Chain*. The Hague. The Netherlands: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

Richter, J. L., Tähkämö, L., & Dalhammar, C. (2019). Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts. *Journal of Cleaner Production, 226*, 195-209. doi:10.1016/j.jclepro.2019.03.331

Roos, S., Sandin, G., Zamani, B., & Peters, G. (2015). *Environmental assessment of Swedish fashion consumption. Five garments – sustainable futures*. Mistra Future Fashion. http://mistrafuturefashion.com/wp-content/uploads/2015/06/Environmental-assessment-of-Swedish-fashion-consumption-LCA.pdf

Rose, C. M., Ishii, K., & Stevels, A. (2002). Influencing Design to Improve Product End-of-Life Stage. *Research in Engineering Design, 13*(2), 83-93. doi:10.1007/s001630100006

Rossi, M., Germani, M., & Zamagni, A. (2016). Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. *Journal of Cleaner Production, 129*, 361-373. doi:10.1016/j.jclepro.2016.04.051

Salomon, E. (2016). Fakta om komposterat eller rötat matavfall som fosforgödselmedel *SLU-nyhet*. Retrieved from https://www.slu.se/ew-nyheter/2016/9/fakta-om-komposterat-eller-rotat-matavfall-som-fosforgodselmedel/

Sonnemann, G., & Magni, M. (2015). *Life cycle managment* (G. Sonnemann & M. Magni Eds.). Netherlands: Springer.

Stahel, W. R. (2010). *The performance economy* (2nd ed.). London, U.K.: Palgrave Macmillan.

Stahel, W. R., & Clift, R. (2016). Stocks and Flows in the Performance Economy. In R. Clift & A. Druckman (Eds.), *Taking Stock of Industrial Ecology* (pp. 137-158): Springer, Cham.

Sundin, E. (2009). Life-Cycle Perspectives of Product/Service-Systems: In Design Theory. In T. Sakao & M. Lindahl (Eds.), *Introduction to Product/Service-System Design* (pp. 31-49).

Tong, S., Fung, T., Klein, M. P., Weisbach, D. A., & Park, J. W. (2017). Demonstration of reusing electric vehicle battery for solar energy storage and demand side management. *Journal of Energy Storage, 11*, 200-210. doi:10.1016/j.est.2017.03.003

Vezzoli, C. (2018). Life Cycle Design. In C. Vezzoli (Ed.), *Design for Environmental Sustainability* (pp. 37-56): Springer.

WBCSD. (2017). *CEO Guide to the Circular Economy*. Geneva. World Business Council for Sustainable Development. https://docs.wbcsd.org/2017/06/CEO_Guide_to_CE.pdf