Doctoral Thesis

Multiple application of statistical entropy: New methods to assess the effectiveness of recycling processes and the recyclability of products

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Dissertation

Multiple Anwendung von Statistischer Entropie: Neue Methoden zur Bewertung der Effektivität von Recyclingprozessen sowie der Recyclingfähigkeit von Produkten

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Abstract

Back in 2015, the first Circular Economy (CE) Package was implemented by the European Union (EU), aiming to establish a more sustainable economy within the EU (European Commission, 2014b, 2014a, 2018b, 2018a; European Union, 2020). The goal of CE is to move away from a linear economy to one that keeps products and materials in circulation, thus significantly reducing resource demand, waste generation and environmental impacts. This transition represents a complex undertaking that needs comprehensive monitoring and evaluation. Therefore, the EU set various actions to promote new assessment methods and indicators, evaluating processes and aspects relevant in a CE. On the one hand, the EU plans to improve existing assessment methods and indicators and, on the other hand, to develop new ones (European Union, 2020).

This thesis aims to develop assessment methods that focus on evaluating recycling-relevant conditions. Previous applications demonstrated that the concept of statistical entropy (SE) offers a suitable measure for assessing various processes in resource and waste management (Rechberger, 1999; Rechberger and Brunner, 2002; Dahmus and Gutowski, 2007; Velázquez Martínez *et al.*, 2019; Parchomenko *et al.*, 2020). SE describes the distribution of materials in a system observed. Strongly mixed materials result in a high SE, while pure materials show a minimum SE. In recycling, the performance significantly depends on the distribution of materials, where pure materials are favourable for recycling, but mixed materials complicate recycling. Thus, SE seems suitable for assessing recycling conditions and is subsequently used for the following thesis.

First, an assessment method is developed that aims to evaluate recycling processes' quantitative and qualitative performance. The background is that the current European method to evaluate recycling performances, namely the recycling rate calculation, is based on a purely quantitative approach, thus neglecting to assess qualitative recycling aspects (purity of the recycled material output). The performance of recycling processes should not only reflect its power to separate target materials from unwanted materials but moreover its power to concentrate target materials of high concentration in the recycling output. The developed assessment method finds a way to express both aspects by establishing separate mass balances of recycling processes, one that displays the total mass flows of the recycling process (= quantitative) and one showing the target material mass flows (= qualitative). By combining these mass balances, the concentration of the target material in the output mass flows can be determined, thus reflecting the recycling process's qualitative performance. The final result is presented as a single value, allowing easy comparisons. The resulting “Recycling Effectiveness” (RE) indicator allows significant comparisons between different recycling processes and thus poses a complementary metric to the conventional recycling rate.

Second, products and their design are analysed concerning their recyclability. Products that comprise pure materials are generally easier to recycle than ones showing material mixture. Also, in this respect, SE seems an appropriate measure for the deduction of the recyclability conditioned by the product's material composition. Further, the structure of the product and thus the possibility of disassembling product parts is considered for the recyclability assessment because disassembly significantly impacts the recovery of concentrated materials. As these product characteristics are decided in the design phase, the assessment concerns this product phase. Thus, the new assessment method and the resulting "Relative product-inherent recyclability" (RPR) indicator evaluate the product-inherent recyclability

based on the product's material composition and structure. The results of the RPR assessment provide relevant insights into the product's recyclability, thus enabling early product design optimizations.

The new assessment methods and resulting indicators offer profound evaluation of recycling-relevant conditions, thus allowing meaningful comparisons and optimizations. Different stakeholders might profit by applying the new indicators to increase the overall recycling performance and create a more sustainable environment. The EU could use the indicators to promote their CE strategies and further evaluate the progress towards a CE.

Kurzfassung

Im Jahr 2015 wurde das erste Kreislaufwirtschaftspaket von der Europäischen Union (EU) umgesetzt, um eine nachhaltigere Wirtschaft in der EU zu etablieren EU (European Commission, 2014b, 2014a, 2018b, 2018a; European Union, 2020). Ziel der Kreislaufwirtschaft ist es, von einer linearen in eine zirkuläre Wirtschaft überzugehen, in der Produkte und Materialien in Kreislauf gehalten werden, wodurch der Ressourcenverbrauch, das Abfallaufkommen und die Umweltauswirkungen deutlich reduziert werden. Dieser Übergang ist ein komplexes Unterfangen, das eine umfassende Überwachung und Bewertung erfordert. Daher hat die EU verschiedene Maßnahmen zur Entwicklung neuer Bewertungsmethoden und -indikatoren festgelegt, mit denen für eine Kreislaufwirtschaft relevante Prozesse und Aspekte bewertet werden. Einerseits plant die EU, bestehende Bewertungsmethoden und Indikatoren zu verbessern und andererseits Neue zu entwickeln (European Union, 2020).

Ziel dieser Arbeit ist es, Bewertungsmethoden zu entwickeln, die sich auf die Bewertung von recyclingrelevanten Bedingungen konzentrieren. Frühere Anwendungen haben gezeigt, dass das Konzept der Statistischen Entropie (SE) eine geeignete Methode für die Bewertung verschiedener Prozesse in der Ressourcen- und Abfallwirtschaft darstellt (Rechberger, 1999; Rechberger and Brunner, 2002; Dahmus and Gutowski, 2007; Velázquez Martínez *et al.*, 2019; Parchomenko *et al.*, 2020). SE beschreibt die Verteilung von Materialien in einem betrachteten System. Stark vermischte Materialien führen zu einer hohen SE, während reine Materialien einen minimale SE aufweisen. Beim Recycling hängt die Leistung wesentlich von der Verteilung der Materialien ab, wobei reine Materialien für das Recycling günstig sind, gemischte Materialien jedoch das Recycling erschweren. Daher scheint SE für die Bewertung von Recyclingbedingungen geeignet und wird in der folgenden Arbeit verwendet.

Zunächst wird eine Bewertungsmethode entwickelt, die darauf abzielt, die quantitative und qualitative Leistung von Recyclingprozessen zu bewerten. Hintergrund ist, dass die derzeitige europäische Methode zur Bewertung der Recyclingleistung, nämlich die Berechnung der Recyclingquote, auf einem rein quantitativen Ansatz beruht und somit die qualitativen Aspekte des Recyclings (Reinheit des recycelten Materialoutputs) vernachlässigt. Die Leistung von Recyclingverfahren sollte nicht nur die Fähigkeit widerspiegeln, Zielmaterialien von unerwünschten Materialien zu trennen, sondern auch die Fähigkeit, Zielmaterialien mit hoher Reinheit im Recyclingoutput zu konzentrieren. Die entwickelte Bewertungsmethode bringt beide Recyclingaspekte zum Ausdruck, indem sie getrennte Massenbilanzen eines Recyclingprozesses erstellt, von denen eine die gesamten Massenflüsse des Recyclingprozesses (= quantitativer) und die andere die Zielmaterialmassenflüsse (= qualitativ) darstellt. Durch Kombination dieser Massenbilanzen kann die Konzentration des Zielmaterials in den Outputmasseflüssen bestimmt werden, was die qualitative Leistung des Recyclingprozesses widerspiegelt. Das Endergebnis wird als ein einziger Wert dargestellt, der einfache Vergleiche ermöglicht. Der resultierende "Recyclingeffektivität" (RE) Indikator ermöglicht aussagekräftige Vergleiche zwischen verschiedenen Recyclingprozessen und stellt somit eine ergänzende Messgröße zur herkömmlichen Recyclingquote dar.

Zweitens werden Produkte und deren Design in Hinblick auf deren Recyclingfähigkeit untersucht. Produkte, die aus reinen Materialien bestehen, sind im Allgemeinen leichter zu recyceln als solche, die ein Materialgemisch aufweisen. Auch in dieser Hinsicht scheint SE ein geeignetes Maß für die Ableitung der Recyclingfähigkeit in Abhängigkeit von der

Materialzusammensetzung des Produkts zu sein. Darüber hinaus wird die Struktur des Produkts und damit die Möglichkeit der Zerlegbarkeit von Produktteilen bei der Bewertung der Recyclingfähigkeit berücksichtigt, da die Demontage einen erheblichen Einfluss auf die Rückgewinnung von konzentrierten Materialien hat. Da diese Produktmerkmale in der Entwurfsphase festgelegt werden, bezieht sich die Bewertung auf diese Produktphase. Die neue Bewertungsmethode und der daraus resultierende "Relative produkt-inhärent Recyclingfähigkeit" (RPR) Indikator bewerten die produkt-inhärente Recyclingfähigkeit auf der Grundlage der Materialzusammensetzung und Struktur des Produkts. Die Ergebnisse der RPR-Bewertung liefern relevante Einblicke in die Recyclingfähigkeit des Produktes und ermöglichen so rechtzeitige Optimierungen des Produktdesigns.

Die neuen Bewertungsmethoden bieten eine fundierte Bewertung von recyclingrelevanten Bedingungen und ermöglichen so aussagekräftige Vergleiche und Optimierungen. Verschiedene Akteure könnten von der Anwendung der neuen Indikatoren profitieren, um die Recyclingleistung insgesamt zu steigern und eine nachhaltigere Umwelt zu schaffen. Die EU könnte die Indikatoren nutzen, um ihre CE-Strategien voranzubringen und die Fortschritte auf dem Weg zu einer CE zu bewerten.

Published articles and author's contributions

The doctoral thesis' results have also been published or at least submitted in peer-reviewed scientific journals as the following three articles:

C. Roithner and H. Rechberger (2020). "Implementing the dimension of quality into the conventional quantitative definition of recycling rates". In: *Waste Management* 105, pp. 586-593. DOI: 10.1016/j.wasman.2020.02.034

C. Roithner, O. Cencic and H. Rechberger (2022). "Product design and recyclability: How statistical entropy can form a bridge between these concepts - a case study of a smartphone". In: *Journal of Cleaner Production* 331, pp. 129971-129980. DOI: 10.1016/j.jclepro.2021.129971

C. Roithner, O. Cencic, M. Honic and H. Rechberger (submitted). "Recyclability assessment at the building design stage based on statistical entropy: A case study on timber and concrete building". Submitted to: *Resources, Conservation & Recycling*.

Author's contributions:

In all three articles, formal analysis, investigation, visualisation and writing – original draft preparation was undertaken by the author of the present doctoral thesis. Conceptualisation, methodology development, data curation, validation and writing – review and editing were performed in cooperation with the respective co-authors.

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1. Introduction

Global resource use increased significantly in the last decades (Krausmann *et al.*, 2017; Wiedenhofer *et al.*, 2019), although it is well known that earth's resources are finite (or scarce) and require sustainable consumption. Extraction and production of resources put significant pressure on the environment in the form of, e.g. air emissions or land use change (Krausmann *et al.*, 2017). Poor material intensities reinforce these developments due to the loss of resources (United Nations Environment Programme, 2016). In addition, stock building leads to a persistent demand for resources, as the high resource inputs do not flow back into the value chain as quickly as necessary (Krausmann *et al.*, 2018). Thus, essential secondary raw material outputs might only be successively available in the future. At this point, it should be noted that the recycling of materials is not always easy, as materials often occur in mixtures, which makes material-specific recycling more difficult.

Therefore, these concerns reached the centre of society and are not just visible for policymakers. Society's awareness of sustainable consumption is raising (Schmeltz, 2012; United Nations Headquarters, 2019). The challenge is maintaining a prosperous economy while achieving efficient resource consumption and low environmental impacts. A trend reversal could be achieved with concepts on decoupling resource use from economic activity and environmental impacts (United Nations Environment Programme, 2011). Recycling and reusing materials are relevant processes in this development by reducing new resource extraction and production. However, the implementation of such concepts requires significant political and social changes. Countries can hardly solve these concerns independently, so global strategies are needed to consider global interdependencies. Thus, in 2015 international commitments have been made to cope with these problems. The United Nations (UN) presented the so-called 17 sustainable development goals (SDGs) that aim to implement a society that is based on environmental, economic and social principles, thereby respecting the different development stages of countries (United Nations, 2015). For example, SDG 12 aims to ensure sustainable consumption and production. Further, the European Union (EU) committed to transforming into a Circular Economy (CE) (European Commission, 2014b, 2014a), reinforced by the Green Deal presented in 2019 (European Commission, 2019b, 2019a). The presented CE Action Plan (CEAP) includes manifold strategies and measures to implement a CE along the whole value chain. In the following, only the CE concept according to the EU is discussed; other political or scientific concepts are not considered.

CE aims to extend the use phase of products and materials, thus moving away from a linear economy that requires large quantities of resources while producing high waste amounts. Waste generation is reduced to a necessary minimum. Circular material use promotes higher resource efficiency and a reduced need for primary resources. Besides that, negative impacts on e.g. climate, water, biodiversity or health, are drastically reduced in a CE. Consumers are provided with products of high quality and long durability that can be recycled, reused or repaired. Concerning quality, recycling outputs are in the focus of the CE, thus promoting a vital secondary materials market. In this context, there is often talk of "closed-loop" and "open-loop" recycling; closed-loop recycling refers to recycled materials that are used in the same product again, while "open-loop" recycling includes recycled materials used in a different product (usually associated with downcycling) (Haupt, Vadenbo and Hellweg, 2017). The primary strategy lies in closed-loop recycling, but some downcycling will be unavoidable. These points already show that the transition towards a CE involves the entire value chain (see Figure 1), requiring different process adaptations and effective stakeholder cooperation. As mentioned in the previous paragraph, the CEAP contains a wide range of measures and strategies that address the individual stakeholders of the value chain.

