1. Introduction

Designing products and services\(^1\) for a sustainable circular economy (CE) (Desing et al., 2020c) has the potential to greatly reduce primary resource needs and improve the availability of secondary material for further utilization in the economy. Primary resource extraction and processing contributes significantly to the global environmental burdens today (Desing et al., 2020a; IRP, 2019), thus reducing demand for primary material is essential to build a sustainable CE. In fact, as the pressure on many vital Earth system processes (e.g. climate or biodiversity) is beyond safe limits today (IPBES, 2019; IPCC, 2018; Rockström et al., 2009; Steffen et al., 2015), it is necessary to reduce the use of resources in the economy to a sustainable level (Desing et al., 2020a). In the design phase of a product, the quality and quantity of materials and energy required for production and operation of the product are defined. Additionally, the design also determines, up to a certain extent, the quality and quantity of materials that are recoverable at the end of the product’s life (Allwood et al., 2011; Reuter et al., 2019) as well as the amount of unavoidable final losses (e.g. abrasion, corrosion, dispersion (Kral et al., 2013)). Therefore, design has a significant leverage to improve material utilization in society (Reuter et al., 2019) and reduce environmental impacts (Allwood et al., 2011; Almeida et al., 2017; Bakker et al., 2014; Brundage et al., 2018; Rossi et al., 2016).

Over the last decades, a multitude of eco-design tools have been developed, either specific to aspects of CE (such as design for disassembly (Vanegas et al., 2018), design for resource circulation (Toxopeus et al., 2018), design for remanufacture (Hatcher et al., 2011), design for product life extension (Den Hollander, 2018), cradle-to-cradle™ (Braungart et al., 2007), design for recycling (Reuter and van Schaik, 2015)) or more general to improve the environmental performance (e.g. in form of guidelines (Bovea and Pérez-Belis, 2018; Schoggl et al., 2017; Telenko et al., 2016; Toxopeus et al., 2018; van den Berg and Bakker, 2015), diagram tools (Van Hemel, 1998) or simplified life cycle assessment (LCA) approaches (Broeren et al., 2016); see also (Lutropp and Lagerstedt, 2006; Rossi et al., 2016; Sheldrick and Rahimifard, 2013)). However, many of these eco-design tools are not applied in industry, because they either require time-consuming and complex procedures and depend upon specific knowledge (Brundage et al., 2018; Rossi et al., 2016), or offer insufficient guidance in trade-offs (Broeren et al., 2016; Byggeth and Hochschorner, 2006; Schoggl et al., 2017). It is further often difficult to choose the appropriate tool from the variety of possibilities for the specific requirements of the company (Rossi et al., 2016). In this context, guidelines have proven to

\(^1\)In this paper we use products as a synonym for products and services, i.e. services are always included when we write about products.
be the most useful eco-design tools in industry, because they are easy to use and informative already for design conception (Lattropp and Lagerstedt, 2006). The main inconvenience of such guidelines is, that they are often too general – unless customized to single product groups (Vezzoli and Sciama, 2006) – and, as they are often selected based on perceived benefits, may lead to hidden burden shifting and trade-offs (Schogg et al., 2017). And even though the usefulness of such design guidelines is widely recognized, they mostly lack quantitative decision support, as only few of them are tied to quantitative indicators.

Life Cycle Assessment (LCA) is a well established tool to quantify environmental impacts of a product (Pennington et al., 2004; Rebitzer et al., 2004). However, being a quantitative assessment tool, it requires detailed data, which usually is available only in later design steps or even at the very end of the design process (Telenko et al., 2016). It offers a very detailed but ex post analysis of the environmental performance, either relative to a reference product or against absolute benchmarks (Bjorn et al., 2016; Brejrod et al., 2017; Hollberg et al., 2019; Ryberg et al., 2018a; 2018b), and is therefore not very useful to influence design decisions (Brundage et al., 2018). In the past few years, so-called ex ante or prospective modelling approaches for LCA have been published by various research groups (for an overview see e.g. (Thonemann et al., 2020)). Common challenges in these approaches are the issues of data availability and their comparability (in order to be able to keep a minimum degree of consistency in the model), as well as the various uncertainty challenges (especially when such new technologies are compared to existing products). Hence, such ex ante LCA studies require even more specialist knowledge than an ex post analysis.

In regard to CE, specific indicators have been proposed to measure the degree of material circulation (Corona et al., 2019; Ellen MacArthur Foundation, 2018; Hashimoto and Moriguchi, 2004), avoided environmental impacts (Haupt and Hellweg, 2019) or saved costs (Di Maio and Rem, 2015; Thomas and Birat, 2013). However, they either require data not available during design (e.g. LCA results (Haupt and Hellweg, 2019)) or measure circulation irrespective of environmental impacts (e.g. Ellen MacArthur Foundation, 2018). In fact, what is needed is an easily applicable method (Rossi et al., 2016) that (i) can inform product designers from the very beginning (Den Hollander, 2018), (ii) gives them clear direction/guidance and (iii) can be used by them without too much (additional) knowledge or training.

To this end, we propose a new design decision support method focusing on the utilization of resources. The method measures the pressure exerted by the product on sustainably available resources (i.e. amount of resources available within Earth system boundaries (Desing et al., 2020a)) with key CE design parameters that can be estimated during the design process. Therefore, we call it the “resource pressure” method. Further, we derive design guidelines based on the resource pressure indicator, that can be considered early in the design phase. In this combination, the method provides both qualitative guidance as well as an ex ante assessment of the “circularity” of the product to quantitatively influence design decisions.

