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108 The resource reduction index – evaluating product design's contribution to a sustainable circular economy

Harald Desing[1], Gregor Braun[1] and Roland Hischier[1]

[1]*Empa – Swiss Federal Laboratories for Material Science and Technology, harald.desing@empa.ch*

Abstract

Primary resource consumption is a main driver for global environmental change, including the climate crisis. Hence, reaching climate targets requires material production to change significantly. For the global scale, we have developed the Ecological Resource Availability (ERA) method quantifying primary resource budgets. If those budgets are respected, major Earth system boundaries are not transgressed with high confidence. Product design and the implementation of circular strategies have the potential to reduce the pressure on these limited resources significantly. Nevertheless, the question, *how much* a product needs to reduce its environmental impacts to reach a sustainable level and respect planetary boundaries remains open. In the present contribution, we define and introduce the resource reduction index (RRI) to answer this question. RRI quantifies and evaluates the degree to which a specific product design respects planetary boundaries. RRI is designed as an absolute and generally applicable indicator, which is able to show the achievements of resource reduction targets on different levels (products, companies, sectors, countries). It is therefore relevant also beyond product and service design. Its applicability is shown here with a case study of a circular jacket, which is designed for an almost perfectly closed material loop. Different scenarios – from a prototype to an industrial scale utilizing the full circular potential – show that circular strategies effectively reduce the pressure on limited resources and the environment. However, only the most advanced scenario, combining multiple and fully implemented circular strategies, can achieve absolute sustainability respecting planetary boundaries.

Keywords: Ecodesign, resource pressure, ecological resource availability, absolute sustainability indicator, planetary boundaries

Introduction

How much better is good enough? In environmental assessments, this question remains usually open due to a lack of suitable methods quantifying the absolute sustainability of an activity (Bjørn et al., 2020). However, it is necessary to provide designers and decision makers with a reference to the scale of the improvements that are necessary to create truly sustainable products, services and other anthropogenic activities. Up to now, all this remains a fundamental challenge, as allocating shares of global environmental boundaries to individual products or activities is at the one hand very influential on the assessment and on the other hand subjective.

In this contribution, we propose a different way of measuring the effects of design improvements on reaching absolute sustainability, which is based on the translation of planetary boundaries to resource budgets, called ecological resource availability (ERA) (Desing et al., 2020). The ERA method calculates the annual primary production amount of each resource, which is available to be used in the economy without violating any of the considered environmental boundary conditions. It necessitates to allocate Earth system boundaries to resource segments (e.g. plastics) and to define the relative share of production for resources (e.g. PET) within each segment. Following the original publication, we use here results generated with the grandfathering allocation approach, i.e. all resource segments may generate impacts in the same proportion as in the past and the relative share of production stays constant on today's level (Desing et al., 2020). Other allocation approaches reflect different societal priorities.

The global use of resources must not exceed the respective resource budgets to be sustainable. As most current resource uses are beyond their resource budgets, the global economy needs to reduce primary resource consumption significantly and/or change the way resources are produced. One-way to achieve this is redesigning products and services to put less pressure on the environment and its resources. Circular economy strategies can reduce primary material input and final losses and their effectiveness can be measured by the resource pressure method (Desing et al., 2021b). This method is an easy-to-use tool quantifying the environmental pressure products cause on planetary boundaries. In this method, the effect of circular strategies reducing resource pressure are considered through the following parameters: reducing the mass of the products $m_{in\,product}$, reduce manufacturing losses γ_m (material efficiency), increasing lifetime t_L, reducing primary material content α', as well as increasing recyclability η_R and cascadability η_C (Desing et al., 2021b). Additionally, primary resource consumption can be reduced through reducing production or resource budgets enlarged through changing material production processes (e.g. hydrogen steel (Bhaskar et al., 2020)). However, the goal of this study is to measure the effectiveness of design improvements through circular strategies on the absolute sustainability of a product in line with planetary boundaries.

Methods

The resource pressure τ is itself already an absolute sustainability indicator (Desing et al., 2021b). If the global sum of all τ_r for a specific resource r is larger than one ($\sum\tau_r > 1$), more of this resource is used than is sustainably available. In this case, the resource use is unsustainable. As straight forward the analysis appears on a global level, as difficult it gets when we want to assess the absolute sustainability of a single activity, be it a product or entity. In one way or another it needs to be determined, how much a single activity is allowed to contribute to the total resource pressure; in other words, how much a single product can utilize from a resource budget.