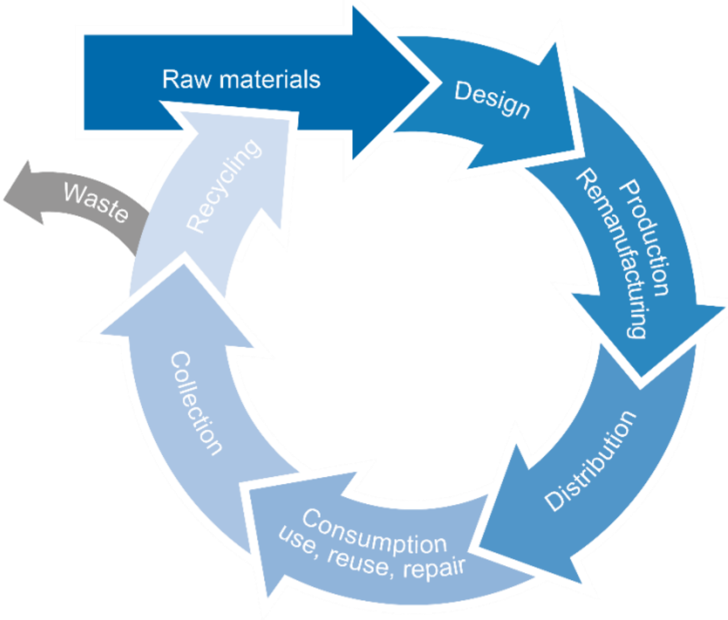

Figure 1 Value chain in a Circular Economy.

One of the first measures implemented by the EU was the significant increase of the existing recycling targets (e.g. from 22.5% to 55% by 2030 for plastic packaging), as maximal recycling is key to a CE. Massive improvements in recycling performances will be required for specific waste streams to achieve these new targets on time. Analogously, improvements in the associated collection and pre-sorting processes are necessary but are not addressed further here. Another implemented measure concerning recycling rates was adapting the calculation to enable a more precise picture of recycling performances, moving the calculation point from the recycling input to the output (European Parliament and European Council, 2018). This adaptation puts additional pressure on the recycling industry, leading to lower recycling rates. A situation might arise in which the increase of recycling rates is primarily based on a quantitative implementation of the recycling industry at the expense of the quality of the recycling outputs. In this regard, recyclers might focus on recycling materials of large quantities (e.g. steel) and high monetary value that are simple and efficient to recycle (Dahmus and Gutowski, 2007; Velázquez Martínez *et al.*, 2019). Such a narrow recycling focus could result in a decrease in the recovery of rare or minor materials (e.g. molybdenum) (Reck and Graedel, 2012), although several of these materials show an ecological and economic significance (see (European Commission, 2020b)). However, such a development would be at odds with CEAP's objective to promote high-quality (recycled) material streams. Beyond that, the recycling market's capacity to absorb low-quality recycling materials is bounded because the application possibilities are limited (Eriksen *et al.*, 2019). Some recyclers tend to increase the material quality by diluting with, e.g. virgin or high-quality recycled material (Haupt, Vadenbo and Hellweg, 2017). However, in the long run, such a system is not sustainable, as the generation of low-quality materials causes irreversible material losses in a CE, which lead to additional environmental and economic expenses for the following cycles (Kral, Kellner and Brunner, 2013; Haupt, Vadenbo and Hellweg, 2017).

Apart from the recycling, preceding value chain processes, namely design and manufacturing, must be significantly involved in the CE transition since they set the conditions for recycling. According to an analysis ordered by the European Parliament, even more than 80% of the environmental impacts associated with a product is determined in the design phase (Keirsbilck *et al.*, 2020). It is more than necessary that designers and manufacturers be held accountable and ensure that products (and their materials) are designed to be recycled (or reused/repaired) in the best possible way. Currently, for most products, the "end-of-life" phase is hardly a crucial factor in the design or manufacturing phase but rather is seen as the main task of waste management. Thus, the responsibility will shift from the recyclers to the designers and manufacturers in a CE, who will ensure that products and materials enable multiple and/or extended use cycles. Recently, several design concepts and guidelines have been developed in the areas of "Design for recycling/reuse/disassembly", which might be forming the basis for future products (McDonough *et al.*, 2003; Anastas and Zimmerman, 2007; Schwede and Störl, 2016; den Hollander, Bakker and Hultink, 2017; van Stijn *et al.*, 2020; Berwald *et al.*, 2021; Dams *et al.*, 2021; Sanchez *et al.*, 2021). Thereby, the „end-of-life" of products is moving into the decision-making process of design. To this end, the CEAP includes several principles to design and manufacture products in line with CE, with increasing the recyclability[1] of products as an indispensable objective. For example, principles have been listed that aim to design more durable, material-efficient or light-weighted products. The announced adaptation of the Ecodesign Directive (European Parliament and European Council, 2009a) aims to set relevant guidelines and requirements that promote recycling-friendly and sustainable product design, thus going beyond energy efficiency. It can be assumed that the list of CE strategies will further increase over the coming decades, covering different aspects concerning product design.

However, to evaluate the implementation of these ambitious CE strategies, meaningful assessment methods are required that help to evaluate and monitor the CE transition. Thus, the CEAP also provides the development of new CE metrics and indicators. Besides "large-scale" metrics that, e.g. measure the circularity of entire systems, "small-scale" metrics are necessary that e.g. assess the product-specific recyclability. This shows that different CE indicators are needed to monitor the CE transition comprehensively, covering the entire value chain. It should be mentioned that the goal cannot be to find the only valid assessment method but, like in a puzzle, to find a suitable combination of metrics that will enable an optimal assessment of the complex CE transition. In the following, the focus lies in monitoring and assessing recycling-relevant conditions.

At present, the EU measures recycling performances with the recycling rate that describes the ratio between the recycled and the generated waste mass. Member States' recycling rates aim to record the achievement of the European recycling targets. This assessment principle was established in 1994 (European Parliament and European Council, 1994). It addressed

[1] There is currently no generally applicable definition of recyclability at the EU level; in this thesis, recyclability is expressed that individual materials from a product can be used again in new products after undergoing a recycling process.

packaging waste and, later, municipal and electrical and electronic equipment waste. Since then, the calculation of the recycling rates has been adapted (as mentioned before). This simply constructed indicator has helped capture recycling performances in the EU for the first time and has since made it possible to monitor recycling activities in the individual Member States. However, after more than three decades of recycling assessment, it is evident that recycling performance should be reflected by quantities and the quality of the recycled (target) material/s. An effective CE requires materials of high quality, which is why recycling processes should also be measured by how pure the materials are in the recycling output, thus preventing material downcycling due to poor quality. Currently, this cannot be expressed with the recycling rate, so a further adaptation of the recycling rate would be necessary, or another metric is used at all.

Presently, there is no assessment method or indicator generally applicable in the EU for evaluating the recyclability of products. First steps in this direction have been taken by introducing consumption and material footprints (European Commission, 2020a). However, these are mainly linked to monitoring the decoupling between economic growth and resource use. Some European product policies address the environmental impacts of products, such as e.g. the EU Ecolabel. The EU Ecolabel aims to identify products or services with a reduced environmental impact during their life cycle (European Parliament and European Council, 2009b). Further, the EU works on the establishment of a so-called “Product Environmental Footprint” (PEF) tool that aims to evaluate the environmental impacts along the product’ life cycle (European Commission, 2013). The EU proclaimed in the CEAP that, among others, recyclability would be a new criterion in the EU Ecolabel (European Union, 2020). Therefore, the EU’s reviewing and adaptation of the Ecodesign Directive will also include aspects of the EU Ecolabel and the PEF tools (European Union, 2020). Overall, a clear need within the EU for assessment methods and resulting indicators regarding product recyclability can be identified.

Scientists and related institutions have already taken up the development of new assessment methods and indicators concerning recycling-relevant conditions. Regarding the inclusion of qualitative aspects in the recycling performance assessment, there is a diversity in the proposed assessment methods, which are based, among other things, on the different interpretations of quality and assessment approaches (Life Cycle Assessment (LCA) and Material Flow Analysis (MFA)). In the study of Haupt and colleagues, the recycling rate defined by the EU (at the time of the study still related to the input) was contrasted with alternative collection and recycling rates (Haupt, Vadenbo and Hellweg, 2017). Of the discussed variations, a recommendation was made for so-called closed- and open-loop recycling rates (see explanations before). With these split recycling rates, different qualities of recycled material are reflected. In the assessment method of Huysman and colleagues, the CE performance of recycling processes is evaluated using several steps (Huysman *et al.*, 2017). Therefore, in the first step, the recycling output’s quality is classified into four categories: high/medium/low/very low quality; the different qualities relate to specific waste treatments, e.g. “very low quality” for incineration. According to the quality and associated waste treatment, the substitution potential of the recycled material is calculated. In the next step, the associated “actual environmental benefits” are calculated; environmental benefits are considered by LCA, focusing on natural resource consumption. In the last step, the actual benefit is set in relation to the “ideal environmental benefit according to quality”. This ratio provides the result for the so-called “circular economy performance indicator” (CPI); the higher the CPI, the better the CE performance. Another method of Eriksen and colleagues deals with the "Circularity Potential" (CP) (Eriksen *et al.*, 2019). The metric aims to assess the ability of recycling processes to close material loops. The CP calculation is based on the recycling process's physical losses and the quality loss of the recycled output relative to virgin material. Eriksen et al. define three quality levels (high/medium/low quality) that reflect application groups (e.g. food packaging for high quality). Thus, the higher the quality of the material observed, the better its CP. To summarize, the different assessment methods and resulting indicators presented are based on certain assumptions regarding quality that may lead to uncertainties concerning the reliability of the results. This shows that the definition of a consistent assessment basis is difficult but necessary to enable an extended evaluation of recycling performances.

Compared to the qualitative assessment of recycling performances, the recyclability assessment seems even more complex because various recyclability-relevant aspects can be considered to deduce the product's recyclability. Relevant recyclability-aspects are, among others, the product's material composition and structure, ease of disassembly or physical/chemical material properties, but also more far-reaching aspects concerning the use and end-of-life phase like, e.g. energy efficiency or durability. Consequently, existing assessment methods differ in the parameters considered (e.g. environmental impacts, economic values or physical quantities) and associated system boundary. While some methods include the whole product life cycle, others cover the recycling or design phase only. However, it seems necessary to cover the design phase since product characteristics impacting recycling are specified in this phase. Existing design concepts, such as "Design for recycling", are readily used in the assessment method development (mainly in the building sector) (Vefago and Avellaneda, 2013; Schwede, 2019; O'Grady *et al.*, 2021). Further, it can be recognized that recyclability assessment sometimes falls under "circularity" assessment. It is essential to differentiate between circularity assessments referring to entire systems (e.g. company performance) or individual products. Generally, circularity assessment measures the transition from a linear to a circular state (Ellen MacArthur Foundation, 2015). LCA has become established in the recyclability assessment, mainly applied to cover more than one product life phase. For example, Huisman and colleagues worked in several studies (Boks, Huisman and Stevels, 2000; Huisman, Boks and Stevels, 2000; Huisman, Stevels and Middendorf, 2001; Huisman, Stevels and Stobbe, 2004) on developing an environmentally weighted recyclability assessment for products that incorporates environmental impacts of the different material fractions. They also add the financial revenues and costs of the specific material fractions to enrich the environmental evaluation further. The overall goal of their assessment method is to improve the product's eco-efficiency at the end-of-life phase. Mesa and colleagues presented an extended LCA assessment approach to describe the so-called "material durability indicator" (MDI). In their method, the durability (e.g. flammability resistance, fatigue strength) and environmental footprint of materials (Mesa, González-Quiroga and Maury, 2020) are assessed. The MDI should help improve the product design and extend the lifespan of products. Apart from LCA-based assessment methods, Linder and colleagues defined a circularity metric at the product level that is based on economic values (Linder, Sarasini and van Loon, 2017). Their method evaluates if a product comprises fractions that originate from a used product and whether activities are required to recirculate materials affected (e.g. transport). Economic values represent the product vendor's costs. Their cost-based indicator should allow an easy application by various stakeholders and help establish recirculation activities. Vanegas and colleagues developed an assessment method based on the disassembly time of products (Vanegas *et al.*, 2017) that aims to evaluate the ease of product disassembly. The developed “ease of Disassembly Metric” (eDiM) describes the effort needed for disassembly, which, among others, depends on product connections or available tools. Also, the well-known Ellen MacArthur Foundation developed a rather complex method to assess circularity, resulting in the “material circularity indicator” (MCI) (Ellen MacArthur Foundation, 2015). The MCI allows measuring the circularity of material flows of products or even companies based on various data like raw material use or product use time. The proposed MCI should act as a decision-making tool for product designers. Even if many assessment methods can already be identified, there seems a need for an indicator that describes product recyclability more fundamentally, allowing widespread application by different stakeholders.

Over the last decades, statistical entropy (SE) analysis has become established as a new assessment approach in waste and resource management that allows the evaluation of fundamental phenomena (see detailed information in Chapter 2). The concept of SE originates from thermodynamics and has been further developed in information theory before being applied in waste and resource management. In principle, SE expresses the material distribution in a system observed by assessing material concentrations and mass flow rates. Such a system could be, e.g. a waste incineration plant that, among others, aims to concentrate heavy metals of the waste input flow in a specific output flow (e.g. the bottom ash) (Rechberger, 1999, 2012). If the concentrations of the heavy metals are equally high in the different output flows, SE is high and thus reflects a worse performance. On the contrary, if the waste incineration plant succeeds in concentrating the heavy metals in a designated output flow, the SE decreases. This principle can also be observed in recycling processes, which concentrate target materials in the intended recycling output flow by effectively separating unwanted materials into another output flow. As a result, a high target material concentration corresponds to a low SE, which is a favourable condition. Furthermore, SE can express quality since a pure material shows the maximum concentration (c; $c = 1$) and thus minimum SE ($SE = 0$). In addition to processes and their material flows, SE also seems suitable for expressing the recyclability of products by assessing the material composition expressed by individual material concentrations. If, e.g. the product shows a complex material composition due to mixing materials, the SE is high, which correlates with increased (or impractical) recycling efforts. Accordingly, recyclability can be derived by SE based on material composition. Overall, SE assessment meets essential requirements previously formulated concerning evaluating quantitative and qualitative recycling performances and product recyclability.

