Framework for analysing resource-efficient solutions

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1 Introduction

In a resource-constrained world, the need for an alternative to the current linear flows of materials is more urgent than ever. The take-make-waste practices of modern society are unsustainable, both for economic and environmental reasons. Circular economy (CE) is being presented as a strategy to decrease the use of natural resources, along with other means for resource efficiency (RE).

Ghisellini et al. (2016) describe circular economy as a way to overcome the current production and consumption model based on continuous growth and increasing resource throughput. They advocate the adoption of closed-loop material flows, according to the 3R´s principles: Reduction, Reuse and Recycle. Their work focuses on urban and industrial waste, to achieve better balance between economy, environment and society. The Ellen MacArthur Foundation describes circular economy as an "industrial system that is restorative or regenerative by intention and design" (Ellen MacArthur Foundation 2012). In a circular economy the "end-of-life" idea is replaced by restoration, energy use is shifted towards renewables, use of toxic chemicals is eliminated, and waste is extinguished. All this is suggested to be accomplished through superior design of materials, products and systems, policies and business models (Ellen MacArthur Foundation 2012).

Similarly, there are various definitions of resource efficiency, and yet there is no single commonly accepted consensus definition (Huysman et al. 2015). Bundgaard et al. (2016) suggest that resource efficiency can be improved by either reducing the amount of material used to produce products or by reducing the environmental impact associated with products. In the flagship initiative "A resource-efficient Europe" (European Commission 2011), resource efficiency is seen as a means for avoiding resource scarcity and for reaching climate goals, and at the same time as an opportunity to achieve business competiveness. The resource efficiency concept is considered not only to include the aspects described above as part of the circular economy but also aspects regarding improvements in e.g. production processes. Yield improvement and decreased scrap rates within production processes are examples of such (Allwood et al. 2011). The importance of considering production and production processes are further acknowledged in the European Commission action plan, "Closing the loop", to achieve the transition towards a circular economy. "Even for products or materials designed in a smart way, inefficient use of resources in production processes can lead to lost business opportunities and significant waste generation" (European Commission, 2015).

Within the fields of resource efficiency and circular economy the number of frameworks to systematise the area is increasing. Huysman et al. (2015) established a systematic framework to classify resource-efficiency indicators. ResCom, an EU-project examining Resource Conservative Manufacturing, is working with developing an innovative methodology and software platform for the industrial implementation of closed-loop manufacturing systems (European Commission 2016). One outcome is a framework to be used as a CE implementation strategy, emphasizing the importance of a combined view of the three aspects; environment, resources, and economic benefits (Lieder and Rashid 2016).

However, despite the publications, frameworks and research currently investigating circular economy and resource efficiency, knowledge is still limited concerning the circumstances under which solutions aimed at being resource efficient really lead to the intended outcome. Transition toward a more resource-efficient economy implies the need for increased knowledge of which means for increasing resource efficiency are suitable for different products, value-chains and sectors. Tukker (2015) draws the conclusion that "despite the large number of surveys, statistical data analysis and even meta-reviews, analysing quantitative data from case studies is still rarely applied". Moreover, instruments to enable systematic learning from assessment studies within the RE field are lacking. Against this background an analytical framework was developed and its pilot version is presented in this paper.

The aim of this framework is twofold. Firstly, a typology of ways to increase resource efficiency based on the physical means of increasing RE is formulated. Secondly, the framework is intended to assist systematic learning from assessment studies of resource-efficient products and services, with the ambition of extracting generic learning regarding when, and under which preconditions, presumably resource-efficient solutions lead to the intended outcome.

The framework covers the various physical means to achieve RE and CE, such as production efficiency measures, more efficient use of products, and efforts to close the loops through reuse and recycling. Such measures may be brought about through a wide variety of organisational and administrative efforts, such as policy interventions and new business models. These are, however, largely outside the scope of the framework. Instead, the typology presented focuses on material flows and conveys alternative ways to improve resource efficiency. The framework is moreover intended to function as support for review of assessment studies of resource-efficient solutions. In this respect the framework is mainly aimed at other researchers. However, analyses based on the framework can inform decisions by policy makers and industrial companies on how to steer and reduce material flows, depending on the type of product or offering.