The first possibility is to allocate resource budgets to the activity under investigation. Such an allocation is however difficult to define (e.g., how much steel, and any other material, is a washing machine allowed to use?) (Ryberg et al., 2018). Alternatively, we can define resource reduction targets for global resource consumption. As several Earth system boundaries are violated today (Rockström et al., 2009; Steffen et al., 2015), it is necessary to reduce the primary resource production to sustainable levels or introduce more environmentally friendly production processes (Desing et al., 2020). For any new product, we can define an equal contribution to this collective effort as a benchmark. Reaching this benchmark on a product level, the product can be considered absolute sustainable in the sense that "if every product provides the same contribution while demand is constant, we will be sustainable collectively." However, not every sector or product type can contribute equally to the global target, as for some this is much harder to achieve. In addition, some activities may be more relevant to society, thus deserving priority and therefore lower reduction obligation.

For this reasons we can combine the former two approaches by allocating resource budget to a defined entity (e.g. product group, industry, company or country as e.g. defined by the science based targets (Pineda et al., 2015) for industries in regard to climate targets) and then specify resource reduction targets for all products and activities contained within. An example for the logic of this combined approach are emission reduction targets in the car industry. These targets are specific for the sector and have to be reached as the average of the fleet of cars sold by a manufacturer.

The approach we present here can be applied to the latter two. However, we show it for global reduction targets as an example. It is a two-step procedure: first, defining the reduction target for each resource necessary for a product (or service) within a defined entity. Second, measuring how well this target is achieved in a specific product.

Reduction target

To illustrate the method and for simplicity, we define and use a global reduction target. Such a reduction target for a resource κ_r can be established by simply dividing the reference global production rate of resource r by its respective resource budget ERA_r.

Please note, ERA budgets are influenced by societal choice, i.e. allocation principles (Desing et al., 2020), and thus will be the reduction target.

$$\kappa_r = \frac{\dot{m}_{prim,r,ref}}{ERA_r}$$

As reference year for the production amount, the latest year is chosen for which data are available and this year is preferably the same as for the reference product. The value of κ_r indicates how much the primary production of resource r in today's global economy needs to be reduced in order to be environmentally sustainable. Values of $\kappa_r < 1$ indicate, that the resource budget is higher than current production and thus production of that material can increase. Values $\kappa_r > 1$ indicate a need to reduce the primary resource intensity of the global economy for this resource or change its production process (e.g. phase out fossil fuels).

When using sub-global entities (e.g. industries, countries or companies), ERA budgets have to be allocated to the respective level and current primary production volume used on that level for the reference year. This results in reduction targets for each resource used within a specific sector.

For products requiring multiple resources, a single reduction target κ_p can be defined by aggregating reduction targets of individual resources used in the product. We propose to aggregate the reduction targets of the resources weighted by the respective resource pressure $\tau_{r,p}$:

$$\kappa_p = \frac{\sum_r \kappa_r \cdot \tau_{r,p}}{\sum_r \tau_{r,p}}$$

In this way, the higher the resource pressure (meaning the less favourable for the environment), the more important the reduction target of the specific resources and it thus weights more in the overall reduction target for the product. This increases the incentive for the product designer to substitute resources with high reduction targets κ_r or focus on the reduction of their resource pressure $\tau_{r,p}$.

Resource reduction index

The resource pressure for a new product can be compared with a reference product from the same year as the primary production data used in the definition of the reduction target. The aim shall be to reduce the resource intensity of the new product at least by κ_p (or κ_r, if only one resource is used or investigated) compared to the reference product. Progress towards this goal is measured by the primary *resource reduction index* (RRI). RRI measures the extent to which the primary resource reduction target for a product κ_p is reached.

$$RRI_p = \frac{\frac{\tau_{cum,p,ref}}{\tau_{cum,p}} - 1}{\kappa_p - 1}$$

It can be evaluated for single materials, products or higher entities (e.g. companies, households). Designs containing different materials can be compared on a product level when comparing the cumulative resource pressure $\tau_{cum,p}$ of the reference product and the new design with the reduction target of the new design κ_p.The RRI equals one when the resource intensity reduction of the product equals the required resource reduction target κ_p. If $RRI > 1$, the reduction target is overachieved and an increase in demand is possible. If $RRI < 1$, the reduction is insufficient to reach sustainability. RRI is zero, if the resource pressure of the reference product is equal to the reference, e.g. when no reduction/change in production processes took place. The reference product shall represent the global average product fulfilling the same function. For example, for a washing machine the reference product is the market share weighted average of the resource pressure exerted by sold washing machines worldwide (see figure 1). Note, for a product creating new demand no reference products exist and therefore the RRI cannot be calculated.