2. Method development

With the resource pressure method developed in this section, we intend to guide the selection of materials and circular strategies from early design phases onward. This method does not intend to provide any guidance on toxic or harmful substances, but it’s aim is to allow a designer (i) to reduce the pressure on primary resources and (ii) to maximize the utility of materials within the socio-economic system. Environmental impacts are considered in so far as they result from primary material production and losses of these materials to final sinks, and are included in the calculation of the material’s ecological resource budget (ERB) (see Section 2.1, Desing et al. (2020a) and bottom part of Fig. 1).

The embodied impacts of resources (including materials, food and fuels) generally show a significant share of the total impacts of a final product (Hauschild et al., 2005; Sheldrick and Rahimifard, 2013) and are globally responsible for about 1/3 of greenhouse gas emissions (Desing et al., 2020a; IRP, 2019), dominate agriculture related impact categories like water stress (IRP, 2019) and contribute about 1/3 of particulate matter related health impacts (IRP, 2019) as well as to energy demand (Desing et al., 2020a). As the choice of material influences the design strongly (e.g. in regard to manufacturing technologies or lifetime), we focus for this first version of the method on environmental concerns related to the required amounts of primary materials only, acknowledging the need to further develop this method – or develop other, complementary methods – to address environmental impacts from further life cycle stages, particularly from recycling and cascading.

For the design method, after having defined the ERB (Section 2.1), we then need to define the resource pressure as a quantitative indicator (Section 2.2) and afterwards link it to the six design parameters shown in Fig. 1 (Section 2.3). The design method itself consists of this quantitative indicator for the evaluation of the resource pressure as well as of qualitative guidelines that are derived from it in Section 2.4.

2.1. Ecological resource budgets as a benchmark

How much of a material can be produced within Earth system boundaries? To answer this question, we have proposed the method of ecological resource availability (ERA) (Desing et al., 2020a), which estimates the annual material availability that is possible for all materials without violating any boundary with more than a defined probability. This method requires the allocation of the global boundaries to resource segments (e.g. all metals) and the definition of shares within these segments. Different allocation scenarios, the optimization of production shares and alternative production technologies (e.g. steel making with hydrogen (Ahman et al., 2018)) can be analysed on their effect on ERA. Calculating ERA budgets based on grandfathering2 is one possible allocation scenario, however, everything but optimal for society as it simply rescales the current economy to fit within Earth system boundaries. The transformation to a sustainable CE requires not just rescaling, but a shift in resource production and use. Using the grandfathered ERA as a benchmark for design is hindering such a transformation, because it entrenches the status quo of today’s unsustainable resource use. Defining a sustainable ERA, which is an optimized composition of society’s resource use to provide for needs and desires (Defila and Di Giulio, 2020; Rao and Min, 2018) within the limits of the planet, is still an open question, both in research and politics. Optimizing the use of such a desirable ERA would be a valid design objective.

Until such a scenario is available, we propose to use the ecological resource potential (ERP) for design guidance, which is based on the material’s impact intensity alone. The ERP shows the maximum theoretical potential for producing one material within Earth system boundaries, when no other anthropogenic activity would take place. Hence, it only depends on the impact intensity on the boundaries and does not require any allocation. Using ERP as a benchmark for the design therefore minimizes the pressure on Earth system boundaries, as it favours materials with low environmental impacts in the most limiting boundary category. This reflects the design objective for minimizing environmental impacts in regard to Earth system boundaries.

These ERPs can be calculated with a slight modification of the ERA method (Desing et al., 2020a) by omitting all steps for allocation and production shares and calculating the ERP for each material separately. The ERP is then defined as the production mass flow that leads to a

---

2I.e. allocating global boundaries to resources according to today’s impact shares and setting the share of production as in today’s pattern of resource use, see (Desing et al., 2020a)
violation of no global boundary with more than a chosen probability of violation $P_v$. In concordance with the ERA method (Desing et al., 2020a) (see also Desing et al., 2020b), we choose $P_v = 0.01$, i.e. each boundary is respected with a confidence of at least 99%. Data necessary for calculating ERP are the uncertainty distributions of Earth system boundaries and cumulative impacts (for all boundary categories) of the extraction and production of primary material as well as it’s final disposal. Note, the most limiting boundary is defining the ERP, therefore no weighting between impact categories is necessary.

In the resource pressure method, either the ERA or the ERP can be used as the (limiting) ecological resource budget ERP, depending on the availability of data and the question to answer. For example, the grandfathered ERA (Desing et al., 2020a) can be used for an analysis of the resource pressure exerted by a current societal activity (e.g. company or country). However, setting future targets and designing related policies requires building scenarios for sustainable ERA. Thus, in a future-oriented product design either ERP can be used for the objective of minimizing environmental impacts or a yet-to-be-defined desirable ERA for the objective of optimizing the use of these limited resources. ERP is a mass flow of primary material to society, usually measured in the unit kg/a.

$$
ERB = \begin{cases} 
\text{ERA for analysis and design for optimizing the use of ERA} & \\
\text{ERP for design for minimizing impacts} & 
\end{cases}
$$

(1)