2 Method

Initial work on the framework consisted of literature-based investigations of different means to increase resource efficiency from a product-chain perspective. Resource efficiency measures in production systems (e.g. Allwood et al. 2011) were distinguished from those addressing the use phase and from efforts to close the material loop through circular economy, (e.g. Ellen MacArthur Foundation 2012). A list of means and activities for increased resource efficiency according to the waste hierarchy; prevention, reuse, recycling and eventually recovery of materials and energy (European Commission 2008) was established based on the reviewed literature.

Moreover, the framework was designed for studying assessment studies such as Life Cycle Assessments (LCA), Life Cycle Cost analysis (LCC), and Material Flow Analysis (MFA). Based on the list of different means for RE and the assessment methodologies, a semi-structured literature search was performed and a number of assessment studies for different products and resource-efficient solutions were found.

An initial review of the assessment studies revealed the need to systemise the evaluation process. Important characteristics of resource-efficient and circular economy solutions found in the literature were classified according to different physical changes to achieve RE. The classification was based on aspects that could be expected to be of importance for RE, as found in the literature and according to the experience of the authors. Next, facilitating conditions, such as those relating to the product chain, but also relating to policy, market and user aspects, were noted. Finally, a classification was created of the RE-offerings and the characteristics for the assessment studies and their results.

The development of the analytical framework was iterative. Parallel to developing the different categories and formulating the typology, a systematic review of a selection of assessment studies was made.

3 Typology

This section presents the typology of ways to increase resource efficiency, with a focus on physical measures and material flows.

3.1 Ways to achieve resource efficiency

Three overarching ways to achieve resource efficiency were identified: *efficiency in production and supply-chain measures, more efficient use of products,* and *closing the loops,* as presented in Figure 1.

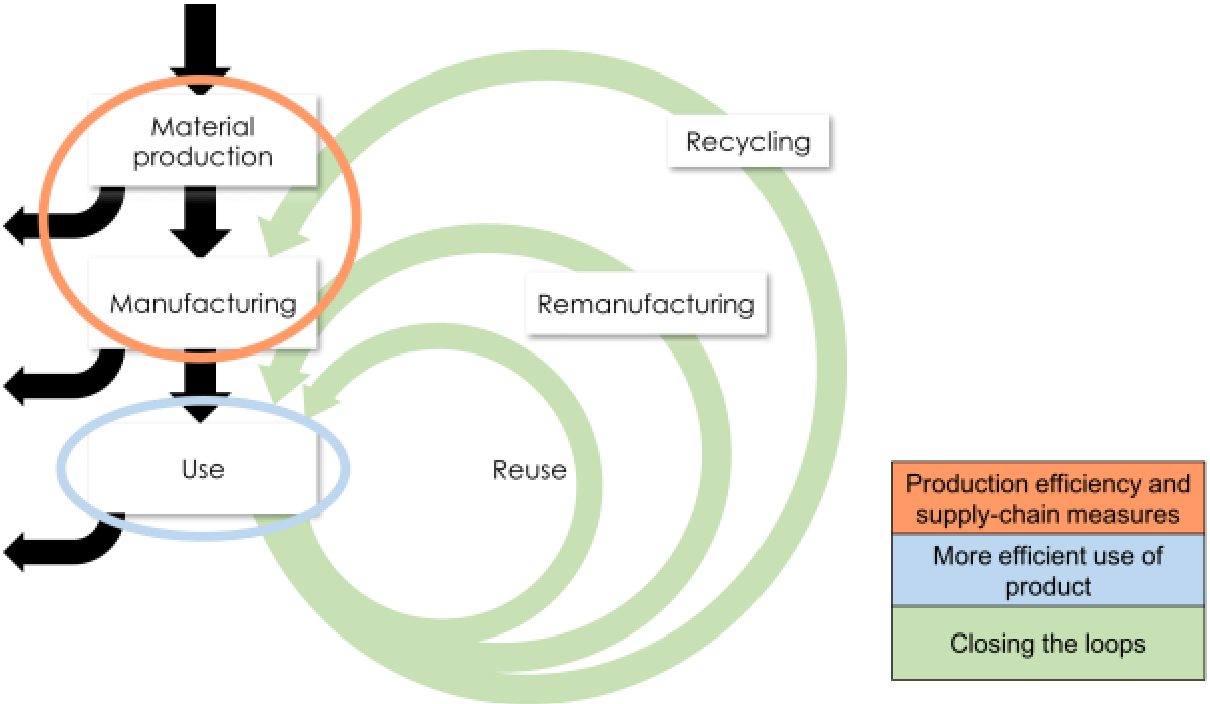

Figure 1. Conceptual picture of the three main ways to increase resource efficiency throughout a product life cycle; efficiency in production and supply-chain measures, more efficient use of product and closing the loop.