This thesis aims to develop assessment methods and thus indicators based on SE to evaluate the quantitative and qualitative performance of recycling processes and, second, the recyclability of products based on fundamental design decisions. The indicators should allow significant comparisons and enable widespread application by various CE actors. The assessment methods should stand out for their simple structure and achieve widespread understanding by expressing fundamental recycling conditions. Consequently, the assessment results should serve as a basis for system optimizations.

Before explaining these assessment methods, Chapter 2 discusses the further development of Rechberger and Brunner's SE assessment approach in this thesis.

In Chapters 3 and 4, the developed assessment methods and resulting indicators are presented, where first, the indicator for the recycling performance assessment is presented and last for the product recyclability evaluation.

Finally, Chapter 5 summarizes relevant conclusions, and Chapter 6 gives an outlook on future applications and developments.

2. Statistical entropy

Statistical entropy (SE) originates from thermodynamics but has constantly been evolved in different research areas, like, e.g. waste and resource management, over the last decades. In simplified terms, SE measures the degree of disorder of a system, respectively. The higher the degree of disorder, the higher is the entropy and vice versa. Generally, it is the goal to keep entropy low. For example, mixed waste collected in a public dustbin represents a state of higher entropy than being collected according to the different fractions in specific collection bins.

In the 1940s, Claude Shannon developed the concept of statistical entropy (H), which is similar to the physical concept of entropy, and measures information transfer and its uncertainty (Shannon, 1948). Shannon defined H as the average information content of a message. The information content of a character (expressed in the unit “bit”) decreases the more frequently it occurs in a message. He formulated Equation (1), where p_i is the probability of occurrence of events and ld is the logarithm to the base 2 (with ld(0) = 0). The H increases, the more events there are and the more uniformly distributed their chance of realization is.

$$H = -\sum p_i \, ld(p_i) \tag{1}$$

For material flow analysis in waste and resource management, Rechberger and Brunner modified Shannon’s SE approach to be able to determine the concentrating or diluting effect of processes on specific substances, describing a decrease or increase of disorder, respectively (Rechberger, 1999; Rechberger and Brunner, 2002). Their basic idea was to interpret the concentration (c) of a substance in a material flow system as a probability (p) (cf. Equation (1)).

In waste and resource management, the aim is to concentrate/separate certain substances, like target materials (e.g. valuable plastics) and pollutants (e.g. heavy metals), thus creating low entropy. For example, the performance of a waste incineration plant can be evaluated by its power to concentrate conservative pollutants (occurring in the waste input) in specific outputs by application of Rechberger and Brunner’s SE approach (Rechberger and Brunner, 2002). The principle of the assessment can be explained with a simplified example: the material flow system of a process shows one input mass flow that consists of a specific target material, and three output mass flows; the process’s objective is to concentrate the target material in a specific output mass flow. If the target material is present in all output mass flows in the same concentration ($c_1 = c_2 = c_3$) after passing through the process, this is the worst-case as entropy is high and all outputs comprise target material (H = Maximum; cf. Figure 2 left). However, if the target material is concentrated entirely in the designated output mass flow, this represents the best case and minimum entropy (H = 0; cf. Figure 2 right). In practice, substance distributions lie between these two SE extremes (cf. Figure 2 middle). This simple example shows that a process produces distribution patterns of substance concentrations in its output mass flows, expressed with SE.

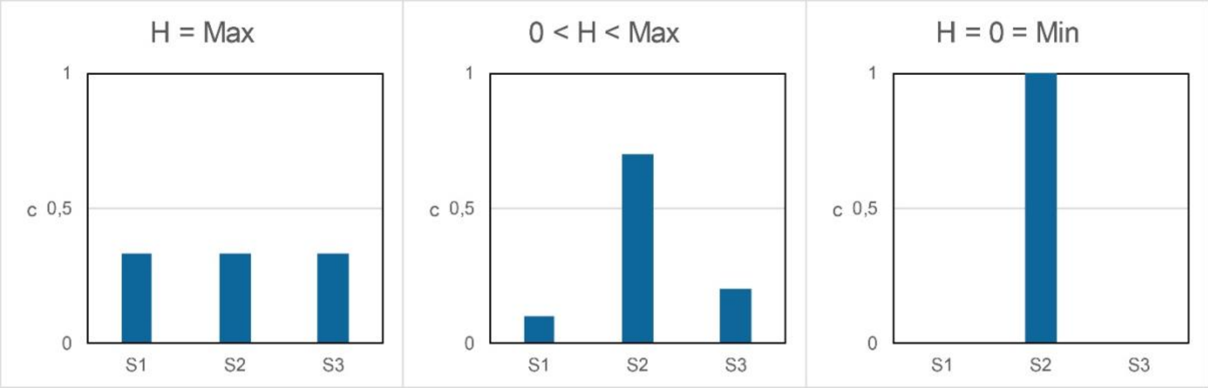

Figure 2 Target material distribution quantified by statistical entropy (H): Target material concentrations (c) in the different output mass flows (S1 – S3) after system processing.

Many subsequent studies followed Rechberger and Brunner's approach, some of them also dedicated to assessing material flow systems (Rechberger and Graedel, 2002; Rechberger, 2012; Sobańtka, Zessner and Rechberger, 2012; Sobańtka *et al.*, 2014; Laner, Zoboli and Rechberger, 2017; Navare, Vrancken and Van Acker, 2021; Velazquez Martinez *et al.*, 2021) or conditions such as e.g. circularity or recyclability of products or specific waste streams (Dahmus and Gutowski, 2007; Zeng and Li, 2016; Velázquez Martínez *et al.*, 2019; Parchomenko *et al.*, 2020, 2021; Nimmegeers and Billen, 2021; Nimmegeers *et al.*, 2021). One of the latest developments is using SE to simultaneously express the concentration of more than one material, e.g. in Parchomenko et al.'s studies (Parchomenko *et al.*, 2020). This approach enables the assessment of complex material compositions occurring in various waste and resource management conditions. All studies conclude that complex processes or conditions can be evaluated with SE in a fundamental and comprehensible way, thus leading to key findings among a wide variety of stakeholders.

In the following two Chapters 2.1 and 2.2, the SE approach is used to evaluate different recycling-relevant conditions and thus presents two new SE-based assessment methods.

2.1 Statistical entropy application to recycling processes

The first SE application assesses recycling processes by their quantitative and qualitative performance. A recycling process can be described with at least one waste input flow and two output flows; one of the output flows receives target material and the other unwanted materials (e.g. contaminated materials or materials of low economic value). In practice, recycling processes can have multiple target materials and thus outputs. The waste input of recycling processes generally shows a mixed composition of targeted and unwanted materials, resulting in a specific effort to separate these materials. Effective separation positively affects the purity and thus the quality of the recycling output and target material(s), respectively. Hence, recycling processes aim to achieve a high target material content in the associated recycling output. In the following analysis, only physical/mechanical recycling processes are considered in which no chemical transformations of materials or substances occur.

These circumstances can also be described in terms of entropy since the role of recycling processes is to minimize the entropy level of the mixed waste input by producing separated outputs for the target material(s) and the unwanted materials (Rechberger and Graedel, 2002; Rechberger, 2012; Velázquez Martínez *et al.*, 2019). Thereby, the SE assessment can be used for two recycling process phenomena: firstly, SE evaluates the quantitative outputs of the recycling process (= quantitative performance), and secondly, the qualities of the target material by looking at the concentration of the target material in the different outputs (= qualitative performance). To summarize, SE allows the combined assessment of recycling processes' quantitative and qualitative performance. Recycling processes should thus aim for a performance that produces large quantities of target materials of high quality.

This combined assessment requires considering two mass balances of the recycling process investigated, namely the total mass balance (= quantitative) and the target material (= qualitative) mass balance (cf. Figure 3). The total mass balance reflects the general inputs and outputs of the recycling process (see the top section of Figure 3). In contrast, the mass balance(s) of the target material(s) (see the bottom section of Figure 3) reflect/s the target material-specific recycling performance. The structure of the total mass balance is equal to the calculation basis of the European recycling rate. The target material mass balance has the same structure but only illustrates the mass flows of the pure target material. Thus, additional data of the content of the target material(s) in the output mass flows ($M_{out,i}$) is required to set up the target material mass balance(s).

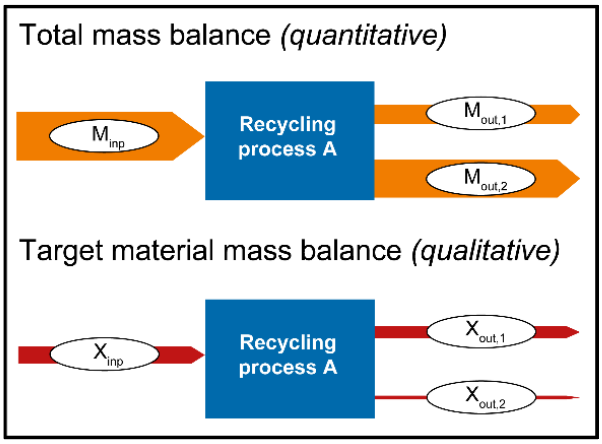

Figure 3 Quantitative (top section) and qualitative (bottom section) consideration of recycling process mass balances: Recycling process A transforms the input mass flow (left side; M_{inp} and X_{inp}) into two output mass flows (right side; $M_{out,1\text{-}2}$ and $X_{out,1\text{-}2}$). (Roithner and Rechberger, 2020)

The total mass balance includes an input mass flow (M_{inp}) representing the collected waste mass and different output mass flows ($M_{out,i}$; i = index for output flows; i = 1, …, k). One of these output mass flows contains the recycled material (with more or less pure target material) and another one the discarded materials. The output of discarded materials can include different materials and target material contaminated or unintentionally lost during the process. Depending on the process's target materials, more than one output mass flow for recycled materials might be necessary to establish.

The establishment of the target material mass balance(s) requires data on the target material concentrations ($c_{out,i}$) applied to the output mass flows ($M_{out,i}$) of the total mass balance, yielding the target material mass flows ($X_{out,i}$; cf. Equation (2)). The target material input mass flow (X_{inp}) results from the sum of the associated output mass flows ($X_{inp} = \sum X_{out,i}$). As with the total balance, one output mass flow represents the recycled materials, and one represents losses.

$$X_{out,i} = M_{out,i} \, c_{out,i} \tag{2}$$

In order to take into account that recycling processes can have different target material inputs (X_{inp}), a functional unit is formulated that enables comparisons between different processes. For this purpose, the output mass flows of the total mass balance must be divided by X_{inp}. The resulting mass ratios ($m_{out,i}$) (e.g. kg plastic per kg PET input) are then input variables for the subsequent SE calculation (cf. (Rechberger and Graedel, 2002)).

$$m_{out,i} = \frac{M_{out,i}}{X_{inp}} \tag{3}$$

Finally, the main inputs of the SE (H_{out}) calculation (cf. Equation (4)) are the variables $c_{out,i}$ and $m_{out,i}$ (cf. derivation in (Rechberger and Graedel, 2002)). If all target material is separated purely in the recycling output, H_{out} is zero, reflecting the best recycling performance from a quantitative and qualitative perspective. On the contrary, H_{out} is maximum (= H_{max}; cf. Equations (5) to (6)) if the target material input (X_{inp}) is evenly distributed among the process's outputs after passing through the process ($c_{inp} = X_{inp} / M_{inp} = c_{out,i}$); thus, no increase in target material concentration could be achieved (= worst case).

$$H_{out}\ (c_{out,i}, m_{out,i}) = -\sum_{i=1}^{k} m_{out,i}\, c_{out,i} ld(c_{out,i}) \tag{4}$$

$$m_{inp} = \frac{M_{inp}}{X_{inp}} = \frac{1}{c_{inp}} \tag{5}$$

$$H_{max} = ld(m_{inp}) \tag{6}$$

Finally, the relative statistical entropy ($H_{out,rel}$) is established to allow meaningful comparisons between different recycling processes or systems (e.g. due to different target material mass inputs) (cf. Equation (7)). This variable results from the division of the H_{out} by H_{max} and is a dimensionless value between zero and one. The higher $H_{out,rel}$, the worse is the recycling performance of the process observed. As mentioned before, H_{max} applies if the target material input (X_{inp}) is evenly distributed in the total mass flow (M_{inp}).

$$H_{out,rel} = \frac{H_{out}}{H_{max}} \tag{7}$$

The final result is expressed by the *Recycling Effectiveness* (RE). Equation (8) is applied since a result of “1” (= 100%) is generally linked with a good recycling performance and zero with a poor.

$$RE = (1 - H_{out,rel}) \tag{8}$$

In conclusion, the RE metric describes how effective the recycling process observed could separate target materials from unwanted materials and concentrate target materials of high purity in the recycling input, thereby covering the quantitative and qualitative recycling perspective. The aim of recycling processes should be to generate a maximum RE result.

2.2 Statistical entropy application to products

The second SE application deals with products and assessing their inherent recyclability based on fundamental design decisions. Product design aims to cover many aspects, such as technical functions, aesthetics, operability, and, more recently, environmental aspects, like recyclability or energy consumption. These aspects show that product design must be dynamic, considering these as best as possible. The following assessment approach focuses exclusively on three product design phenomena (caused by design decisions) affecting the product-inherent recyclability that SE can express.