### 2.2. Resource pressure

Products need material input and generate output in form of emissions and solid waste. Sooner or later, every input is turned into an output, latest at end-of-life (EoL) due to mass conservation. Providing the product’s functionality over time requires a product system, consisting of a continuous flow of replacement products. Averaging the material flows induced by such a product system over time, it can be considered in steady state, i.e. requiring constant inputs and generating constant outputs. The design of the product thereby essentially defines the necessary inputs as well as the generated outputs, both in terms of quantity and quality. These inputs and outputs can be attributed to one of the following three groups of materials:

- **Consumed materials:** represents the required primary input (e.g. gasoline fuel) as well as all final losses (e.g. combustion emissions).
- **Cascaded materials:** secondary material input from higher technical quality level and output to lower technical quality level (e.g. aluminium wrought alloy → cast alloy).
- **Recycled materials:** closed loop recycling, where output is a possible input within the same product system, at least in principle (e.g. PET bottle-to-bottle recycling). In reality, recycling without losing quality can also take place between product systems (e.g. glass bottle to glass container (Haupt et al., 2017a)).

Primary material input consumes a part of the material’s ERP, which we define as the resource pressure $r$. The less material a specific design requires from the sustainably available primary resource base (i.e. from ERP), the lower also the pressure on this specific resource and the lower the associated environmental impacts. The resource pressure cannot only be calculated for the materials contained in the product, but also for energy and auxiliary materials throughout the product’s lifecycle, covering the respective environmental impacts (see Fig. 1). Direct impacts from life cycle stages (e.g. manufacturing or recycling) are not covered with the resource pressure method, however, generally contribute little to the overall impact. The resource pressure can therefore be indicative for the selection of different materials and circular strategies in early design stages, but does not replace a more detailed ex post analysis, as not all environmental impacts are covered. The resource pressure $r$ is evaluated for each material separately and aggregated in the end for products containing more than one material. The resource pressure $r$ is dimensionless and can be defined as the mass flow of primary material required $m_{prim}$ divided by ERP.

$$
r = \frac{m_{prim}}{ERP}
$$

(2)

In the current global societal metabolism, the inflows of primary materials are larger than the outflows, as material stocks are growing (Krausmann et al., 2018), leading to a time lag between when an inflow is turned into an outflow (Gloser et al., 2015). But when looking at the resource flow over time, the output equals the input due to mass conservation. In a sustainable CE (Desing et al., 2020c), where resource use is restricted to what is possible within Earth system boundaries, the metabolism tends towards a steady state when the resource use is maximised for society (i.e. stocks are constant, and as a consequence inflows equal outflows). Looking at the mass conservation, the resource pressure $r$ can be measured from two sides: (i) input compared to ERP, or (ii) output compared to losses to final sinks$^3$, with the latter being

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$^3$Final sinks are stockpiles of materials no longer available in a useful form to society. In principle, these materials can be made available again with equal or more effort than primary production (e.g. CO₂ capture from air). A glossary of
equal to ERB in steady state (see Fig. 2).

However, this measurement from both sides is only equal for the entire socio-economic system. When looking at a single product, the primary input and the final losses do not have to be equal. For example, a product can be built from cascaded material only (i.e. no primary input), but become waste completely at its EoL (i.e. $m_{\text{loss}} = m_{\text{product}}$). Therefore from a product perspective, both of these two sides are relevant to measure the exerted resource pressure. While the use of primary material directly induces primary material production, final losses lead to a demand for primary material elsewhere in the socio-economic system and thus are like this responsible for a resource pressure as well. In other words, to create an environmentally benign product, it is necessary to reduce both the direct primary material intake as well as the creation of final waste. And the design of a product influences the resource pressure on both sides (e.g. through the choice of material (input) or connections between different materials affecting the recyclability (output)). Thereby, material that can be recovered with the same quality (recyclability, i.e. can potentially be used as an input to produce the same product) or at a lower quality level (cascadability) (Desing et al., 2019a) remains available in the socio-economic system without exerting pressure on the respective primary level. Making these secondary materials available again, however, entails the use of auxiliary materials (e.g. solvents) and energy for the reconditioning, i.e. inducing pressure on those resources.

Hence, in order to include both the input and output perspectives, we modify the pressure indicator $\tau$ (Eq. (2)) and define it as the average from both perspectives (Eq. (3)).

$$\tau = \frac{1}{2} \frac{m_{\text{prim}}}{\text{EBR}} + \frac{1}{2} \frac{m_{\text{loss}}}{\text{EBR}} - \frac{m_{\text{prim}} + m_{\text{loss}}}{2\text{EBR}}$$

(Eq. (3)) can also be interpreted as an equal measurement of the resource pressure on ERB and the pressure on final sinks. This equity is based on the assumption of a steady state, i.e. the capacity of final sinks is equal to ERB (see Fig. 2, Desing et al. (2020a)). In principle, different weights could be given to the input and output sides, however, in our opinion they are equally important in product design.