Figure 1 illustrates the typology of the framework. The arrows denote the material flows in the product chain, and the flows leaving the system illustrate materials being lost as scrap or waste. The first way to address resource efficiency is to address production and the supply-chain, e.g. through reducing scrap rates and increasing yields. Production losses can then be decreased and an overall increased resource efficiency can be obtained. The second way to increase the resource efficiency is through a more efficient use of the product, e.g. through sharing, prolonging the product lifetime, or improving energy efficiency during use. The third way encompasses different means for closing the loops by reuse, remanufacturing or recycling the product and its materials.

Table 1 presents the typology in more detail. A number of more specific activities were identified for the three ways of achieving resource efficiency. For efficiency in production and supply-chain measures, reduced material use in products and reduced scrap rates were identified. Efficient use of products entails prolonging life, intensifying use through sharing and prolonging product life through maintenance and repair. Closing the loop can be achieved by closed-loop reuse, open-loop reuse, remanufacturing and repair, functional recycling and non-functional recycling. These are described in more detail in the following sections.

Table 1. Typology of the analytical framework conveyed in table format constructed of three different ways to achieve resource efficiency-related activities.

Ways to improve resource efficiency	Activities	
Efficiency in production and supply-chain measures	**Concrete measures** **-physical and infrastructural changes**	**Design measures**
Reduced material use in products **Reduced scrap rates**		
Efficient use of products	**Concrete measures** **-physical and infrastructural changes**	**Design measures**
Prolonged life **Intensified use** **Maintenance & repair**		
Closing the loops	**Concrete measures** **-physical and infrastructural changes**	**Design measures**
Closed-loop reuse **Open-loop reuse** **Remanufacture & repair** **Functional recycling** **Non-functional recycling**		

3.2 Efficiency in production and supply-chain measures

Reducing material by improving the production processes in the manufacturing system of a product is a common way of achieving resource efficiency (Allwood et al. 2011). For example, the journal of Cleaner Production presents a multitude of studies of improved production systems. Two main means of improving RE in production and supply-chain were identified; *reduced material use in products* and *reduced scrap rates*.

3.2.1 Reduced material use in products

A reduction of material decreases the amount of material used in the product. This can either be achieved by changing material or using less of the same material. In both cases the result is less material but maintained function of the product.

3.2.2 Reduced scrap rates

Reducing scrap rates would reduce scrap volumes and waste in the production chain and could include both material and energy. This can be achieved by using resources in a more efficient way to increase yields, by re-introducing the scrap into the production processes or by valorising and using by-products.

3.3 More efficient use of products

Another way to increase resource efficiency is focused on alternative ways of improving the use of the products. This can either be done by *prolonging the life* of the product, *intensifying the use* of a product or providing/improving the *maintenance and repair* of the product. These measures enable a more efficient use and keep the product in the use-phase longer, thus preventing it from reaching the end-of-life phase. The product is assumed to either be kept by the same user or shared among several users.

3.3.1 Prolonged life

A “prolong-life-measure” increases the lifespan of a product. One example of this is designing the product for durability and robustness, e.g. using more or stronger material to increase its technical lifetime (Amaya et al. 2014). Other examples are increased lifespan though changed user behaviour, e.g. using the product for its full technical lifespan or behaviour that inflicts less wear and tear on the product.

3.3.2 Intensified use

Intensified use means that a product is used more times during its lifetime. For products with a low use-frequency this is a suitable solution, since these products can be seen as unexploited resources. Examples include cars and bicycles that are approximately only used twice a day á 15 min (Amaya et al. 2014). This can be accomplished by sharing the product between a few or many owners (Mont 2004). Many different business models are possible to accomplish sharing, e.g. leasing and function sales.

3.3.3 Maintenance & repair

Maintenance of a product is the process of keeping it in good condition. For the purpose of this framework we regard maintenance as an activity performed without changing the user. Maintenance activities are activities that need to be performed to prevent product breakdown, e.g. changing oil, filters, use of lubricants, or simply improve the aesthetic appearance of the product by painting or cleaning it. Moreover, maintenance can also imply change of larger components expected to breakdown or become worn.