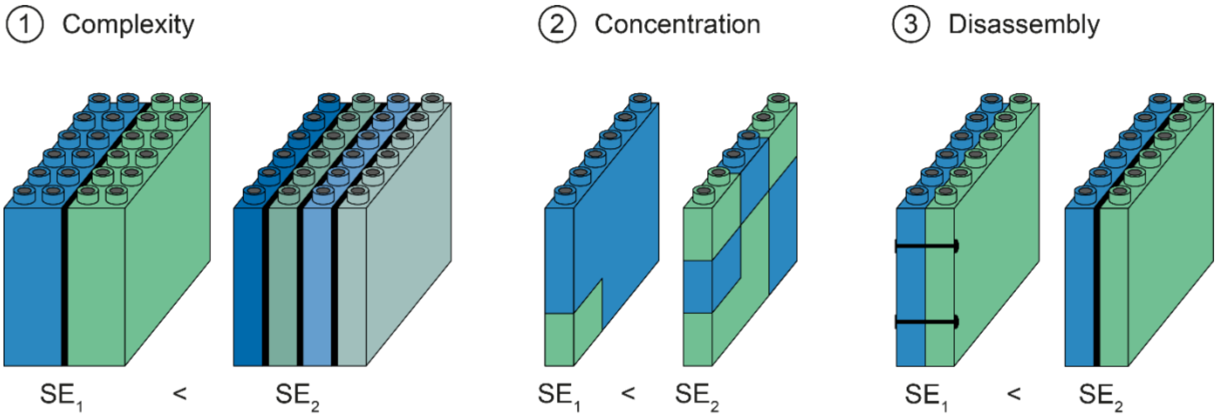

Figure 4 Three product design phenomena illustrated with wall systems that can be expressed with SE: 1. phenomenon on complexity, 2. phenomenon on concentration and 3. phenomenon on disassembly.

One of these phenomena concerns the *complexity* (= phenomenon no. 1) of products. The more materials there are in a product, the higher its SE tends to be. In Figure 4 on the left, two wall examples illustrate this fact: the right wall, consisting of four layers of different materials, has a higher complexity and, thus, a higher SE than the left wall, composed of two layers only.

The second phenomenon deals with the *concentration* (= phenomenon no. 2) of materials in products or parts, respectively. In SE, products that show a high material mixing perform worse than products with highly concentrated materials. In Figure 4, the second wall comparison demonstrates this phenomenon. Both wall examples comprise two materials; however, the SE of the right wall is higher because materials occur in mixed and nearly equally high concentrations, while the left wall shows an almost pure material concentration, thus showing a lower SE.

The last phenomenon regards the potential *disassembly* (= phenomenon no. 3) of products. Products usually consist of several parts connected in different ways, reflecting a specific product structure. Product disassembly significantly depends on the selected connection type and, in this respect, whether it enables disassembly or not. For example, screwed product parts can usually be separated. It can be stated that product parts that allow disassembly are easier to recycle, thus enabling the recovery of individual materials. On the right in Figure 4, the effect of two connection types on disassembly is presented. The layers of the left wall are screwed and can be disassembled, while the layers of the right wall are glued, thus preventing disassembly. Due to the possible separation of the left wall, two layers of pure material composition can be recovered (SE = 0). On the contrary, the right wall results in mixed material composition, resulting in a higher SE.

The third phenomenon introduces the consideration of material concentrations of product parts depending on the disassembly level in terms of the SE calculation. This consideration is demonstrated by three theoretical product examples in Figure 5, illustrated in the form of a tree structure. The leaves mark the SE calculation-relevant product parts and levels, respectively. Product 1 (P1) cannot be further disassembled; thus, the material concentrations are considered for the entire product. Contrary, product 2 (P2) can be disassembled into individual components (C1-C3). In this case, the component level is calculation-relevant. The product structure of the third product (P3) shows the highest complexity. The product (P3) can be disassembled into components (C1-C3), where C2 and C3 can be further disassembled into sub-components (C2 in SC1-SC2 and C3 in SC3-SC4). Additionally, SC3 can be disassembled into its sub-sub-components (SSC1-2). Thus, for P3, the material concentrations of the lowest levels are considered, which are C1, SC1, SC2, SSC1, SSC2 and SC4. These product examples in Figure 5 show a significant difference in consideration of material concentrations depending on the different disassembly levels, where the most detailed information can be obtained from the "lowest" level. Therefore, it is recommended to trace the product parts to the lowest possible level of disassembly. Thus, SE calculation should always be based on the product information of the highest detail.

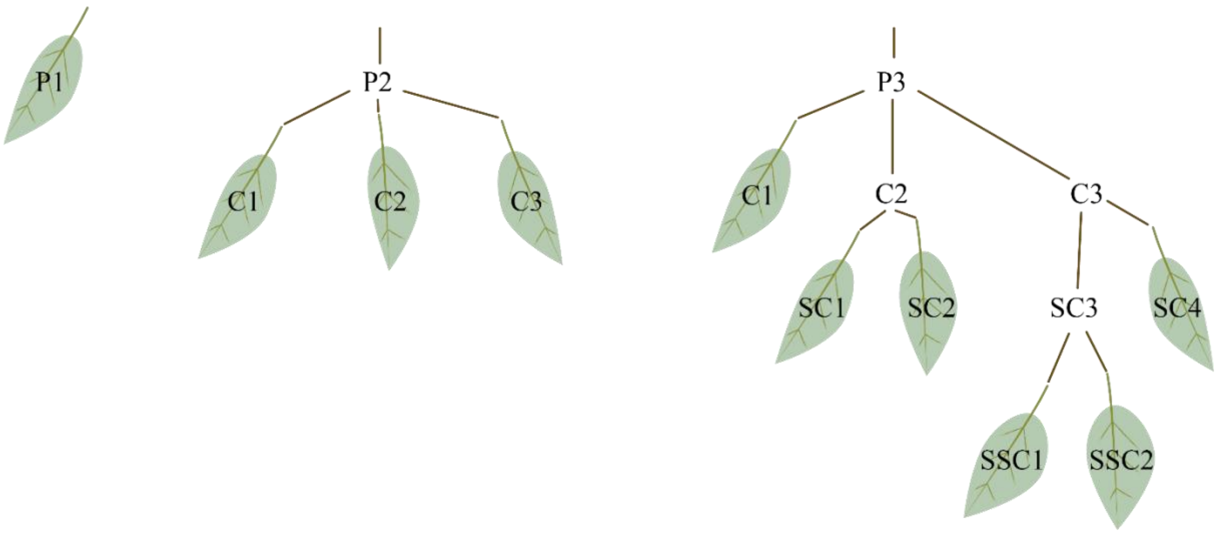

Figure 5 Product structure of three theoretical products (P1-P3) illustrated in tree structure: leaves mark the calculation-relevant levels (C ... components; SC ... sub-components; SSC ... sub-sub-components).

These phenomena do not necessarily represent a design limitation for designers and manufacturers. However, they are essential for recyclers, as they can significantly influence the recyclability at the end of a product's life cycle. In recycling, complex material compositions usually require higher recycling efforts, reinforced by a product structure that hinders the recovery of individual materials. It can be stated that complex products that cannot be disassembled make recycling complicated or even impractical. In this respect, every product has a certain inherent recyclability, which can be fundamentally described with the mentioned phenomena, which are in the following described with the *material composition* and the *product structure with its associated separability* of product parts. For all phenomena, the SE decreases the better the design allows recycling.

In the following paragraphs, these phenomena (design decisions) are built into a SE-based assessment method, expressing the product-inherent recyclability.

As mentioned in Chapter 2, SE is based on material concentrations (c_i). In accordance with product separability, the material concentrations in the different product parts considered ($c_{i,j}$) (j = index for product parts; j= 1, …, N_e) are calculated according to Equation (9), where the mass of material i in product part j ($M_{i,j}$) is divided by the total mass of the product part (M_j). Because here, all materials found in one product part are considered at once, Equation (1) is used directly instead of Equation (4), which would, in contrast, consider one material in all product parts. The N_m material concentrations are used to calculate the SE of the product part considered (H_j) (cf. Equation (10)).

$$c_{i,j} = \frac{M_{i,j}}{M_j} \tag{9}$$

$$H_j = -\sum_{i=1}^{N_m} c_{i,j} \operatorname{ld}(c_{i,j}) \tag{10}$$

The SE of the entire product (H_p) is calculated with the mass weighted average of the N_e statistical entropies (H_j) of the product parts concerned (cf. Equation (11)). According to Equation (12), the mass weight m_j is the mass fraction of product part j (M_j) related to the mass of the entire product (M_p). The term m_j times H_j in Equation (11) is the absolute contribution of product part j to the total H_p of the product. H_p reflects the SE of the product disassembled into its specific product parts. The lower H_p is, the better is the product's inherent recyclability. If a product cannot be disassembled, the entire product is considered the only product part available. Thus, $N_e = 1$ and $M_j = M_p$.

$$H_p = \sum_{j=1}^{N_e} m_j H_j \tag{11}$$

$$m_j = \frac{M_j}{M_p} \tag{12}$$

The relative SE (H_{rel}) should be considered for product comparisons, calculated according to Equation (13). H_{rel} relates H_p of Equation (11) to the maximum SE (H_{max}) of the observed product. H_{max} describes the situation where all N_m materials appear in equal concentrations, and no disassembly is possible (= worst case). According to Equation (14), the H_{max} of a product is calculated. As in Chapter 2.1, H_{rel} is a dimensionless value between zero and one; H_{rel} increases the worse the product's inherent recyclability is.

$$H_{rel} = \frac{H_p}{H_{max}} \tag{13}$$

$$H_{max} = \mathrm{ld}\,(N_m) \tag{14}$$

The final *Relative product-inherent recyclability* (RPR) result is expressed by Equation (15) and follows the explanation described in Chapter 2.1 (cf. Equation (9)). It must be noted that a RPR of zero (i.e. $H_p = H_{max}$ or $H_{rel} = 1$) does not mean that the product cannot be recycled; however, from the product design perspective, it represents the worst situation.

$$RPR = 1 - H_{rel} \tag{15}$$

The RPR metric expresses the product-inherent recyclability of the product observed based on design decisions on the product's material composition and structure. The aim of the product design should be to achieve a high RPR. In the extreme situation in which the product only comprises of one material ($N_m = 1$, $H_p = 0$), Equations (13) and (15) are not defined because of $H_{max} = \mathrm{ld}(N_m) = 0$ (division by zero problem). However, since lim ($N_m \rightarrow 1$) 1 – 0 / $\mathrm{ld}(N_m) = 1$ and $H_p = 0$ always represent the best case of product-inherent recyclability, RPR is defined as 1 in this situation.

The product's RPR can also be written as the mass weighted average of the product parts' RPR (cf. Equation (16)), where m_j times RPR_j expresses the absolute contribution of component j to the RPR of the entire product. The RPR of the specific product parts are calculated according to Equation (17).

$$RPR = \sum_{j=1}^{N_e} m_j \, RPR_j \tag{16}$$

$$RPR_j = 1 - \frac{H_j}{H_{max}} \tag{17}$$

3. Recycling effectiveness of recycling processes

In the following paragraphs, the recycling performances of two hypothetical recycling processes are evaluated using the presented RE metric. The case studies were limited to a minimum necessary complexity to enable a simple demonstration of the advantages of the developed SE assessment method compared to the conventional recycling rate (= recycled waste output divided by the total waste input). The term *Recycling process* includes the performance of standard recycling activities, which include necessary pre-recycling steps such as sorting, shredding and washing. The investigated recycling processes treat plastic packaging waste with polyethylene terephthalate (PET) as the target material. The recycling processes' capacities are freely chosen purely for demonstration purposes.

Based on three realistic cases, the sensitivity of the SE approach in incorporating qualitative recycling aspects will be demonstrated. The recycling processes' total and target material (= PET) mass balance are described in all cases (see the top two sections of Figure 6 to 8), following the scheme in Figure 3. The concentration of recycled target material ($c_{out,1}$) should be higher than the concentration of target material losses ($c_{out,2}$) because otherwise, target materials would get concentrated in the wrong process output and thus not reflect a meaningful recycling situation. In addition, the Best-case and Worst-case recycling situations will be assessed to show maximum and minimum SE generation (cf. Figure 9).

3.1 Case study: Plastic packaging recycling

3.1.1 Case 1

Considering the total mass balance (see the top section of Figure 6) and thus from a purely quantitative perspective, both recycling processes achieve an equal high recycling output (= 70 t plastics/d). Thus, the recycling rate (RR) is the same for both processes (also equal high waste inputs), namely 70% (= 70 / 100) (see left at the bottom section of Figure 6). However, if the target material balance is considered too (see the second section of Figure 6), it becomes apparent that Recycling process 2 (RP2) achieves a higher recovery of PET than Recycling process 1 (RP1). The recycled target material output of RP2 is 58 t PET/d, and that of RP1 is 54 t PET/d. This qualitative difference can be expressed with the SE assessment by applying Equations (2) to (8) to each recycling process. The recycling processes' final Recycling Effectiveness (RE) results are displayed right at the bottom of Figure 6. According to the RE results, RP2 achieves a better recycling performance than RP1 ($RE_{RP1} = 0.47 > RE_{RP1} = 0.23$), which reflects the more effective concentrating power of RP2 ($c_{out,1,RP2} = 0.83 > c_{out,1,RP1} = 0.77$ and $c_{out,2,RP2} = 0.07 < c_{out,2,RP1} = 0.20$). To summarize this case, it can be shown that the initial quantitative performance assessment of the recycling processes is not sufficient if qualitative differences exist and thus need to be considered. The application of the RE metric delivers a result that unifies these quantitative and qualitative recycling aspects, reflecting relevant differences in the purity of recycled plastics.