### 2.3. Linking resource pressure and design parameters

To be useful in the design process, Eq. (3) needs to be linked to design parameters, which are described in the following subsections. This link is established here based on a simplified material flow in the product system (Fig. 2). The total mass flow required by a product is composed of its related primary ($m_{\text{prim}}$), secondary ($m_{\text{s}}$, i.e. cascaded from higher quality) and recycled ($m_{\text{r}}$, i.e. closed loop recycling at same quality) material flows. Similarly, the output flows generated (at EoL but also during other life cycle stages, e.g. corrosion) of such a product divides into final losses $m_{\text{loss}}$, cascading $m_{\text{c}}$ and recycling $m_{\text{r}}$ flows. Recycled material $m_{\text{r}}$ is the mass flow of material that is recovered at a quality high enough to be used in the production of the same product again, at least in principle. It is defined as the output of the closed-loop recycling system (Haupt et al., 2017a). Losses during the recycling processes are contained in the final loss $m_{\text{loss}}$ or cascading $m_{\text{c}}$ flows. As the system is modeled in a steady state, the recycling flow that can be recovered at EoL equals the recycling flow available as an input (see Fig. 2). The mass balance for one material in the product system (Eq. (4)) is the basic equation to relate the primary material inflow $m_{\text{prim}}$ and the final outflow $m_{\text{loss}}$ with design parameters:

$$m_{\text{product}} = m_{\text{prim}} + m_{\text{s}} + m_{\text{r}} = m_{\text{loss}} + m_{\text{c}} + m_{\text{r}}$$

(Eq. (4))

### 2.3.1. Mass flow required for the production of a product

We can calculate the (theoretical) continuous mass flow of one material $m_{\text{product}}$ required to provide the functionality of the product over time by spreading the required mass for the product over its lifetime $t_c$. The required mass of a material for the product is thereby the mass contained in the finished product $m_{\text{product}}$ enlarged by the manufacturing losses $\gamma_{m}$.

$$m_{\text{product}} = \frac{m_{\text{product}}}{t_c}(1 + \gamma_{m})$$

(Eq. (5))

This mass flow is a theoretical construct, valid for the assumption of a steady state of the product system under investigation. It can also be scaled with the expected production numbers to evaluate the resource pressure exerted by the product sales. Similarly, the pressure on a specific resource from one cooperation, sector or country can be

---

**Fig. 2. Flow of a material through the socio-economic metabolism in steady state. ERB is utilized in different product systems $i$, which can exchange materials from higher to lower quality levels (cascading) as well as recycle material at the same quality level within the product system. Material that can neither be recycled nor cascaded to another product system is lost to final sinks.**

(footnote continued)

key terms is provided in the SM.
estimated by inserting the (measured) mass flows on the respective levels. In this paper, we however focus on single products only.

Functional equivalence

The mass of the material in a product \( m_{\text{product}} \) is usually different for two designs based on different materials, although every design variant needs to fulfill the same functionality (e.g. bending stiffness for a beam). In most cases, there are several material options possible to fulfill a certain function in a product, while the material choice can significantly influence the design of a product. Weight differences of designs due to the choice of alternative materials can be estimated based on material properties of the respective materials (Ashby, 2005; 2012; Broeren et al., 2016). For example, a pillar with the same load bearing capacity out of different materials will have a different weight in relation to the difference in the material’s strength. Weight differences can also be estimated by developing design sketches detailed enough to allow a calculation of how much mass is required to fulfill the function. As a result, for each design alternative the final mass in the product can be estimated.

Product lifetime

Prolonged service life reduces the material intensity per service unit directly. The lifetime of different design variants can differ due to the materials chosen (e.g. vulnerability to corrosion) or due to engineering parameters (e.g. sizing, surface roughness, surface treatment) (Desing, 2013). Depending on the product type, the lifetime \( t_s \) represents a physical time (e.g. for a bridge), an operating time (e.g. for a power plant) or a number of service cycles (e.g. for a coffee machine).

The lifetime \( t_s \) is defined in this paper as an attribute specific to the part the material is used in. For example, an engine block can have a higher lifetime than the engine, if it is used in a new engine again (remanufacturing). As a counterexample, a bearing that has to be replaced in regular intervals has a shorter lifetime than the product it is used in. In this manner, circular strategies with no or minor changes to the integrity of parts – like reuse, remanufacturing, repair, refurbish, upgrade and similar – can be considered through their change in lifetime of the concerned parts.

Manufacturing losses

Possible material alternatives are likely to require different manufacturing technologies, leading to different manufacturing losses (e.g. casting vs. machining). The total material requirement for a specific design is the mass in the final product plus these manufacturing losses. These losses can be expressed as mass fraction of the finished product.

\[
y_\text{m} = \frac{m_{\text{lost}}}{m_{\text{product}}} \in [0, \infty)
\]

For certain manufacturing technologies, such process losses can be circulated internally (e.g. casting channels in a foundry). Such internally recycled material is not part of the losses, as defined in this method. All other losses that have to be treated in other processes or industries (such as off-cuts and swarf from machining) are lost for the manufacturing process and need to be counted as such. They may, however, be recycled or cascaded and are not necessarily final losses.

2.3.2. Specifying material input and output

The required mass flow for the product can be provided by primary, cascaded or recycled material inputs. At the EoL of the product or during its service life, these inputs are transformed into final losses, cascadable or recyclable material outputs (see Fig. 2). These six flows need to be specified. The mass balance equations at the in- and output side (Eq. (4)) and the condition that the recyclable output equals the recycled input allow to calculate three out of six flows, making it necessary to specify three flows explicitly. We choose to specify the recyclability, cascadability and primary material content, which are described in the following paragraphs.