Repair returns a failed product to working condition again and thus prevents the product from reaching its end-of-life.

3.4 Closing the loops

Closing the loops as a way of increasing resource efficiency implies reduced material use compared with linear production systems (Ellen MacArthur Foundation 2012). The “tighter” the circle, the less a product needs to be changed, e.g. in order to be reused or remanufactured, and the faster it can be returned to being used again. A “tight” return loop (e.g. reuse as compared to recycling) also implies a higher potential for savings related to the materials, labour, energy and capital embedded in the product and associated environmental impact (Ellen MacArthur Foundation 2012). A large number of closing-the-loop options are mentioned in the literature, such as to reuse, maintain, refurbish, repair, repurpose, remanufacture, up-cycle, recycle, or down-cycle. However, there is considerable overlap between many of these concepts. In our framework we chose to use as simple and inclusive categories as possible, namely re-use (closed loop and open loop), remanufacture & repair, and recycling (functional and non-functional). In line with the waste hierarchy, the above arguments about “tightness” of material loops, the means for RE are listed in descending order, whereas the efforts towards reuse/recycling increase down the list.

Finally, in order to draw a line between *more efficient use* and *closing the loop* strategies, products are considered to belong to the closing the loop category when reused by a new user (as opposed to reuse by the same user, which is regarded as a way to prolong product life).

3.4.1 Closed-loop reuse

A closed-loop reuse denotes a reintroduction of a product for the same purpose, and in its original form, to a new user by providing minimal maintenance interventions or aesthetic improvements. An example is the reuse of a photocopier after quality assurance (Kerr and Ryan 2001).

3.4.2 Open-loop reuse

Open-loop reuse conversely means that the product is reused but for a new purpose, in a new context and with a new function, often due to deteriorating performance (so called repurposing). It requires merely minor maintenance interventions. An example of this is using a battery from an electric vehicle, discharged due to decreased performance capacity, as an energy storage in a PV-system. We consider it important to distinguish between closed-loop reuse and open-loop reuse, since different preconditions and activities may be needed to achieve these different solutions.

3.4.3 Remanufacturing & repair

Remanufacturing is the process of restoring a non-functioning product to its functional state and bringing it back to a good as new or even better state (Parker and Butler, 2007). The process itself includes disassembling, repairing or exchanging components, re-assembling, quality assurance and aesthetic enhancement. This can vary from very small interventions that thus only require small repairs or exchanges of components with minor aesthetic enhancements, to large interventions including major reparation activities and exchange of the majority of the inner components and moreover require a number of activities to improve the appearance of the product. Functioning parts can be taken out and rebuilt into a new product. Remanufacturing is seen as an activity that "brings the product back to life" and thus is an end-of-life activity, while maintenance is instead done during the product lifetime. Moreover, remanufacturing can include activities defined as upgrading, which entail the use of components or the product to produce a new product, e.g. designing and producing new clothes from secondhand clothes.

3.4.4 Functional recycling

Functional recycling is a recycling process in which the properties and function of a material are maintained, thus replacing the need for extracting virgin raw materials (adapted from Guinée et al. (1999) and Graedel et al. (2011)). This can either be done by reintroducing the material into the same product chain as before, *closed-loop functional recycling*, or into a separate product chain, *open-loop functional recycling*.

3.4.5 Non-functional recycling

Conversely, non-functional recycling means recycling of a material without retaining the material properties and the function of the material. The quality is lowered and the material therefore cannot be used for the same function once again (Graedel et al. 2011).

3.5 Concrete measures and design measures

All the measures described above may be brought about through design measures and/or other concrete measures related to the physical product or related infrastructure. These are noted as entities of their own in the framework (see Table 1), instead of as part of the typology itself. Rather, when using the framework to systematise learning from assessment studies there is a need to note what the specific study more concretely concerns. Examples include the reduction of material use in a floor maintenance solution (Larsson 2009), reduction of scrap rates in production of a temporary building (Smidt Dreijer 2013), prolonging the lifetime of a core-plug through changing the material (Lindahl et al. 2014), or the remanufacturing of photocopiers by making them modular (Kerr and Ryan 2001). Concrete changes may also be needed for the infrastructure around the offering, e.g. when introducing a maintenance activity for a bicycle sharing scheme, physical maintenance stations are required (Amaya et al. 2014).

Design change is noted as an entity of its own, design being a key enabler of different means for RE, such as design for changed material, design for durability, and design for disassembly, etc.