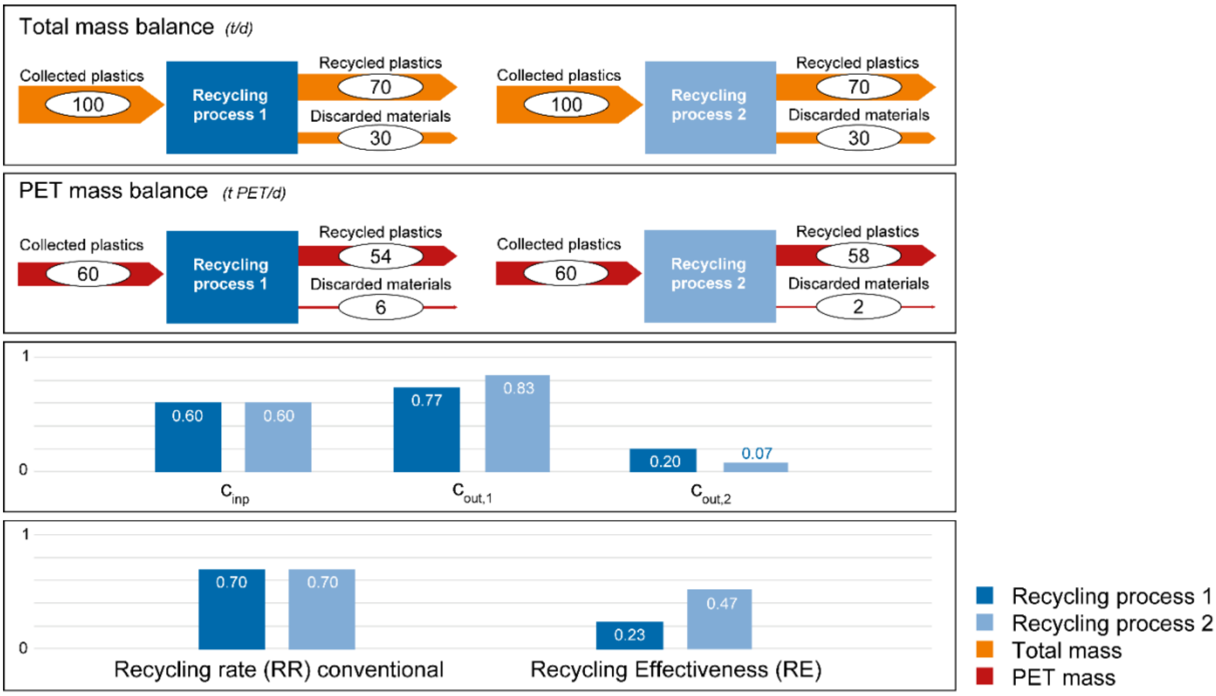

Figure 6 Case 1: Total and PET mass balances and PET concentrations of two different recycling processes that achieve equally high Recycling rates (RR), but a different Recycling Effectiveness (RE). (Roithner and Rechberger, 2020)

3.1.2 Case 2

In the second case, the quantitative recycling performance of the recycling processes is different (see the top section of Figure 7). RP2 shows a higher recycling output than RP1 (80 > 70 t plastics/d). RP2 achieves an increased recycling output of 10 t plastics/d, while RP1 achieves the same high recycling output. As a result, RP2 achieves a RR of 80% and RP1 of 70% (see left at the bottom section of Figure 7). Thus, from this purely quantitative perspective, RP2 is preferable. However, if the PET mass balance is considered, it turns out that both recycling processes could not increase their PET outputs compared to Case 1. Thus, the RE of RP1 remains equally high (= 0.23), while the RE of RP2 decreases (from 0.47 to 0.23) due to the decreased concentrating power of RP2 ($c_{out1,RP2,Case1}$ = 0.83 > $c_{out1,RP2,Case2}$ = 0.72; see the third section of Figure 6 and Figure 7). Thus, both recycling processes achieve an equal RE (see right at the bottom section of Figure 7). This case shows that an increase in the total amount of recycled plastics does not automatically entail a qualitative increase in recycling performance. As in Case 1, a purely quantitative assessment can be misleading if qualitative aspects are not considered.

This case could also represent a possible development in the European recycling industry to achieve the new recycling targets on time. The recycling industry could focus on the massive increase of recycling outputs at the same or lower quality, which would result in a higher RR but low RE.

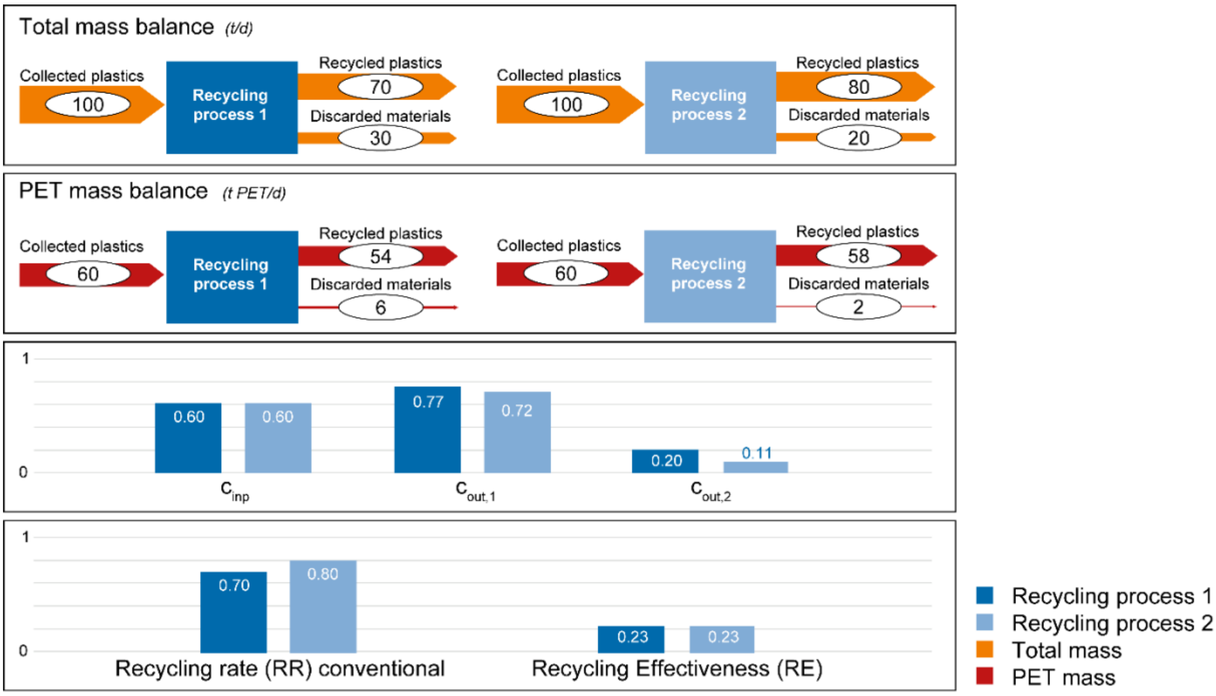

Figure 7 Case 2: Total and PET mass balances and PET concentrations of two different recycling processes that achieve different RR, but an equal RE. (Roithner and Rechberger, 2020)

3.1.3 Case 3

In Case 3, the recycling processes' PET input mass flow differs ($X_{inp,RP1}$ = 50 t PET/day < $X_{inp,RP2}$ = 60 t PET/d; see the second top section of Figure 8), while the recycled plastics and PET output masses are equally high for both recycling processes (= 70 t plastics/d and 46 t PET/d). As in Case 1, both recycling processes achieve a RR of 70% (see left at the bottom section of Figure 8). However, the difference in the PET input masses significantly affects the RE. The increased output of "Discarded materials" of RP2 leads to a negative impact on the RE result because more PET is concentrated in the wrong output. This is reflected in the very low RE result of RP2, with a value of 0.02. The RE of RP1 remains unchanged at 0.21. Overall, RP1 achieves a better recycling performance than RP2. Case 3 shows that several variables are crucial in the SE assessment of the qualitative performance of recycling processes.

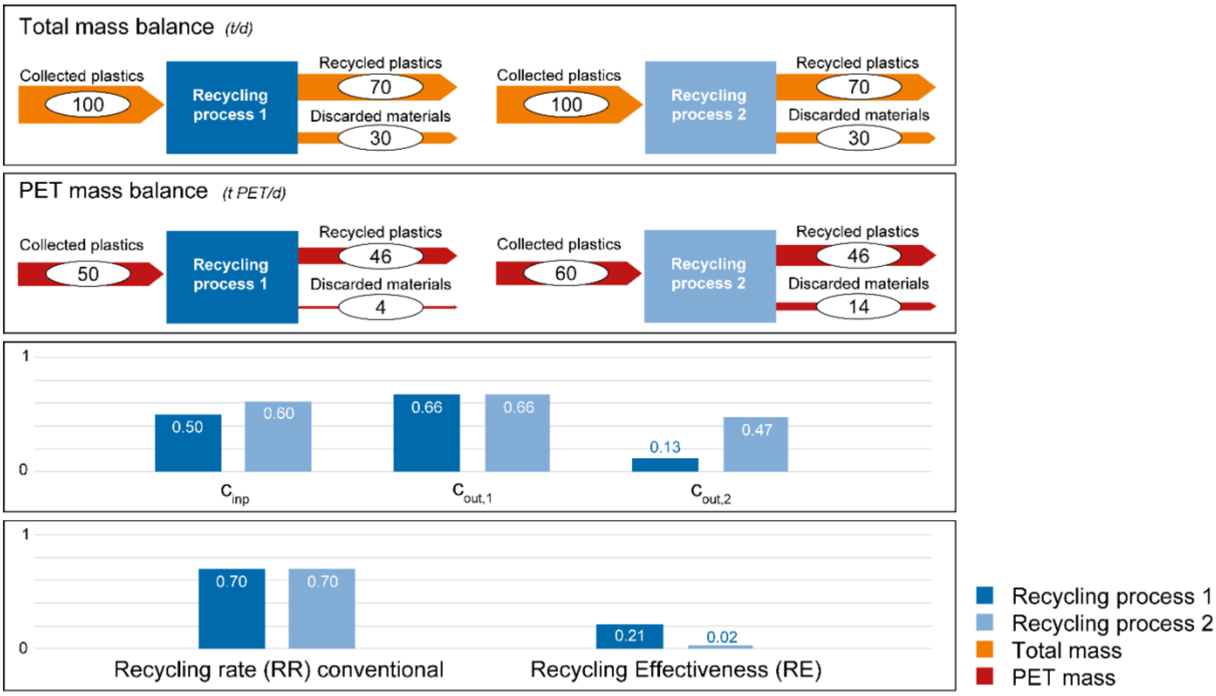

Figure 8 Case 3: Total and PET mass balances and PET concentrations of two different recycling processes that achieve equally high RR, but a different RE. (Roithner and Rechberger, 2020)

3.1.4 Best-case, worst-case

In the last two cases, extreme recycling situations are presented from the point of view of SE. They should contribute to a better understanding of the range of real recycling performances.

In Figure 9, RP1 represents the best-case recycling situation. The target material can be found completely in the recycling output ($c_{out,1,RP1}$ = 1 and $c_{out,2,RP1}$ = 0; see third section of Figure 9); PET occurs in pure form. Thus, RP1 most effectively separated target and unwanted materials, resulting in the maximum RE (= 1) (see right at the bottom right of Figure 9).

Contrary, the performance of RP2 corresponds to the worst-case. The PET concentrations in the output mass flows are equally high ($c_{out,1,RP2}$ = $c_{out,2,RP2}$ = 0.7; see the third section of Figure 9)), which means that no further separation between the target material and unwanted materials occurred during the processing. The performance of RP2 results in the maximum SE, where H_{out} = H_{max}, and thus a RE of zero (see right at the bottom right of Figure 9). Suppose this case were to continue and the mass of rejects would further increase (> 21 t PET/d), the outcome of this recycling performance could be called an "inverted recycling process" as more target material is concentrated in the wrong output.