Recyclability

At the end of the product’s life, some material \( m_r \) can be recovered to be used as an input to produce the same product again, at least hypothetically. This condition ensures, that the recycled material needs to have the same quality (often also called closed-loop or functional recycling). As materials degrade (e.g. polymer chain length reduction), get contaminated with unwanted elements (e.g. alloying elements of other parts (Lovik and Müller, 2014)) and are chemically transformed during service life (e.g. corrosion) or EoL treatment (e.g. slag (Nakajima et al., 2009)), only part of the recoverable material flow can satisfy the quality requirement for closed loop recycling. The recyclability \( \eta_r \) is determined by the functional requirement in the design as well as the contamination with impurities at EoL (Desing et al., 2019a). Some proposals exist in the literature to estimate the recyclability of a product based on recycling process simulations (Reuter and van Schaik, 2014; 2015; van Schaik and Reuter, 2007; 2010), which are data intensive and require detailed process knowledge. There is a need to develop design support methods to estimate recyclability by the product design team itself (Desing et al., 2019a). If the recyclability is unknown, it needs to be set to zero.

\[
\eta_r = \frac{m_r}{m_{\text{product}}} \in [0, 1)
\]

Cascadability

When material cannot be used for the same function again, they may be used for lower quality applications and cascaded as an input to another product system (Lovik et al., 2014; Nakamura et al., 2014; Rigamonti et al., 2018). The cascadability \( \eta_c \) is the fraction of the product mass flow, that can be used as an input in another (and lower) function.

\[
\eta_c = \frac{m_c}{m_{\text{product}}} \in [0, 1 - \eta_r]
\]

The remaining material that cannot be recycled at the quality level required for the initial function of the product leaves the quality level and cascades to one or multiple, lower quality levels. This procedure can be repeated multiple times while gradually reducing quality levels. For example, once the threshold for alloying elements in an aluminum wrought alloy is crossed, it can be used as a cast alloy, which allows higher alloying element concentrations (Lovik et al., 2014). Cascading prolongs the useful service life of a material, even if it is no longer suitable for its initial quality. Each added cascading step increases the utilization of the respective material. Therefore, keeping the cascaded material in the socio-economic system reduces the pressure on primary resources. In this initial version, we don’t consider different quality levels (Desing et al., 2020c; Haupt and Hellweg, 2019), which is a potential area for further research.

A material flow is only then considered cascadable, if there is a (potential) market for it (i.e. it needs to be determined how “resource like” the waste stream is (Park and Chertow, 2014)). Materials, which have too low quality for any feasible use or if there is no (big enough) market for it, have to be considered final waste. Market feasibility studies usually precede product design, therefore data on market potential for material outputs can, in principle, be estimated during design. For example, truck tarpaulin is to a small extent further processed into hand bags after its intended use. This cascading reduces the resource pressure exerted by the tarpaulin only to the extent of the market for secondary material. The large amounts of tarpaulin, which are not cascaded to a second application because the market is too small, have to be considered final waste. On the other hand, the bag producer uses 100% cascaded material and thus does not exert pressure on primary resources, however on final sinks at the end of the bag’s life. In comparison to virgin material intake for a bag, the resource pressure is reduced by half.

Primary material content

The primary material mass fraction \( \alpha \) for one material is determined as the flow of primary material \( m_{\text{prim}} \) contained in the material flow required by the product \( m_{\text{product}} \).
\[
\alpha = \frac{m_{\text{prim}}}{m_{\text{product}}} \in [0, 1 - \eta_r]
\] (9)

Due to the mass balance at the input, the primary material mass fraction needs to satisfy \(\alpha \leq 1 - \eta_r\), i.e. it depends on the recyclability \(\eta_r\) as the sum of all input flows needs to equal the mass flow required for the product. In some cases, a certain primary material content \(\alpha\) is required in the product (e.g. to satisfy impurity thresholds). Then it can also happen that the recyclability is restricted by the requirement for primary material content \(\alpha\) (i.e. \(\eta_r \leq 1 - \alpha\)). The cascading material flow \(m_s\) results from the mass balance (Eq. (4)): \(m_s = m_{\text{product}}(1 - \alpha - \eta_r).\)

However, often primary material content is known for the inflow of material to the product system (i.e. \(m_{\text{prim}} + m_s\)), before the recyclable material flow \(m_s\) is added (see Fig. 2). It is therefore useful to define a modified primary material content \(\alpha'\), which is the relation of primary material mass flow \(m_{\text{prim}}\) to the combined mass flow of primary and secondary (i.e. cascaded from higher quality) material \((m_{\text{prim}} + m_s)\).

\[
\alpha' = \frac{m_{\text{prim}}}{m_{\text{prim}} + m_s} = \frac{1}{1 + \frac{m_s}{m_{\text{prim}}}} \in [0, 1]
\] (10)

\[
\alpha = \alpha'(1 - \eta_r)
\] (11)

The modified primary material content is as a parameter independent from the recyclability. Furthermore, it corresponds to the primary and secondary material content of material supplied from global markets to the product system. Global data on secondary material content (e.g. Frosch et al. (1997), Graedel et al. (2011), United Nations Environmental Program (2011)) can therefore be used as a first estimate to determine \(\alpha'\).

2.4. Design evaluation and guidance

Using the design parameters introduced in Section 2.3 and the mass balance (Eq. (4)), we can rewrite Eq. (3) to:

\[
\tau = \frac{1}{2} \frac{m_{\text{product}}}{\text{ERP}} \frac{1}{\text{lt.}} (1 + \gamma_c)(1 + \alpha - \eta_r - \eta_d)
\] (12)

\[
= \frac{1}{2} \frac{m_{\text{product}}}{\text{ERP}} \frac{1}{\text{lt.}} (1 + \gamma_c)(1 + \alpha' (1 - \eta_r) - \eta_r - \eta_d)
\] (13)

Eq. (13) links for each material the parameters specific to the design directly to the resource pressure \(\tau\). It can be therefore used during the design process to identify the most effective strategy to reduce the pressure on the sustainably available primary materials.