3.6 Facilitating conditions

Although the focus of the framework is on physical measures to achieve RE, many assessment studies are made in the context of a changed business model or some policy intervention. Such contextual aspects are noted as facilitating conditions in the framework. Moreover, it should be noted that the division between the external facilitating conditions and the activities related to the concrete measures and design measures is that the latter have implications on the actual material and energy use. In contrast, facilitating conditions in terms of policies, business models and user behaviour, do not have direct implications in the same way on the material use. They were classified as conditions regarding the *product chain*, *policy and market*, and *user behaviour*, as presented in Table 2.

Table 2. Typology of ways to improve resource efficiency together with facilitating conditions for product chain, policy and market, and user behavior.

Ways to improve resource efficiency	**Facilitating conditions**		
Efficiency in production and supply-chain measures	**Product chain**	**Policy, market**	**User behaviour**
Reduced material use in products			
Reduced scrap rates			
Efficient use of products	**Product chain**	**Policy, market**	**User behaviour**
Prolonged life			
Intensified use			
Maintenance & repair			
Closing the loops	**Product chain**	**Policy, market**	**User behaviour**
Closed-loop reuse			
Open-loop reuse			
Remanufacture & repair			
Functional recycling			
Non-functional recycling			

3.6.1 Product chain

Facilitating conditions related to the product chain or the organisation around the product can be of importance when it comes to realisation of a resource-efficient activity. This could be e.g. having a collection system and thus enabling closing-the-loop solutions, such as a secondhand store with furniture and clothes (Castellani et al. 2015).

3.6.2 Policy and market

The market for the product and policies influencing the product and its market are two important aspects for the feasibility of a resource-efficient solution. For instance, public procurement can affect the market substantially. Legal requirements have an impact on both the market and the companies operating in it, with some directly affecting the possibility of implementing a certain type of solution. Lastly, market forces such as the demand for a sharing solution and a willingness to shift ownership are decisive for success.

3.6.3 User behaviour

Facilitating conditions related to user behaviour could be connected to a number of aspects. User behaviour decides whether the product is used for its full functional lifetime or is decommissioned while functioning. It is also the user who decides what to do with the product when it has reached its end-of-life, e.g. whether to donate it for secondhand sales, to recycle it or to simply discard it as waste. In a sharing system user behaviour also influences the need for maintenance.

4 Systematise learning from assessments

The second aim of the framework is to enable systematic learning from assessment studies. To achieve this, firstly a characterisation of the offering was needed. Secondly, the type of assessment study and its key features needed to be noted. Thirdly, the most important results from the assessment study identified by the authors needed to be summarised. The fourth and last category enables the analyst to include his/her own most important reflections on the study in a non-constrained manner.

4.1 Offering characteristics

The characteristics in the framework cover a broad spectrum of aspects connected to the physical product and its surrounding system. Table 3 distinguishes the characteristics of the conventional and alternative, supposedly more resource efficient, offering and enables the analyst to detect the differences between the two.

Table 3. Matrix of offering characteristics to enable generic information about two offerings studied in the assessment study.

Offering characteristics	Conventional offering	Alternative offering
Type of offering		
Function of offering		
Main measure		
Sector		
Type of business		
Fast technological development		
Fashion-driven		
Lifetime		
Energy-intensive use phase		
Component in larger product		
Product structure complexity		
Material diversity		
Consumable product		
Consumable components		
High maintenance needs		
Low frequency of use		
Scarce materials		
Toxic materials		

The inclusion of each category is based on understanding from the literature as well as on the experience of the authors of the aspects that are relevant from a life-cycle perspective.

4.1.1 Type of offering

An assessment study is related to an offering and is either a product, service, or a combination of the two. This category states which type of offering has been investigated in the analysed study. Examples include products such as a mobile phone or a car, and services such as façade cleaning or combined product/service offerings such as car pools.

4.1.2 Function of offering

The function of an offering is what is delivered by it, e.g. communication (e.g.by means of a landline phone or mobile phone), washing clothes (using private or collective washing machines), or transportation (by car, bicycle or bus). Stating the function enables comparison between offerings.

4.1.3 Main measure

The main measure denotes the activity that makes the alternative offering potentially more resource-efficient. Examples include reducing material use in production by changing material, more efficient use of products by introducing a sharing solution, and closing the loops by remanufacturing the product.