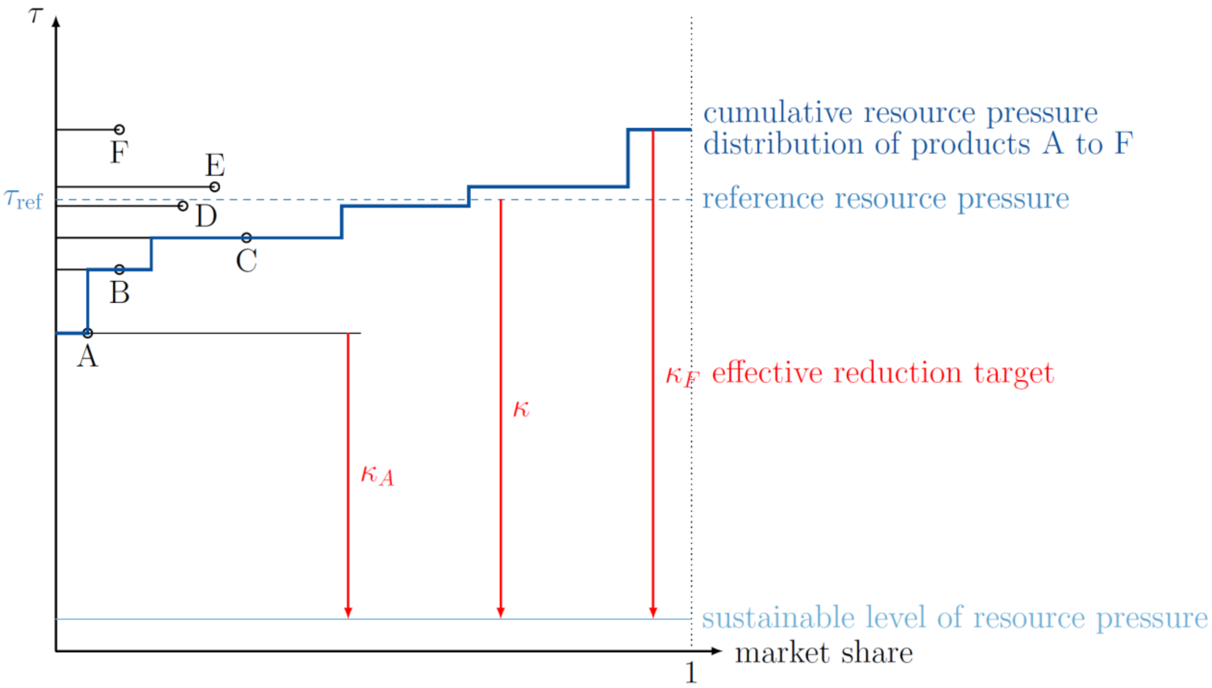

Figure 1. The reference resource pressure τ_{ref} can be calculated as the market share weighted average of the products on the market (A to F). Product A, which has a lower resource pressure than the reference, also has a lower effective reduction target κ_A as part of the reduction is already achieved. On the contrary, product F has a higher reduction target as its resource pressure is larger than the reference.

RRI can be increased by the product design by decreasing the resource pressure of the new design and by avoiding resources with high reduction targets κ_r. Additional to products, the indicator can be applied on different levels, e.g. on company, sector, country and global levels.

Case study

RRI is applied in an illustrative case study of an innovative circular textile product designed by the wear2wear™ consortium (www.wear2wear.org). The product under investigation is a work-wear jacket integrating several circular economy principles. The jacket itself is made of few and easily separable materials to enable a straightforward recycling process at end-of-life (EoL). An innovative sewing yarn is used for the seams, which dissolves in boiling water. In this way, the zipper can easily be separated from the jacket at EoL and reused up to three times. To ensure that the jacket returns for recycling, it is rented out – not sold – to the costumer. During the use-phase, an industrial washing service is provided. The polyester jacket is regranulated in a polymer melting process and the recycled granulate is again spun into new filament fibers. Overall, the jacket consists of a three-layer laminate (outer material, membrane, lining), a zipper, yarn, pocket magnets, shanks and buttons. For more information regarding the design of the product system, please see the respective Life Cycle Assessment (LCA) carried out by Braun et al. (2021). The mentioned LCA study compares the circular jacket to a linear reference jacket to understand the improvements/ deteriorations of designing a textile with circular elements. Therefore, the fictive linear jacket contains the exact same components. However, it does not include the recycling and reusing elements and is in fact incinerated at EoL. The results of the LCA show a reduction potential of the circular jacket of 1/3 in terms of greenhouse gas (GHG) emissions compared to a linear one.