Most products consist of more than one material. Therefore, the resource pressure needs to be calculated for each material used in the product separately and aggregated to an overall value for the design. The resource pressure can be also calculated for consumables during the service life (e.g. fuels, lubricants, cleaning detergents, water) and energy (Desing et al., 2019b). To arrive at an overall value for a design \(d\), the cumulative resource pressure \(\tau_{\text{cum,d}}\) is calculated as the sum over all resources \(j\) required.

\[
\tau_{\text{cum,d}} = \sum_j \gamma_{c,j}
\] (14)

A quantitative indicator (Eq. (13)) can only become useful, once the required data is available. During the fuzzy front end of innovation (Koen et al., 2016), which is the early phase of product design when everything is still fuzzy, this required data is not available yet. As many important and far reaching decisions are taken already in this step, qualitative guidelines can be a useful tool to support these decisions.

Hence, to extent the applicability of our developed design method to earlier design phases, we derive general design guidelines in Fig. 3 from the quantitative resource pressure indicator (Eq. (13)). These general rules of thumb can be considered already at early design stages when conceptualizing alternative designs. Please note, the guidelines are not meant to be exhaustive, but rather specific to the scope of the method developed here (i.e. the reduction of the pressure on sustainably available resources).

3. Case study and results

Together with V-Zug\(^5\), a Swiss appliance manufacturer, we tested the above presented design method on a heat exchanger for a tumble dryer as a first case study. Highly efficient tumble dryers for households require a heat pump, which greatly reduces the electricity demand. The heat pump system consists of two heat exchangers (evaporator and condenser), a compressor and a throttle valve. The heat exchanger was selected because (i) the designers want to evaluate which material alternative (aluminium or copper) was preferable from an environmental point of view and (ii) changes in the design of the heat exchanger have a negligible effect on the performance of the device in the use phase. This is because every design variant needs to deliver the same thermal performance (i.e. transferred heat flux) and the pressure loss in the tube can be held constant by adjusting the diameter in relation to the length. Consequently, the investigated design variants can be evaluated independently of the rest of the device. The details of the studied heat exchangers are described in the supplementary material (SM). The ERP for Cu and Al are calculated with process data from ecoinvent v.3.5 (Wer gent et al., 2016) and a probability of violation of \(P_2 = 0.01\) to \(\text{ERP}_{\text{Cu}} = 5.68 \times 10^{10}\text{\ g/a}\) (biodiversity boundary is limiting) and \(\text{ERP}_{\text{Al}} = 4.36 \times 10^{10}\text{\ g/a}\) (CO\(_2\) boundary is limiting) (Desing et al., 2020b).

3.1. Description of design variants

The initial design is a heat exchanger with tubes and fins from aluminium (Al/Al). It is cheap to manufacture because the fins are stacked on the continuous tube, requiring an elongated hole and leading to manufacturing losses of \(\gamma_{\text{Al/Al}} = 0.11\), which are collected and can be recycled without losing quality. The elongated hole results in a small contact surface between tubes and fins, leading to a poor heat transfer and a bulky design \((m_{\text{product, Al/Al}} = 1.04\text{\ kg})\), see Fig. 4.

Virgin aluminium is necessary, as the required alloys (1XXX) are very pure (\(\alpha' = 1\)) (Lovik et al., 2014). At the end of life, the devices are currently treated in the Swiss e-waste management system (the devices are sold on the Swiss market exclusively). In this system, the devices are shredded, sorted and further processed. Through the shredding, the Al stream is heavily contaminated with other elements (e.g. Fe, Cu), therefore we do not know how much of this Al can be recycled at the same quality (\(\eta_{\text{rec,Al}} = 0\)). Consequently, the Al fraction is cascaded to cast alloys. And as contaminant concentrations are generally smaller than what is tolerated in various Al cast alloys (e.g. AlSi12Cu1(Fe)), we consider it marketable as a whole. In the cascading processes there are losses of about 20% (Boin and Bertram, 2005), leading to an overall cascadability of \(\eta_{\text{rec,Al}} = 0.72\). The manufacturing losses are directed to closed loop recycling with a yield of approximately 90% (Boin and Bertram, 2005), leading to an overall recyclability of \(\eta_{\text{rec,Al}} = 0.09\).

To improve the technical performance, a design with copper tubes and aluminium fins (Cu/Al) is considered. Fins are stacked on hair-pin shaped tubes, which are connected with U-bends. This design increases the contact between fins and tubes and therefore the thermal performance. Simultaneously, the manufacturing losses for Al are reduced \((\gamma_{\text{Cu/Al}} = 0.04)\) as well as the overall size \((m_{\text{product,Cu/Al}} = 0.84\text{\ kg})\). The required copper can be sourced from the world copper market.

\(^5\)www.vzug.com
containing secondary material ($\alpha' = 0.69$) (Copper development organization, 2019). Shredding of the mixed material heat exchanger will lead to a low separation due to the ductile materials. Both the Cu and Al fraction will contain significant amounts of the respective other material, which is lost for its recovery. We estimate that 30% of each material is lost to the other fraction. In the Cu processing, the Al content is removed (Reuter et al., 2019) and the Cu content recovered with high purity and a yield of approximately 98% (Copper alliance, 2019). Therefore, the recyclability of Cu is $\eta_{r,Cu} = 0.69$ and no material is left for cascading ($\eta_{c,Cu} = 0$). In the Al processing, the Cu is not removed, leading to very high concentrations of Cu in the resulting Al-alloy. The alloy has to be diluted with primary material to meet a cast alloy's
specification, but it is still considered marketable for such a dilution process. We therefore estimate for Al the recyclability (resulting of manufacturing losses) to \( \eta \text{Al} = 0.035 \) and cascadability (resulting from EoL output) to \( \eta \text{Al} = 0.56 \).