4.1.4 Sector

The sector states the business sector the offering belongs to, e.g. transportation, hygiene products, or food sector. The sector a product belongs to could have a bearing on its characteristics and performance. This has been investigated in the project "Resource efficient business models" conducted by the Royal Swedish Academy of Engineering Sciences (IVA 2015).

4.1.5 Type of business

The intention of this category is to distinguish between types of business setups, i.e. business with other companies (B2B), business to consumers (B2C), and business to governance or public organisations (B2G). Depending on the type of business, different business models can be more or less feasible, different regulations may affect the operations, or the user behaviour might differ and consequently the demands upon the product may differ. For example, B2C, which entails consumer products, are often fashion-driven with other demands on the product than for B2B products.

4.1.6 Fast technological development

Rapid technological development makes certain product types out-dated in a relatively short time. Computers are one example, where both energy efficiency, software and capacity develop rapidly.

Moreover, new technological products tend to contain more electronic components, and thus more scarce materials (Greenfield and Graedel 2013). Another important aspect is the possibility that a high speed of innovation undermines the economic potential of reuse and of leasing schemes (Tukker 2015).

4.1.7 Fashion-driven market

In a fashion-driven market commodities are discarded when the aesthetic appearance is out-of-date and not when the function has failed, which results in a higher consumption. Another consequence can be a large secondhand market with an inflow of products that can be seen as out-of-date, but are still well functioning.

4.1.8 Lifetime

The lifetime of a product expresses the expected time a product should last before it reaches its end-of-life. For a long-lasting product the lifetime is important for the overall RE, in contrast to fast moving consumer goods such as washing detergents, diapers and toilet paper. Having a long lifetime can e.g. make the product more suitable for a sharing scheme, since a product with a long lifetime is often robust and resistant to wear and tear.

4.1.9 Energy intensive use phase

An offering with an energy intensive use phase is one that requires a large amount of energy in the use phase, e.g. cars, lamps or fridges. Trade-offs could exist regarding e.g. remanufacturing of such products, which keeps obsolete products on the market (Smith and Keoleian 2004).

4.1.10 Component in a larger product

There are often high technical demands and specifications on components in a larger product. These might limit innovation for RE, but may also drive innovation. Being a component in a larger product also affects the reusability of the component and possible remanufacturing activities are also affected e.g. by the mounting of the component.

4.1.11 High product structural complexity

A product with a complex structure and many components that are integrated can be said to be a product with high structural complexity. This characteristic makes the product difficult to disassemble. Design for disassembly could enable remanufacturing of a more complex product (Sundin et al. 2009). On the contrary, a product with few materials and simple structure potentially facilitates maintenance, remanufacturing of the product and functional recycling of the materials in the product.

4.1.12 Material diversity

Material diversity means having a high variety of materials in a product, e.g. vehicles and electronics. The possibility to recycle a product or its components is connected to how many types of materials the products consist of and in what way these are integrated with each other. High material diversity combined with a complex product structure could hinder closing-the-loops. Having fewer materials, clustering of similar materials, being designed for disassembly, or labelling of the constituent materials, would increase the possibility for functional recycling (Sundin et al. 2009).

4.1.13 Consumable product

A consumable product is one that is either directly or gradually consumed (e.g. food and toothpaste), or is a product that significantly declines in quality and function while being used (e.g. a battery). Having a consumable product may hinder the possibility for closing-the-loop solutions due to the nature of the product. Instead improvements in production, supply-chain, function, or end-of-life measures could be more suitable.

4.1.14 Consumable components

A product containing consumable components has components that regularly need to be replaced in order for the product to function. Vehicles are a good example of products containing many consumable components; batteries, oil, oil filters and brake blocks, to name but a few. Moreover, having a product with consumable components is often concomitant with having high maintenance needs.

4.1.15 High maintenance needs

An offering with high maintenance needs includes a product that needs to be regularly taken care of in order to function. This could be lubrication of mechanical parts, regular performance-tests to assure that components are in good condition, or regular external cleaning. Products with consumable components or a product with high frequency of use may require a high maintenance. Having a traditional business model with product sales for this product type can in some cases include having a large after-sale market with different maintenance activities, e.g. component exchange or lubrication. On the contrary, a business model with the ownership shifted to the producer would make the after-market sales a cost for the producer and thus create an incentive to improve the offering and reduce the need for maintenance.