Figure 2. The wear2wear production loop. Starting from the light green field, the fibres are spun either from virgin PES or recycled granulate. The fabric is a three layered laminate just made of PES to guarantee optimal recycling at the EoL, where new fibres are made again from remolten granulate *(*wear2wear™, 2020*).*

In this study, we use the same two products and compare them based on the resource pressure method and RRI. In total, five scenarios are investigated in detail, comprising varying parameters for the circular jacket. Each scenario is compared to the linear reference case (scenario *Linear*). A detailed description of the scenarios is given in Table 1.

Table 1. Parameters for the resource pressure method for each scenario of the linear and circular jacket. Each parameter is the sum of the different product components. The *Linear* scenario includes no recycling/ cascading activity at the EoL (instead incineration with energy recovery) and manufacturing losses are low. The manufacturing losses of all circular scenarios are assumed equal to the *Linear* version except for the first *Circular* scenario, which represents the prototype manufacturing process with higher losses. The primary material input reduces with an increasing value for recyclability/ cascadability. Moving from *Circular* to *Circular R+*, the primary material input decreases due to less manufacturing losses. The *Circular R++* scenario goes one-step further and assumes that even manufacturing losses are recycled (and thus increasing the recyclability value). In the Circular optimal scenario, it is additionally assumed that everything that is not recycled (due to quality issues), is cascaded and all material inputs are taken from secondary production.

Scenario	Linear	Circular	Circular R+	Circular R++	Circular optimal
Resource budget (kg)	6.28E+08				
Mass in product (kg)	0.39				
Manufacturing losses (kg)	0.23	0.29	0.23	0.23	0.23
Lifetime (years)	4				
Primary material input (kg)	0.62	0.42	0.36	0.15	0.02
Recyclability (kg)	-	0.26	0.26	0.47	0.47
Cascadability (kg)	-	-	-	-	0.11

The ERA budgets and the mass in product are the same for each scenario, because each jacket contains the same amounts of the same materials. The manufacturing losses for the "original" circular jacket (scenario *Circular*) are higher compared to the other scenarios. This is because at the point of data collection, the wear2wear production system was still in its prototyping phase, which results in higher manufacturing losses. Reflecting industrial scale production, the same amount of manufacturing losses are assumed in scenario *Circular R+*, *Circular R++* and *Circular optimal* as for the linear jacket. Note, that manufacturing losses summarize all losses along the entire supply chain (from fibre spinning to the manufacturing of the final product). The lifetime is assumed equal for all jackets. The primary material input is higher for the linear compared to the circular jacket. It decreases with a higher recyclability. Recyclability is divided into two categories: first, for material that is recycled at EoL of products and second, for manufacturing losses. In the scenario *Circular*, no recycling of manufacturing losses is assumed, as during the prototyping phase this was not the case. In scenario *Circular R+* and onwards, recycling of manufacturing losses is assumed with a recyclability of 95%, as these materials are pure and can be easily recycled. Materials are not cascaded (i.e. downcycled) except in scenario *Circular optimal,* where everything that is not recycled is assumed to be cascaded (except for glue & yarn). Additionally, the *Circular optimal* scenario assumes that all materials are made from secondary production (cascaded materials from higher quality, e.g. food-grade PET bottles).

We calculate in the next chapter the resource pressure for all materials contained in the jacket and neglect the contributions from all auxiliary materials (e.g. washing detergents) and energy (i.e. for production, use and recycling). ERA budgets are calculated following the grandfathering allocation approach as presented in (Desing et al., 2020). Environmental impact data for plastics are taken from ecoinvent v.3.6 (Wernet et al., 2016) and production amounts for 2015 from (Ryberg et al., 2019). ERA budgets and production amounts for metals are taken from (Desing et al., 2020).

Results and Discussion

Before the RRI can be calculated for all scenarios, the reduction targets must be set. We defined the reduction targets for our case studies based on a comparison between the resource budgets with today's production. This is a simplification and it would be best to define Science-based Targets (Pineda et al., 2015) for individual materials, industries, or countries to account for differences in the production processes, maturity of the technologies applied, etc. The reduction targets and the resulting RRI for each scenario are presented in table 2. Our current way of setting the reduction target would require all scenarios to decrease the resource pressure equally by a factor of 32.