Both designs are integral parts of the device and thus have the same lifetime \( (t_0 = 15 \text{a}) \). However, there is no technical reason inhibiting the reuse of the heat exchanger in a new device, i.e. giving it a second life. This scenario \( (\text{L}+) \) requires the take-back of the old devices, dismantling, cleaning and leak-testing of the heat exchanger as well as the standardization of this component for other designs. The design of the heat exchanger itself does not have to be altered for this scenario.

To increase the recoverability of the metals contained in the heat exchanger, dismantling and separate recovery is investigated in the scenario \( \text{R}+ \). For the Al/Al design, the dismantled part can be smelted without further processing (and thus without contamination), leading to a very high recyclability \( \eta \text{Al/Al,R+} = 0.85 \), leaving no material to be cascaded \( (\eta \text{Al/Al,R+} = 0) \). For the Cu/Al design, a manual separation of fins and tubes is too labour-intensive to be economically viable and therefore a shredding process is still necessary to separate the two materials. This leads to still low recovery of Al \( (\eta \text{Al,R+} = 0.035, \eta \text{Al/Al,R+} = 0.56) \) but increased recovery for Cu \( (\eta \text{Cu,R+} = 0.8, \eta \text{Cu/Al,R+} = 0) \).

In total we examined eight scenarios formed out of the combination of the design variants mentioned before (see Fig. 4). The resource pressures on auxiliary materials and energy are neglected in this case study for simplicity and because they are expected to give minor contributions.

### 3.2. Results

The results for the eight scenarios (see Fig. 5) show that for the comparison of the two material alternatives in the initial scenario, the Cu/Al variant has a lower resource pressure and is thus preferable. The same holds true for simply doubling the lifetime \( (\text{R}+) \), as this has a direct effect on the resource pressure for both variants. The picture changes when considering dismantling and separate recovery for the heat exchanger. In this scenario \( (\text{R}+ \text{Cu}) \), the Al/Al variant shows significantly larger reduction in resource pressure (factor 3.7 for \( \text{R}+ \) and \( \text{R}+ \text{Cu} \)) than the Cu/Al variant (factor 1.7 for \( \text{R}+ \) and \( \text{R}+ \text{Cu} \)) due to the increased recyclability.

As a design conclusion, the Al/Al variant is preferable in combination with a modular design to allow both reuse in a new product and easy dismantling for separate recovery. If dismantling and separate recovery is not possible, the Cu/Al variant is preferable. However, increasing the lifetime – which requires a modular design – leads to a larger reduction in resource pressure than changing materials.

### 4. Discussion

In contrast to most existing design methods, the proposed method is both qualitative (guidelines, Section 2.4) and quantitative (resource pressure indicator, Eq. (12)-(14)). The guidelines are derived specific for the objective of reducing the resource pressure and not meant to be exhaustive. Also, increasing the lifetime of a product is not in all cases preferable from an environmental point of view, as it may be beneficial to replace early-stage technology prematurely with more efficient alternatives (Gensch and Blepp, 2015). In these cases, the environmental impacts caused in the use phase need to be considered, leading to an optimal environmental lifetime. For mature technology and products that do not cause impacts during their service life, however, increasing the lifetime is an effective strategy to reduce environmental impacts. Additionally, lightweight design may need to be balanced with increasing lifetime, as reducing the weight may reduce the lifetime and vice versa.

For the calculation of the quantitative indicator, only six parameters are necessary, which can be estimated throughout the design process. The calculations are simple (e.g. can be done in a spreadsheet) and can be performed timely during the design process, providing results that give clear design guidance in regard to resource utilization. The influence of each parameter on the resource pressure can be quickly evaluated, allowing to focus the design efforts on the most effective circular strategies.

The presented method is based on a combination of the effect of the in- and output flows on the resource pressure. This underlines the importance of design for defining the quality and quantity of both material in- and outputs (Reuter et al., 2019). Thus far, the bottle-neck to apply the method is the estimation of recyclability and cascadability. In this paper, we have estimated these two parameters based on experience with the Swiss e-waste recycling industry and literature data. Another approach is to define these parameters through detailed process simulations (van Schaik and Reuter, 2010). However, both require specific knowledge and thus cannot be applied by a design team easily.

Therefore, there is a need to develop an easy-to-apply method correlating design parameters with the recyclability as well as the cascadability in the future (Desing et al., 2019a). Further, the method does not yet distinguish different quality levels of cascaded material (Desing et al., 2020c; Haupt and Hellweg, 2019), which is a potential area for further research. It is possible in principle to also consider upwards cascading in the method, which requires to define objective criteria for when it can be considered an improvement of technical properties.

When comparing the resource pressure to results from a simplified LCA (see details in SM), we find that reducing r is indicative for reducing impacts across different impact categories (Fig. 6).