4.1.16 Low frequency of use

A product with a low frequency of use is not efficiently used, even if the product is functioning. The degree of low frequency of use can be between once a year, e.g. the use of a drill in a household (Mont 2004), to use twice a day for 15 minutes, such as the use of a bicycle (Amaya et al. 2014). A high frequency of use product is a product that could be used many times per day or for a long period of time every day, e.g. mobile phone, bed or floor.

A product could be used more efficiently by being shared among several users, consequently resulting in a lower consumption of the product in total and thus lower material use (Mont, 2004). On the other hand, if the product has a high frequency of use, increased maintenance could be required during its lifetime for it to function effectively, for example a floor that needs to be polished and cleaned (Larsson 2009).

4.1.17 Scarce materials

Scarce materials, such as rare earth metals, are increasingly used in products due to e.g. the increased amount of electronics in new technology (Greenfield and Graedel 2013). Moreover, scarce materials are often used in very small amounts and due to this fact may be difficult to functionally recycle.

4.1.18 Toxic materials

Toxicity is the degree to which a substance can damage or be harmful to an organism and toxic materials are substances that can cause this damage. A product containing a toxic material can release toxic substances during use due to leakage in many potential ways. Release to air (e.g. VOC in paint) or to water (e.g. silver in socks) during use or during recycling into both air and water. This could be a hindrance for reuse or recycling, as the toxic substance might be maintained in the product for a long time, even after the substance has been prohibited, e.g. additives in plastic.

4.2 Assessment study characteristics

As a further support for systematic learning from assessment studies, characteristics describing the type of assessment study are investigated. In Table 4 the analyst documents the methodological characteristics of the study.

Table 4. Matrix for summarising assessment study characteristics.

Assessment study characteristics	Comments
Goal	
Assessment method	
Functional unit	
System boundaries	
Geography	
Time perspective	
Environmental indicator	
Economic indicator	
Material use indicator	
Energy use indicator	
Key assumptions	

4.2.1 Goal

The goal of the assessment study sets the boundaries for what aspects are to be included in the study and also which perspectives are adopted and considered important.

4.2.2 Assessment method

Different assessment methods have different scopes, and thus include different aspects. For example, LCA studies analyse the environmental impacts connected to a product life-cycle, LCC studies analyse the costs connected to a product life-cycle and MFA studies quantify the stocks and flows of materials in a specific system.

4.2.3 Functional unit

Whether the study is a LCA, LCC, MFA or similar, stating the functional unit is a central part of the assessment methodology. The functional unit is the unit that all flows and results are related to. An example for a drill is "fulfilling a drilling function for 10 years, for 10 households". The functional unit reveals what the focus of the study is and enables comparison between alternatives. It can be used to distinguish between which conclusions can (or cannot) be drawn from the study.

4.2.4 System boundaries

The system boundaries denote which aspects are included in the system under study and to a large extent determine what type of result and conclusions can be drawn from the study (Baumann and Tillman 2004). For example, if the system boundaries are cradle-to-grave, instead of cradle-to-gate, this provides information on the whole product system and makes it possible to draw conclusions about the use-phase, which is often important.

4.2.5 Geography and time perspective

Stating the geographic location of the study could be of use to determine if the results are location-specific or not.

It is also important to understand whether the case concerns a hypothetical system, the current system, past systems or a future system. The time perspective provides important information, since the conclusions drawn from an assessment of a hypothetical case could be limited due to the lack of real data. Another possibility is that the assumptions made for the system may no longer be valid if the study regards a past system.

4.2.6 Environmental and economic indicators used

Knowing the environmental and economic indicators used in the assessment hints at the level of detail in the results. For example, presenting the environmental impact such as global warming potential in CO_2-equivalents rather than presenting the total impact in a more aggregated format, such as eco-point, provides more detailed information and makes it possible to detect which environmental aspects are investigated in the study.

4.2.7 Material and energy use indicator

These indicators offer the possibility to acquire knowledge on whether the study explicitly investigates material use or energy use.

4.2.8 Key assumptions

Key assumptions denote highlighting assumptions made in the assessment that are significant for the focus of the study, such as the system boundaries.

4.3 Results from assessment study

After identifying the traits of the assessment study, its results are collected. If the study is of a comparative nature, the results from the "conventional offering" are presented in one column and the "alternative offering" that aims to be more resource efficient is presented in a separate column.

Table 5. Matrix for noting results from assessment study for a conventional and alternative offering.