Based on these input parameters the resource pressure of each product in the above-mentioned scenarios is calculated. Figure 3 compares them to each other. The resource pressure for the linear jacket is highest. The resource pressure of the *Circular* scenario is about half the linear one; while the reduction for the *Circular R+* scenario is 2.2 times, the *Circular R++* scenario 2.6 times and the *Circular optimal* scenario 35 times lower than the linear version. Comparing the circular and linear scenarios, the reduction of resource pressure (1/2) is somewhat higher than the reduction of greenhouse gas emissions (1/3) found in the original LCA by Braun et al. (2021). This is due to the above mentioned simplifications made for the analysis of the resource pressure.

Table 2. Resource pressure, reduction target and RRI for each scenario. Small changes in reduction targets are due to different resource pressures for each component in the various scenarios.

Scenario	Linear	Circular	Circular R+	Circular R++	Circular optimal
Resource pressure	5.56E-09	3.16E-09	2.66E-09	9.85E-10	8.22E-11
Reduction target	31 – 33				
RRI	0	0.03	0.04	0.05	1.1

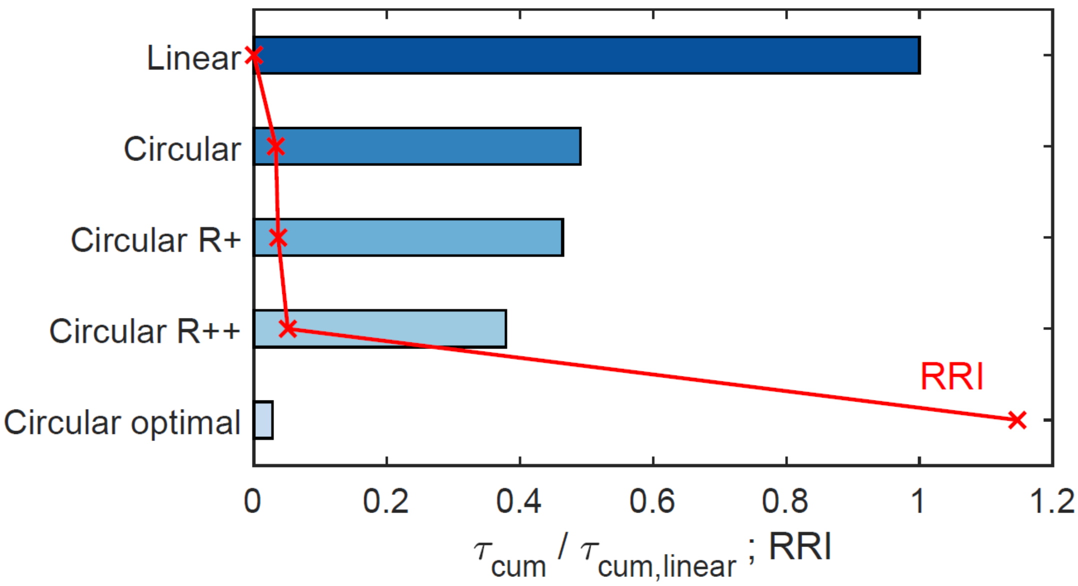

Figure 3. Resource pressure of each product in each scenario (blue bars) and RRI in each scenario (red line). The *Circular optimal* scenario reduces the resource pressure the most – 35 fold – and thus overachieves the reduction target (RRI>1).

The RRI indicator is for the first three scenarios far below one and only for the last scenario >1. That means that the circular textile in the *Circular optimal* scenario has sufficiently reduced its resource pressure to be considered absolute sustainable within planetary boundaries. All other scenarios fall short of the reduction target, therefore the circular strategies of *refuse* and *reduce* (Reike et al., 2017) decreasing the production amount would need to be applied in order to stay within planetary boundaries. The RRI increases with the improvements in the scenarios. As the RRI is proportional to the reduction factor, large initial reductions in the resource pressure τ_r