The relative ranking of the design variants with both the resource pressure and 15 different impact categories from the environmental footprint (EF) method (Fazio et al., 2018), is rather similar, though not in all impact categories. On the one hand, LCA can provide a much more in-depth analysis than the resource pressure method. On the other hand, the overall LCA results do not necessarily give a clear guidance, which design is superior to the other in environmental terms. For example, in the initial scenario, the Al/Al is superior in the impact categories freshwater ecotoxicity, freshwater eutrophication, and non-carcinogenic human health effects while it is e.g. inferior in the categories for climate change, carcinogenic effects and ozone layer depletion. LCA shows the trade offs, however does not provide a clear guidance for the designer when considering different impact categories, which would require weighting between impact categories. In contrast, weighting of impacts is not necessary when calculating ERB, even though multiple impact categories are considered, as the most critical boundary is limiting the resource budgets (see Desing et al. (2020a,b)). In this way, multiple impact categories are considered and still a clear guidance is possible.

All parameters (except ERB) necessary for the calculation of the resource pressure are also used as an input for a LCA calculation, however the latter additionally requires process data. The resource pressure can thus serve as an indicative method during the design
process, which then should be validated with a LCA study of the (final) engineered product. The presented case study shows that the method is both easily applicable during the design process as well as effective in guiding towards a design that results in reduced environmental impacts across many impact categories.

The method presented in this paper focuses on the utilization of ERB to assess the resource pressure at the level of a material to society. For example, carbon dioxide (CO₂), land use (soil quality index). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Results of the LCA study for 15 EF 3.0 midpoint (Fazio et al., 2018) impact categories, each of them relative to the score of the Al/Al initial design variant, in comparison to the Al/Al final variant (light bars with thick red lines, see Fig. 5). The impact categories displayed are: climate change: total (kg CO₂eq. 100a); ecosystem quality: freshwater ecotoxicity (CTUe), freshwater eutrophication (kg P-eq.), marine eutrophication (kg N-eq.), terrestrial eutrophication (mol N-eq.); human health: non-carcinogenic effects (CTUh), carcinogenic effects (CTUh), ionizing radiation (kBq rel. to ²³⁵U), ozone layer depletion (kg CFC-11-eq.), photochemical ozone formation (kg NMVOC-eq.), respiratory health effects from particulate matter (decrease incidences); resource use: minerals and metals (kg Sb-eq.), dissipated water (kg), fossil resource depletion (MJ), land use (soil quality index). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Conclusion and outlook

Design is pivotal to reduce the resource pressure at the level of products and instrumental to reduce the consumptive use of resources on a global level. The here described method allows to both analyse societal activities and guide product design to a lower resource intensity, contributing to reach the global vision of a sustainable circular economy (Desing et al., 2020c). Various, currently ongoing trials for the application of the method in Swiss companies indicate that it meets the desired objective of (i) providing guidance for product design from the very beginning through qualitative guidelines, (ii) indicating clear direction for design decisions with a single score indicator and (iii) being straightforward to apply with little training by the designers themselves. We can conclude that the resource pressure method is already useful to guide design decisions towards more sustainable products, i.e. for a relative assessment using the ecological resource potentials (ERP). The method is thereby does not replace well established tools like LCA, but rather complements them in the sense that it offers a quantitative assessment throughout the design phase. The resource pressure is designed as a tool preceding a LCA study, providing clear guidance in regard to the effectiveness of design choices on the resource pressure of the product. It further prepares for the detailed LCA assessment, as parameters necessary in the resource pressure are also required in the LCA.

The method is thereby not limited to a relative assessment, but can also be turned into an absolute sustainability tool, when ERA is used as a benchmark. ERA provides an absolute sustainability benchmark for primary material use globally (Desing et al., 2020a), making the resource pressure indicator $r$ essentially absolute as well. The global economy can be considered sustainable in regard to the use of a resource, if the cumulative pressure on it is smaller or equal to one, i.e. if it’s global use is equal or smaller than ERA. For a single product, company or even country, the absolute sustainability is however not straight forward to assess. To do so, there is a need to develop an approach to connect the contribution for reducing primary resource use by a single product/company/country with the global goal for reaching sustainability, i.e. connecting the bottom-up and top-down perspectives. Resource intensity reduction targets can be defined for the product under investigation (e.g. determined by technical feasibility (Pineda et al., 2015) or necessity for a decent life (Rao and Min, 2018)) and/or by allocating ERA to the area of investigation (e.g. an economic sector, company or country).

The resource pressure method is in fact not limited to the objective of reducing the pressure on primary resources and final sinks (i.e. increasing the utility of a material to society). For example, carbon
capture and storage has the objective to remove CO2 from the atmosphere and store it in final sinks. In this case, the resource pressure on CO2 should be increased. Another objective could be to remove harmful or toxic substances from anthropogenic material cycles and therefore require to increase their final losses and at the same time decrease primary input.

Furthermore, a successful implementation of improved designs requires to align business models with the design (Sumter et al., 2018), making it necessary to treat design as an integral part of the business model innovation process (Takacs et al., 2020). Design of both, the business model and the product, can have a significant influence on the user behaviour and consequently the overall environmental performance. For example, resource wasteful behaviour can be made more effortful for the user by a design encouraging an efficient use (Srividhava and Shin, 2013). Also these aspects have to be addressed to create products for a sustainable future.

CRediT authorship contribution statement

Harald Desing: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. Gregor Braun: Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. Roland Hischier: Supervision, Project administration, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.jresconrec.2020.105179.

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H. Desing, et al.
Resources, Conservation & Recycling 164 (2021) 105179