Results from assessment study	Conventional offering	Alternative offering	Comments/ general
Results (material)			
Results (energy)			
Results (environment)			
Results (economy)			
Trade-offs			
Dominant life-cycle phase			
Risks, barriers and drivers			
Potential improvements offering			
Potential improvements study			
Key assumptions			
Main conclusions			

4.3.1 Result (material, energy, environment and economy)

In this field the results found for material use, energy use, environmental impact and economy are stated. Absolute numbers or the percentage difference between the conventional and alternative offering may be used. Such information is intended to enable analysis of how efficient different solutions are.

4.3.2 Trade-offs

Specifying the trade-offs identified in the study provides a basis for analysing the pros and cons of a specific offering with RE solutions. An example of a trade-off is a solution that aims to be energy efficient, but may on the other hand contain more scarce materials and have a more complex component structure.

4.3.3 Dominating life-cycle phase

The dominating life-cycle phase can give an indication of the most important parameters when designing resource efficient solutions around certain types of products.

4.3.4 Risks, barriers and drivers

If risks, barriers and drivers for the resource efficient offering are stated in the study it is relevant to catch them with the framework. This could be e.g. supply risks, use of potentially hazardous materials, consumer acceptance, identified demands and identified policy drivers (this acts as a support for identifying the facilitating conditions in Table 2).

4.3.5 Potential improvements of the offering

The author of the assessment study may have identified potential areas of improvements for the offering. This entry enables identifying future improvements in connection with the offering and could thereby assist in analysing the feasibility of a resource-efficient solution.

4.3.6 Potential improvements of study

In line with the category above, the author of an assessment may have identified potential areas of improvement for the study. For example, a study of a secondhand store may only have included jeans and t-shirts and the inclusion of more clothing items would be a good improvement. Gathering these details could provide useful information for future studies.

4.3.7 Key assumptions and main conclusions

Key assumptions are any assumptions made in the assessment that are particularly important for reaching the results. For example, if the study includes the use-phase of a product, the user frequency and behaviour are key assumptions for the results of the study.

Finally, which findings do the author(s) consider to be the main conclusions of the assessment study?

4.4 General conclusions and comments

The last section of the framework is designed to gather general learning from the assessment study, together with the most important results. Moreover, aspects to highlight and discussion on the part of the analyst is reported here, e.g. questionable assumptions and methodological choices.

5 Further work

The framework presented here has the aim of fulfilling two purposes. Firstly, to present a typology of ways to increase resource efficiency, focused on material use, and secondly to provide a tool to systematise learning from assessment studies of resource efficient offerings.

It is possible to argue that the two purposes of the paper have therefore been fulfilled. However, the usefulness and the suitability of the typology for assisting systematic learning from assessment studies is not discussed or evaluated here. Instead that work is presented in a related paper by Böckin et al. (2016), where we have tested and evaluated the framework by reviewing a selected number of assessment studies of different products and services. The evaluation presented in Böckin et al. (2016) will guide future revisions of the framework.

6 Conclusions

The typology presented here conveys three different ways to improve resource efficiency along the product chain. Firstly, through *efficiency in production and supply-chain measures* by reducing material use in the offering or by reducing scrap rates. Secondly, by *efficient use of products* by prolonging life, intensifying use or by maintenance and repair. The third way is by *closing the loops*, which involves closed-loop reuse, open-loop reuse, remanufacturing and repair, functional recycling and non-functional recycling.

This division is considered to be exhaustive and inclusive of any potential measures for reducing resource flows, since it includes means that focus on the production and supply-chain, in addition to circular solutions, which are most commonly addressed within circular economy. Addressing the production processes as one way to increase RE is similarly concluded to be of importance by the European Commission in their action plan towards circular economy. One reason to not only focus on closing material loops is that not all types of products can be recirculated or used more efficiently. Some products, such as food, are disposable by nature and the only way to decrease their impact is by efficient production or reduced consumption.

The second aim of the framework is to function as a tool to systematise learning from assessment studies in the field, with the ambition to extract generic learning about when resource-efficient solutions lead to the intended outcome and under which conditions. Implementation of the framework will prove how useful and efficient the framework is for this purpose. A first test of these characteristics will be presented by Böckin et al. (2016) and the findings and conclusions regarding usefulness will be incorporated in future versions of the framework. Subsequently the framework will be used with a large number of assessment studies to reach generic conclusions on resource efficiency.

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