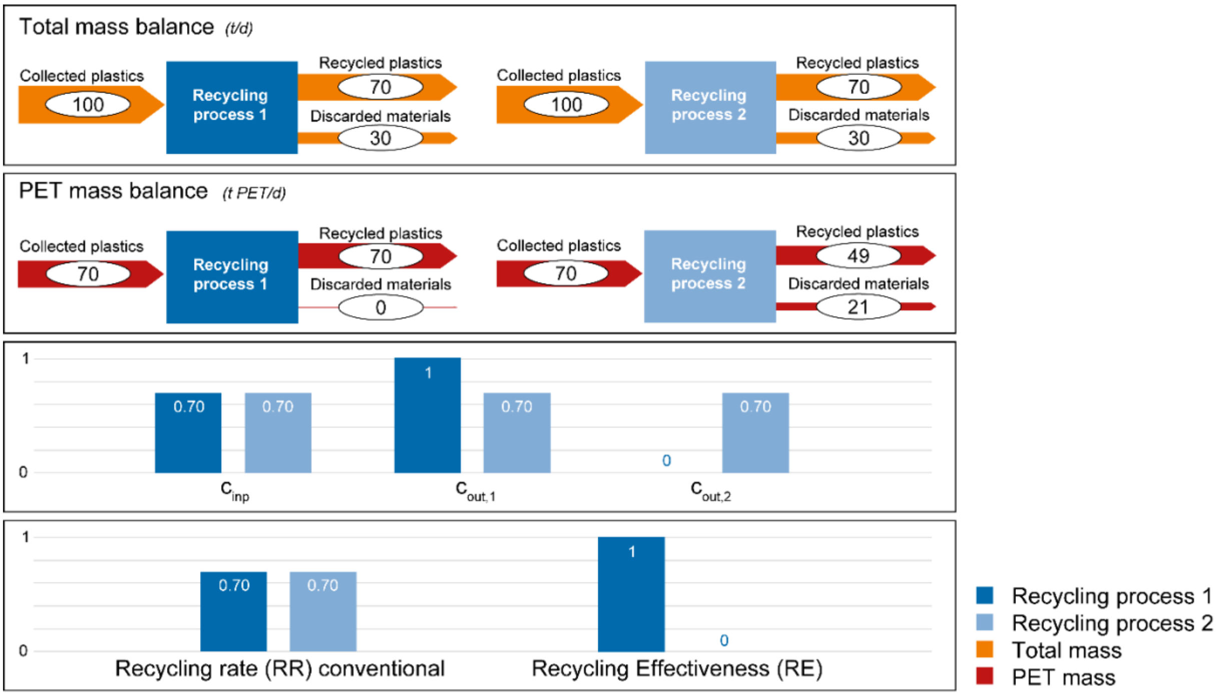

Figure 9 Best-case, Worst-case: Total and PET mass balances and PET concentrations of two different recycling processes that achieve equally high RR, but a different RE. (Roithner and Rechberger, 2020)

3.1.5 Summary of the Cases

The Cases' results (cf. RR and RE results in Table 1) show that the current calculation of the RR only allows a one-sided assessment, i.e. limited to quantitative recycling aspects (total mass balance), so essential qualitative aspects are not considered. Such a recycling process assessment can be misleading if there are significant differences in the quality and thus purity of the recycled material. Therefore, the consideration of target material mass balances in assessing recycling performances appears to be indispensable. In the RE assessment method, the target material concentrations ($c_{out,1}$ and $c_{out,2}$) are significant variables since they allow conclusions on the quality and purity of the recycling outputs. The RE results show that qualitative differences in the recycling processes' power to concentrate target materials in the recycling output can be observed. It seems reasonable to use the new RE metric complementary to the RR to comprehensively investigate processes' performance.

Table 1 Cases 1 to 3, best-case and worst-case: RR and RE results and target material concentrations ($c_{out,i}$) of RP1 and RP2.

	Case 1		Case 2		Case 3		Best-case, worst-case	
	RP1	RP2	RP1	RP2	RP1	RP2	RP1	RP2
RR	0.70	0.70	0.70	0.80	0.70	0.70	0.70	0.70
RE	0.23	0.47	0.23	0.23	0.21	0.02	1	0
$c_{out,1}$	0.77	0.83	0.77	0.72	0.66	0.66	1	0.70
$c_{out,2}$	0.20	0.07	0.20	0.11	0.13	0.47	0	0.70

3.2 Suitability of the RE metric as recycling performance indicator

The RE metric represents an indicator based on SE that allows assessing quantitative and qualitative recycling aspects combined. Thus, the indicator aims to close the gap in the existing recycling performance assessments, which currently omit to assess qualitative recycling aspects (cf. European recycling rate) or fail to do so fundamentally and independent of specific quality classes (cf. presented assessment methods/indicators in Chapter 1).

In the RE method, quality is expressed unbiased by the concentration of target material in the recycling output. The purity of the target material can be derived from the target material concentration in the outputs of the recycling process observed. The performance of the recycling process increases, the higher the concentration of target material in the associated recycling output is. The assessment method allows identifying significant differences in the concentrating power of recycling processes and thus the quality of recycled target materials.

The SE method requires establishing at least two mass balances (depending on the number of target materials): the total mass balance and the target material(s) mass balance(s). Therefore, similar to the RR calculation, the mass flows of the recycling process are required and added by data on the target material concentrations. Since the data collection of recycling companies is usually extensive, e.g. to achieve specific product standards, the measurement of target material concentrations by e.g. in-house or external laboratories seems feasible. In this respect, the developed RE method does not involve high additional effort in data procurement but can instead be linked to the existing RR evaluation.

The combined assessment allows significant comparisons between different recycling processes, as shown by the Case study on plastic packaging recycling (cf. Chapter 3.1); purely quantitative assessments can lead to a strong performance bias if qualitative circumstances are disregarded. Increased target material concentration unambiguously improves the processes' RE result. Specific calculation steps of the RE method (cf. Equations (5) and (7)) enable consistent comparisons between different recycling processes (e.g. with varying amounts of target material input). Further, it can be assumed that the RE method can be applied to recycling processes of any complexity.

It must be noted that the RE assessment method is based purely on material flows, thus not covering any other aspects impacting the effectiveness of recycling processes, like energy consumption. The qualitative recycling aspect is expressed by considering the target material concentrations during the recycling process only; following conditions, e.g. concerning a down- or upcycling of the recycled material, are not considered further and require a different assessment.

4. Product-inherent recyclability

Two case studies on different product groups, namely smartphones and buildings, are established to show the broad applicability of the RPR metric. In the first case study, the recyclability of a modelled smartphone is investigated (cf. Chapter 4.1), and in the second case study, building variants originating from the study of Honic et al. (Honic, Kovacic and Rechberger, 2019) are examined (cf. Chapter 4.2). These product groups were considered because smartphones are highly complex products subject to rapid technological development, and buildings have a high impact on resource consumption and are composed of large material masses.

In both case studies, the product's RPR is calculated for all possible disassembly levels according to Equations (9) to (15). The product's RPR is first calculated for the "product level" that assumes that the product cannot be disassembled at all, and in the following, for the different disassembly levels. In addition, the product part-specific RPR_j are calculated at specific disassembly levels, according to Equation (17).

In the smartphone study, the RPR was additionally investigated for a theoretical "disassembly order" (cf. x-axis in Figure 11) within the individual disassembly levels, which is fictitious but should reflect a logical and manual disassembly of the smartphone parts. With each additionally separated smartphone part, the smartphone's RPR changes. It is mathematically assumed that the other smartphone parts located below in the disassembly order represent a unit. The RPR result at the end of the disassembly order represents the final RPR result of the smartphone at the disassembly level observed, which is achieved in this case with the Printed circuit assembly (PCA). Additionally, two scenarios, namely Scenario 1 and 2, were set up to demonstrate two different recyclability situations induced by different product designs. While in Scenario 1, the components Speaker, Cameras, SIM tray, Vibration motor and Housing represent individual components; in Scenario 2, these components are combined into one component (called "Component 6"). This product design modification is intended to reflect product design that prevents product disassembly. As a result of the component aggregation, Component 6 has no sub-components.

The case study on the building variants is intended to show that the RPR assessment method is suitable for meaningful product comparisons, highlighting significant differences between products and their design.

4.1 Case study: Smartphone

4.1.1 Smartphone

The smartphone's material composition was modelled using collected literature data (Tarantili, Mitsakaki and Petoussi, 2010; Palmieri, Bonifazi and Serranti, 2014; Ueberschaar *et al.*, 2017; Tan *et al.*, 2017; Bookhagen *et al.*, 2018, 2020; Holgersson *et al.*, 2018; Singh *et al.*, 2018; Smodiš *et al.*, 2018; Fontana *et al.*, 2019; Liu *et al.*, 2019) and information from internet researches. Based on the data collected, a fictitious smartphone was modelled (from now on referred to as "Smartphone"), comparable to smartphones launched around 2012. Simultaneously with the modelling of the Smartphone, the product structure was provided with individual disassembly levels. The entire Smartphone (without disassembly) is represented at the “product level”. Different structural product parts of the Smartphone that can be regarded as stand-alone (e.g. a battery) belong to the “component level” (cf. second column in Figure 10). As several of the Smartphone’s components comprise sub-parts (e.g. magnets), the “sub-component level” is also introduced (cf. third column in Figure 10). Generally, the distinction between product parts should follow functional, technical or other design aspects. In this case, no further sub-levels were taken into account, even though this might be the case for other smartphones showing different complexities. Parts of the Smartphone connected to make disassembly practically impossible are regarded as one unit (e.g. the Screen of the Smartphone). Connecting elements (e.g. screws or solder) and their materials are also considered; these usually occur either loosely (e.g. screws to open a smartphone for the first time) or as part of a sub-/component (e.g. solder as part of a vibration motor).

The final Smartphone is displayed in Figure 10, comprising 11 components and 32 sub-components (SC). The SC “Others” comprises electronics and wires. The material composition of the Smartphone and its components is shown in Table 2. Detailed information on the material masses at the different levels is presented in Appendix A (see Table 9 to Table 20). The Smartphone consists of a total of 49 materials. The term “material” includes chemical elements (e.g. silver), chemical compounds (e.g. pure ABS), materials (e.g. plastics with additives) and material groups (e.g. collection of different glass types). The specific chemical composition of the materials and material groups listed in Table 2 is not considered. The material group “Others” includes materials like liquids, adhesives and epoxy, and “Glass” acts as a collective term for all kinds of glasses. The material group “REE” stands for the group of rare earth elements. Note that the structure of the Smartphone and the list of materials do not claim to be complete. As shown in Table 2, the sum of all material masses equals the total mass of the Smartphone, complying with the law of mass conservation.

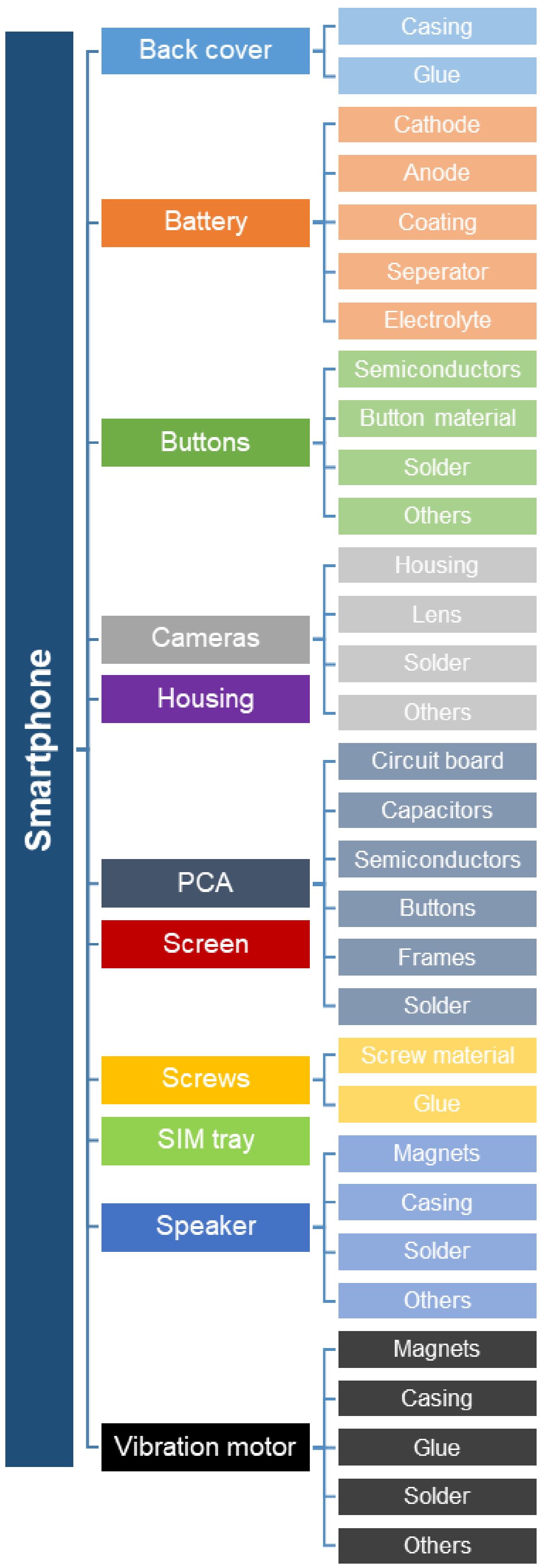

Figure 10 Smartphone structure: Product level, component level and sub-component level (from left to right) (PCA … Printed circuit assembly). (Roithner, Cencic and Rechberger, 2022)

Table 2 Mass (g) and number of materials (N_m) in the individual Smartphone components.