result in a low increase of the RRI (e.g. from *Linear* to *Circular* scenarios), while additional reductions in τ_r have a stronger effect on RRI (e.g. from *Circular R++* to *Circular optimal* scenarios). The reason is explained by a simple, fictive example: if τ_r is reduced by 50% - meaning that a product has decreased its environmental impacts from 1 to 0.5 (minus 0.5), the reduction factor is 2 – still far away from the reduction target of 32. If the product's impact can be further reduced in a second step from 0.5 to 0.05 (minus 0.45), the reduction factor now is already 20, even though the impact has only been reduced by 0.45 (compared to 0.5 in the first step). In other words, the RRI reacts most strongly for small improvements closer to the reduction target, whereas large improvements around the reference resource pressure value have a small effect on the RRI. This can be justified by the extra efforts that need to be taken for additional reduction on an already low level of resource pressure. For our textile product *Circular R++* scenario, many improvements have been assumed compared to the scenario *Circular* (reduction of manufacturing losses by 0.06 kg, decrease of primary material input by 0.27 kg, increase of recyclability by 0.21 kg) with a resulting RRI improvement of 0.02. In comparison, when moving from *Circular R++* to *Circular optimal* (primary material input decreases by 0.13 kg, cascadability increases by 0.11 kg) the RRI increases by 1.1. This sharp increase can be traced back to eliminating most primary material input and final losses in combination with the already implement circularity in the previous scenario, thus reducing the resource pressure significantly. In the *Circular optimal* scenario it is assumed that every material for the jacket is delivered by secondary production (e.g. cascaded from PET bottles) and that everything that is not recycled at the EoL will be cascaded. That means, no primary materials are required as an input to the product system (except for the glue & yarn) and everything leaving the system is recycled or cascaded. The combination of these measures leads to the drastic reduction in the resource pressure indicator (and thus increasing RRI) which is in line with the idea of the methodology itself (Desing et al., 2021a). Implementing the *Circular optimal* scenario in practice will require extraordinary efforts in comparison to the other scenarios, therefore also the "award" by the RRI is reasonable.

Moreover, there are certain limitations to the RRI for the moment. We show here the application of the RRI indicator on global reduction targets. This would require all industries to reduce their resource pressure equally. However, as some products and services are more necessary (e.g. food) than others (e.g. racing cars), it will be more relevant to define reduction targets on the level of product groups or industries. Furthermore, to determine the RRI indicator, we must compare the new design to a reference product. This choice is critical for the result as a reference product with high environmental impacts allows achieving the reduction target easier than a reference product with low impacts. We propose that the reference product should represent a global average product with global average values for the parameters in τ, because resource budgets (Desing et al., 2020) are based on global averages as well. For new products that fulfil similar functions as existing products, the average of existing products can be taken as a reference. However, for innovation creating a new demand, no reference exists and therefore RRI cannot be determined. Additionally, in the case that materials are substituted in the design in regard to the reference (e.g. use of paper instead of plastic for shopping bags), the RRI indicator is not fully consistent, as the reduction target is set by the materials of the new design. However, it still provides guidance on the question, if the design can reduce the resource pressure more effectively and thus ensure a higher utility of the sustainably available materials to society. All these limitations are potential areas for further development of the RRI.

Conclusions

In this contribution, we introduce the Resource Reduction Index (RRI) and show its application in a case study of a circular textile product. RRI measures to what extent the target for reducing primary resource consumption can be fulfilled with the circular redesign of a product or service. Reaching the target (i.e. getting a RRI≥1) through reducing the resource pressure in the activity under investigation by circularity measures means that the demand for this activity can be kept constant and still be environmentally sustainable. Not reaching the target (i.e. getting a RRI<1) means that either circular strategies of "refusing" and "reducing" the demand are necessary or that the production process of materials themselves must be redesigned (to cause less environmental impacts and thus increasing their resource budgets) to reach absolute environmental sustainability. RRI is indicating to the designer and business developers how much circular design improvements can help in reaching a sustainable level of resource consumption. However, absolute environmental sustainability cannot be analysed and guaranteed by a focus on a single activity alone, but must be assessed and respected on a global level at all times.

RRI contributes an easy-to-handle indicator for measuring absolute sustainability of products and services to the ongoing scientific effort. Before implementing the RRI, a discourse on "desirable" resource budgets is necessary (Desing et al., 2020). This includes to explore different allocation principles (Kulionis et al., 2021; Ryberg et al., 2020) and their effect on global resource budgets, while ensuring to provide basic needs for a decent life globally (Millward-Hopkins et al., 2020; Rao and Min, 2018). It further requires an international harmonization and agreement on resource budgets and their distribution among countries and industries (Pineda et al., 2015), so that resource reduction targets can be applied consistently to all products and services.

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