Material	Back cover	Battery	Buttons	Cameras	Housing	PCA	Screen	Screws	SIM tray	Speaker	Vibration motor	Total
No. of materials (N_m)	2	10	16	17	1	42	3	2	1	13	15	49
ABS				2.00							0.40	2.40
PC	12.74				20.00	0.27				0.30		33.31
PE		2.60										2.60
PP		0.52										0.52
PVC			<0.01								<0.01	0.02
Ag				<0.01		0.03						0.03
Al		2.08	0.12	<0.01		0.14				<0.01	<0.01	2.35
As						<0.01						<0.01
Au			<0.01	<0.01		0.01					<0.01	0.03
B										<0.01	<0.01	0.01
Ba						0.08						0.08
Be						<0.01						<0.01
Bi						<0.01						<0.01
C (Graphite)		6.24										6.24
Ca				<0.01		0.04						0.05
Cd						<0.01						<0.01
Co		0.46	0.01	0.01		<0.01				0.01	0.01	0.51
Cr				0.02		<0.01						0.02
Cu		1.56	0.26	0.93		1.99				0.23	0.26	5.22
Fe			0.03	0.27		1.48		1.96	2.00	0.54	0.44	6.72
Ga			0.02			<0.01						0.02
Ge						<0.01						<0.01
Hf						<0.01						<0.01
In						<0.01	23.04					23.04
Li		0.57				<0.01						0.57
Mg						<0.01						<0.01
Mn		0.46	<0.01	<0.01		0.03				<0.01	<0.01	0.51
Mo						<0.01						<0.01
Na						<0.01						<0.01
Nb						<0.01				<0.01	<0.01	0.01
Ni		3.70	0.06	0.10		0.19				0.03	0.02	4.10
Pa			0.02									0.02
Pb				<0.01		<0.01						<0.01
Pd						0.06						0.06
Pt						<0.01						<0.01
Rb						<0.01						<0.01
Sb						<0.01						<0.01
Si			0.72			0.33						1.05
Sn			0.23	0.57		0.66	2.56			0.10	0.43	4.56
Sr						<0.01						<0.01
Ta						0.38						0.38
Ti				<0.01		0.64						0.64

V						<0.01						<0.01
W						<0.01						<0.01
Zn			0.02	0.08		0.02				0.02	0.02	0.16
Zr						<0.01						<0.01
REE			<0.01			<0.01				0.23	0.19	0.42
Others	0.26	7.81	<0.01	<0.01		2.49		0.04		<0.01	0.21	10.82
Glass			0.48	1.00		3.28	6.40					11.16
Total	13.00	26.00	2.00	5.00	20.00	12.15	32.00	2.00	2.00	1.50	2.00	117.65

4.1.2 Results

In the following, the RPR results of the modelled Smartphone are presented according to the different disassembly levels and the freely selected “disassembly order” for Scenario 1 and 2. The increasing RPR of the Smartphone due to progressive disassembly into its sub-/components is shown in Figure 11. The disassembly order at the different disassembly levels always starts with the Back cover and ends with the PCA (= final RPR result of the disassembled Smartphone). Component 6 (= aggregation of several components) from Scenario 2 is highlighted as a grey shaded box in Figure 11. The RPR results are shown twice, namely at the component level (see bright lines in Figure 11) and the SC level (see dark lines in Figure 11). This demonstrates the impacts if material concentrations are considered for the entire product or lower disassembly levels, namely the component and SC level in this Smartphone case. The RPR of the Smartphone without disassembly (= product level) is the starting point for all scenarios, with an equally high value of 40.8% (see left in Figure 11). Both scenarios show that the modelled Smartphone cannot achieve the maximum RPR (= 100%), as disassembly into pure materials is impossible. This finding might apply to most complex products. However, with progressive disassembly in both scenarios, the RPR increases, which argues for disassembly into sub-/components. The Smartphone’s final RPR result varies significantly between the different scenarios (cf. PCA values in Figure 11). The highest RPR value can be observed for Scenario 1, at the SC level, amounting to 87.3%, whereas the counterpart value of Scenario 2 is only 79.8%. This comparison shows that the aggregated Component 6 negatively impacts the recyclability of the Smartphone. The RPR values are even lower, namely 74.1% for Scenario 1 and 68.9% for Scenario 2 if the SC are not considered for disassembly (= component level), resulting in a decrease between 10% and 15% compared to the RPR results at the SC level.

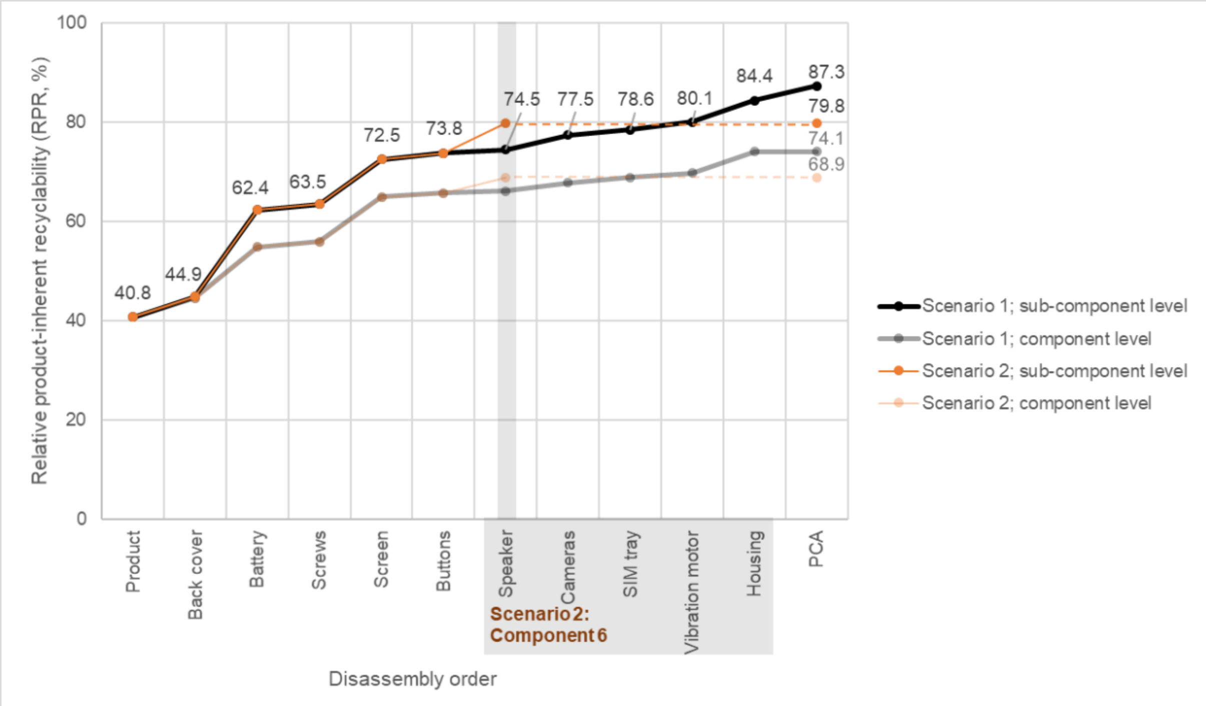

Figure 11 Scenario 1 and 2: Relative product-inherent recyclability (RPR) of the Smartphone, as a function of disassembly order, at the component and sub-component level.

In order to gain an insight into the recyclability of the individual Smartphone components, the RPR_j of the components was calculated with Equation (17). In Figure 12, the RPR_j results are presented alphabetically and considered at the component and SC levels. Following the previous finding, the RPR_j of the specific components is higher if the SC are disassembled too. The difference in the RPR_j values could be explained with a different product design that enables or prevents disassembly (cf. Component 6 of Scenario 2). The components Housing, Screen and SIM tray achieve equally high results at the component and SC level as they cannot be further disassembled into SC. The components Back cover, Housing, SIM tray, and Screws reach the maximum RPR_j (100%) at the SC level because the associated SC comprise pure materials (cf. Table 17, Table 11, Table 16 and Table 20 in the Appendix). The RPR_j of the Back cover and Screws at the component level decrease because of the mixing with glue. Compared to the other RPR_j at the SC level, the RPR_j of the Screen is relatively low (80.5%) because it comprises three materials that appear in a similar material concentration. The PCA shows the lowest RPR_j (74.0% at the SC and 46.1% at the component level), explained by its complex material composition (cf. Table 10 in the Appendix). The remaining components achieve average RPR_js, namely between 82.0% and 90.1% at the SC and 50.6% and 58.3% at the component level. These components show a similar composition of SC, mainly involving parts such as magnets, semiconductors and other parts that exhibit a strong material dilution, thus leading to similar RPR_j results.

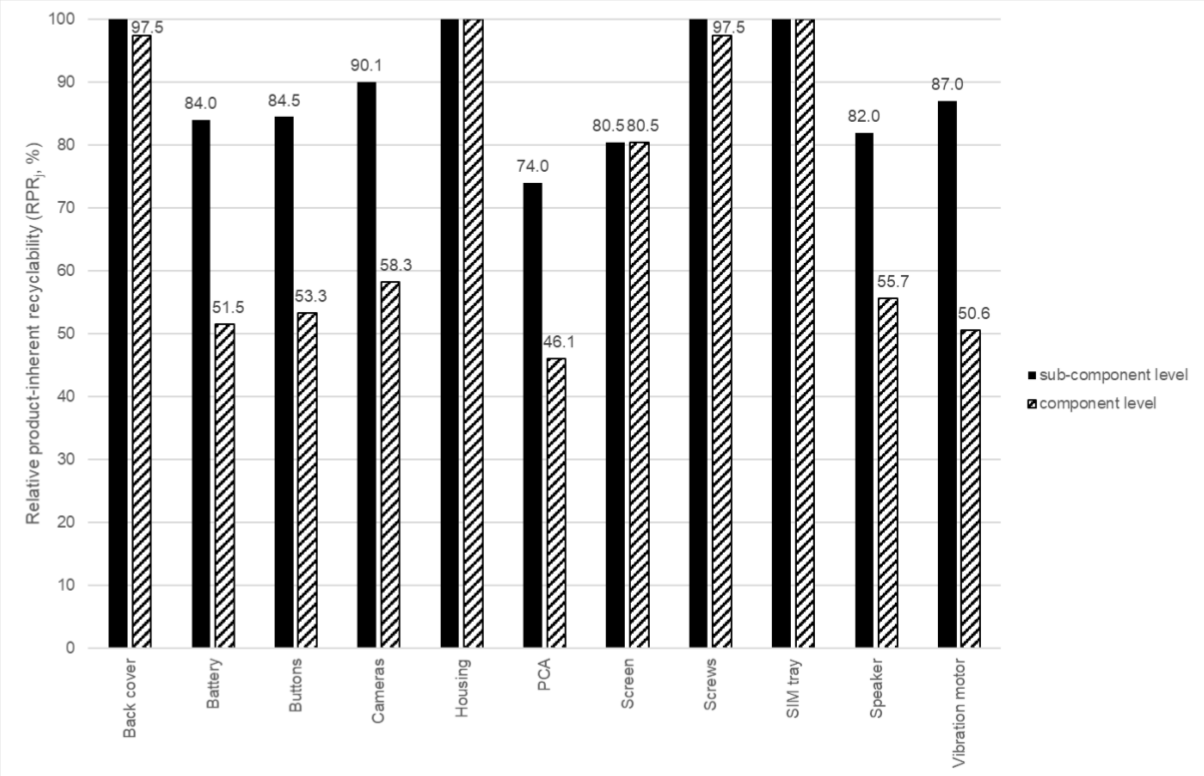

Figure 12 Scenario 1: RPR_j of the individual Smartphone components at the component and SC level.

Table 3 summarizes the mass weights (m_j), H_j and RPR_j (at the component and SC level) of the Smartphone components in Scenario 1 and further lists the component's contribution to the total RPR. The component-specific m_j vary considerably, which manifests in a different influence of the specific H_j and RPR_j on the total H_p and the final RPR, respectively. For example, the components Back cover, Battery, Screen, Housing, or PCA show a relatively high mass weight, resulting in a significant impact on the Smartphone's RPR. The values of the components' H_j and RPR_j at the SC level are computed from the mass weighted average of the respective metrics of their SC. The results at the SC level illustrate that the components Screen, Speaker and PCA show an exceptionally high SE (H_j), while components such as the Back cover, Screws, SIM tray and Housing show a minimum H_j (= 0). The differences between the absolute RPR contributions at the different disassembly levels (see the last column of Table 3) present the absolute increase in the RPR due to the consideration of SC. The three highest contributions are from the Battery (+7.2%$_{abs}$), the PCA (+2.9%$_{abs}$) and the Cameras (+1.3%$_{abs}$).

Table 3 Scenario 1: Mass weight (m_j), H_j and RPR_j of the individual Smartphone components at the component and SC level.

Component	m_j	Sub-component level				Component level				Δ
		H_j	RPR_j (%$_{abs}$)	m_j RPR_j (%$_{abs}$)	m_j RPR_j (%$_{rel}$)	H_j	RPR_j (%$_{abs}$)	m_j RPR_j (%$_{abs}$)	m_j RPR_j (%$_{rel}$)	m_j RPR_j (%$_{abs}$)
Back cover	0.11	0	100	11.0	12.7	0.14	97.5	10.8	14.5	0.3
Battery	0.22	0.90	84.0	18.6	21.2	2.72	51.5	11.4	15.4	7.2
Screws	0.02	0	100	1.7	1.9	0.14	97.5	1.7	2.2	<0.1
Screen	0.27	1.10	80.5	21.9	25.1	1.10	80.5	21.9	29.5	0
Buttons	0.02	0.87	84.5	1.4	1.6	2.62	53.5	0.9	1.2	0.5
Speaker	0.01	1.01	82.0	1.0	1.2	2.49	55.7	0.7	1.0	0.3

Cameras	0.04	0.56	90.1	3.8	4.4	2.34	58.3	2.5	3.3	1.3
SIM tray	0.02	0	100	1.7	1.9	0	100.0	1.7	2.3	0
Vibration motor	0.02	0.73	87.0	1.5	1.7	2.77	50.6	0.9	1.2	0.6
Housing	0.17	0	100	17.0	19.5	0	100.0	17.0	22.9	0
PCA	0.10	1.46	74.0	7.6	8.8	3.03	46.1	4.8	6.4	2.9
Total	1.00	0.71	87.3	87.3	100	1.45	74.1	74.1	100	13.2

4.2 Case study: Buildings

4.2.1 Building variants

For the following case study, two building variants from the study of Honic et al. are used (Honic, Kovacic and Rechberger, 2019). In their case study, Honic et al. designed a residential building (with five floors) in two variants in BIM software. One building variant is constructed in timber, and the other is concrete. The building variants comprise the same components; however, they vary in their material composition (e.g. windows of timber in the timber building and of aluminium in the concrete building). Both building variants show an equal U-value that describes the heat conductivity of building elements. Honic et al. assessed the modelled building variants with the “Material Passport” method, thereby considering selected building components (exterior walls, roof, slabs and windows).

For the optimal application of the RPR assessment method, the modelled building variants from Honic et al. are interpreted in more detail. Three significant modifications are necessary for this:

First, the material catalogue of the building variants is extended (cf. Table 5 and Table 6), as the RPR method requires a detailed consideration of materials. Therefore, the building materials in Honic et al.’s study are further differentiated into individual “material components”. For example, “concrete” is a composite material differentiated into cement and gravel, or “wool insulation” into wool, binding agents and mineral oil.

Second, all connecting elements (e.g. screws or nails) and their materials between the building's SC and sub-sub-components (SSC) are considered. Relevant information on the composition of building materials and connecting elements was obtained from internet research and the online platform "eco2soft" (baubook GmbH, 2021).

Third, the disassembly of the buildings and their parts is comprehensively considered. By introducing connecting elements (as mentioned before), new possibilities for disassembly arise that are not covered in Honic et al. (Honic, Kovacic and Rechberger, 2019). Thus, all building parts are analysed for possible separation. For some building parts, an advanced disassembly is assumed, which may seem too far-reaching at present. For example, it is assumed that all wall layers (= SC) are separable, e.g. including a spatula layer, or, e.g. reinforced concrete parts, windows and doors are disassembled into their sub-parts. However, given the ambitious CE movement, these might soon be realistic disassembly strategies. A total of four disassembly levels are established: building level, component level, SC level and SSC level. The “building level” (cf. product level in Chapter 2.2) reflects the situation without disassembly, which could be equated with a conventional building disassembly without separating individual materials. Information on building disassembly was collected in literature and internet research.

Despite these modifications, the masses and areas of the buildings and their components are the same (see Table 4), as in Honic et al. (Honic, Kovacic and Rechberger, 2019). However, a difference can be observed in the material composition of the individual components, listed in Table 5 and Table 6. Most of the timber building's components contain more materials than those of the concrete building, which can be attributed, among other things, to the additional need for insulation and fire prevention agent materials. Overall, the timber building's material composition only includes one more material than the concrete building (30 vs 29 materials) (cf. Table 5 and Table 6). Detailed information on the material masses at the different levels is presented in Appendix B (see Table 23 to Table 52). Table 4 shows that the area of both buildings is equal (in total 6,761 m²), but their total mass differs; the concrete building has a larger total mass than the timber building (3,772 t vs 1,694 t). Further, the timber building's components contain more SC and SSC than those of the concrete building (68 SC and 101 SSC vs 53 SC and 64 SSC). The timber building's higher number of SC and SSC can be explained by the consideration of disassembly and the additional need for insulation and fire prevention. Doors and windows are considered stand-alone components and not as sub-parts of walls, following Honic et al. (Honic, Kovacic and Rechberger, 2019).

Table 4 Area (m²), mass (kg) and number of SC and SSC of the individual timber and concrete building components.

Component	Area (m²)	Timber building Mass (kg)	Timber building No. of SC	Timber building No. of SSC	Concrete building Mass (kg)	Concrete building No. of SC	Concrete building No. of SSC
External wall	1,897	224,409	8	23	897,480	4	4
External wall; ground floor	282	66,439	7	18	133,585	4	4
Flat roof	717	163.663	9	18	423,890	8	11
Slab against outdoor air	682	298,675	10	12	381,607	7	13
Slab 1. floor	2,002	620,029	10	15	1,301,038	8	16
Slab 2. floor	682	218,006	10	15	520,369	8	16
Doors	15	675	4	---	675	4	---
Windows	484	102,424	10	---	113,839	10	---
Total	6,761	1,694,319	68	101	3,772,482	53	64

Table 5 Mass (kg) and numbers of materials (N_m) in the individual timber building components. Lines 3 – 16: organic resources (coloured green); lines 17 - 27: mineral resources (coloured yellow); lines 28 - 32: metallic resources (coloured blue).

Material	External wall	External wall; ground floor	Flat roof	Slab against outdoor air	Slab 1. floor	Slab 2. floor	Doors	Windows	Total
No. of materials (N_m)	11	14	13	21	21	21	7	8	30
Acrylic								20	20
Binding agent	3,479	518	114	959	336	166	51		5,622
Bitumen			1,130	360	1,057	360			2,907
Cardboard	1,814	270	343		957	326			3,710
Glue	131	21	82	692	2,032	692			3,650
Mineral oil	14	2	23	4	20	17			80

Nylon	1,733	260	585	331	973	453			4,334
Paraffin	801	119		214					1,134
Polyethylene			1,636	1,554	1,712	583			5,485
Polyurethane								41	41
Silicone								348	348
Styrene-butadiene-styrene				90	264	90			444
Timber	174,011	26,403	82,326	104,418	250,052	89,532	450	14,339	741,531
Wood glaze				79	233	79	5		396
Adhesive agent				2	6	2			10
Cement		2,502		12,823	21,021	7,159			43,504
Fluxing agent				239	701	239			1,178
Glass				120	352	120		81,939	82,532
Gravel			64,572						64,572
Gypsum	34,467	5,130	6,518		18,187	6,194			70,496
Lime		5,004		11,328					16,333
Rock wool	2,787	415	4,431	1,968	7,248	4,472			21,321
Sand		25,022		96,969	118,416	40,328			280,735
Shale				150	440	150			740
Split				65,452	192,188	65,452			323,092
Aluminium								2,048	2048
Chromium							18		18
Nickel							10		10
Steel	5,135	767	1,888	917	3,808	1,582	140	3,683	17,921
Zinc	36	5	13	6	27	11	0	4	104
Total	224,409	66,439	163,663	298,675	620,029	218,006	675	102,424	1,694,319

Table 6 Mass (kg) and numbers of materials (N_m) in the individual concrete building components. Lines 3 - 16: organic resources (coloured green); lines 17 - 26: mineral resources (coloured yellow); lines 27 - 31: metallic resources (coloured blue).

Material	External wall	External wall; ground floor	Flat roof	Slab against outdoor air	Slab 1. floor	Slab 2. floor	Doors	Windows	Total
No. of materials (N_m)	9	9	16	15	13	13	7	7	29
Acrylic								23	23
Binding agent	324	48	290	2,725	7,629	2,658	51		13,725
Bitumen			3,397						3,397
Expanded polystyrene	5,665	843	2,742	1,584					7,384
Glue				406	1,193	406			2,006
Mineral oil				4	27	21			52
Nylon				44	314	249			606
Polyethylene			2,271						2,271
Polyurethane								46	46
Silicone								387	387
Styrene-butadiene-styrene			871						871

Synthetic resin	373	56	24	167					526
Timber				14797	43,449	14,797	450		73,493
Wood stain				52	154	52	5		264
Cement	173,271	25,790	65,582	62,233	182,339	62,097			570,384
Glass			1,162					91,071	92,233
Glass wool				729	267	91			1,087
Gravel	691,143	102,872	287,218	248,390	729,354	248,390			2,307,366
Gypsum	10,244	1,525	2,798		5,105	1,739			29,504
Rock wool					4,902	4,007			8,909
Sand	1,894	282	26,746	529					25,829
Shale			1,452						1,452
Silicates	5,839	869		2,761					9,470
Split			2,5829						25,829
Aluminium			88					18,214	18,303
Chromium							18		18
Nickel							10		10
Steel	8,727	1,299	3,419	46,878	324,086	184,583	140	4,093	573,225
Zinc			1	308	2,220	1,279	0	5	3,813
Total	897,480	133,585	423,890	381,607	130,1038	520,369	675	113,839	3,772,482

4.2.2 Results

The following RPR calculations are based on the buildings' extended material composition and (partly advanced) disassembly assumptions, as described in Chapter 4.2.1. In this building variant case study, the material catalogue is defined by N_m of the timber building due to its higher material number (cf. Table 5; H_{max} = ld(30)). Figure 13 shows the building's RPR results depending on the disassembly level, starting left with no disassembly (= building level) to the rightmost, representing complete disassembly of the building (= SSC level). It can be noted that both buildings achieve relatively high RPR values, which is due to the large building parts that are usually characterized by materials with a high mass fraction (e.g., timber or concrete). The RPR results demonstrate that the recyclability of both buildings significantly increases if disassembled progressively; the RPR of the timber building increases from 49% to 96% and the one of the concrete building from 63% to 88% (values rounded). This means that the probability increases with each further disassembly level that more concentrated materials can be separated from the building parts.

The recyclability of the concrete building is higher than for the timber building ($RPR_{\text{Concrete building}}$ = 63%; $RPR_{\text{Timber building}}$ = 49%) if no disassembly occurs. This statement can also be made for the component level ($RPR_{\text{Concrete building}}$ = 70; $RPR_{\text{Timber building}}$ = 62%). Two materials dominate the building and component level results: "timber" for the timber building and "gravel" for the concrete building; both materials occur in relatively high concentrations, thus significantly impacting the SE and thus RPR result. However, during the subsequent disassembly levels, it becomes apparent that the recyclability of the timber building is higher than that of the concrete building (at the SC level: $RPR_{\text{Timber building}}$ = 94%, $RPR_{\text{Concrete building}}$ = 86%; at the SSC level: $RPR_{\text{Timber building}}$ = 96%, $RPR_{\text{Concrete building}}$ = 88%), showing that the timber building comprises more (sub-) parts (cf. number of SC and SSC in Table 4) that when disassembled enable the recovery of more concentrated materials.

The concrete building's RPR result at the SSC level is based on the advanced assumption that the SC "reinforced concrete" is disassembled into its SSC "concrete" and "reinforcing steel". Since this could be a critical disassembly assumption, the RPR for this level was also calculated without disassembly of "reinforced concrete". At the SSC level, the concrete building's RPR decreases 1.3% (from 88.3% to 87.0%).

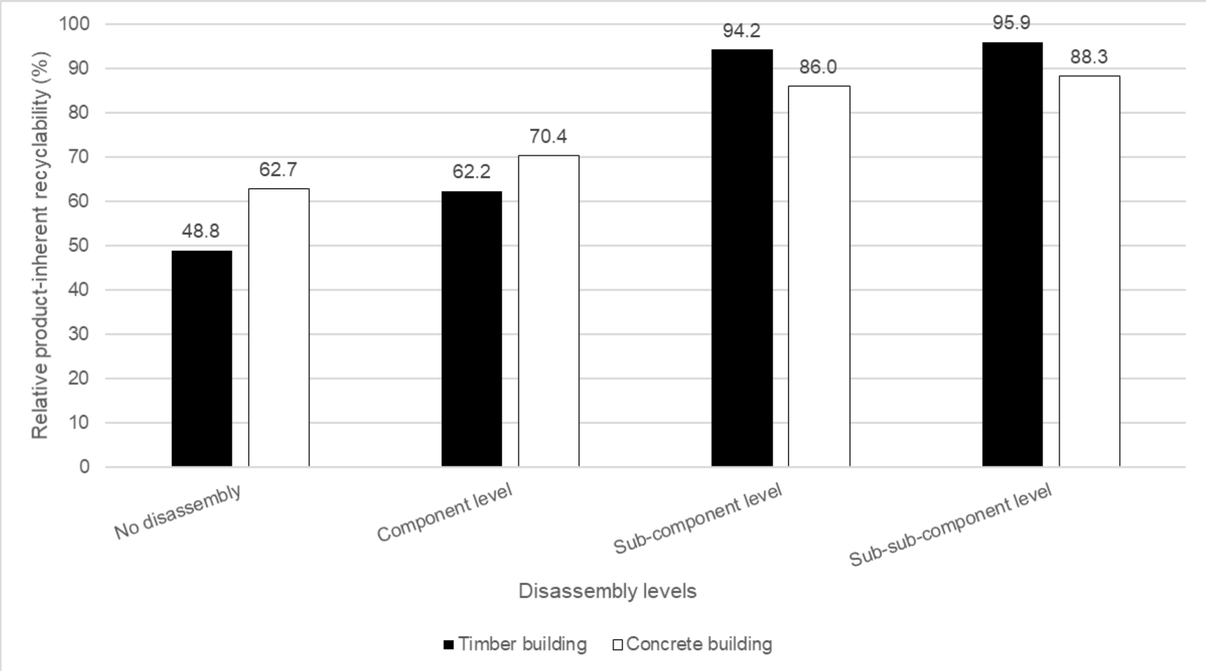

Figure 13 RPR of the timber and concrete building at the different disassembly levels.

Figure 14 and Figure 15 display the RPR results of the buildings' components (= RPR_j) calculated (following Equation (17)) at the component and SC level, respectively. When considering the RPR_j results at the component level (cf. Figure 14), the concrete building's components perform better than those of the timber building, as previously noted with the RPR results for the entire buildings. However, this trend is reversed when the RPR_j of the components are considered at the SC level (cf. Figure 15); almost all timber building components perform better.

The RPR_j of the individual components can vary considerably depending on the building variant and disassembly level considered. For example, the RPR_j of the "external wall on the ground floor" calculated at the component level differs by 21.6% between the building variants. This is because the materials in the timber building's component are more equally distributed than in the concrete building, thus resulting in a higher SE (H_j) in the timber building's external wall. For example, at the SC level, a significant RPR_j difference between the buildings can be observed for the "flat roof", amounting to about 17%. The RPR_j differences of the other components range between 2.4%$_{abs}$ and 8.6%$_{abs}$ across the component and SC level. The components' RPR_j results at the SSC level would be partially higher than at the SC level. However, this does not apply to components that cannot be further disassembled into SSC.

As mentioned in Chapter 4.2.1, an advanced disassembly is considered for doors and windows. This means that all individual parts of doors and windows, which could be identified during the internet research, are disassembled individually, e.g. frames or seals of windows. The effect of this disassembly strategy can be demonstrated by comparing the components' RPR_j results at the component and SC levels (cf. Figure 14 and Figure 15). The doors' RPR_j increases from 71% to 88% and the windows' from approximately 81% to 100%, thus positively affecting recyclability.

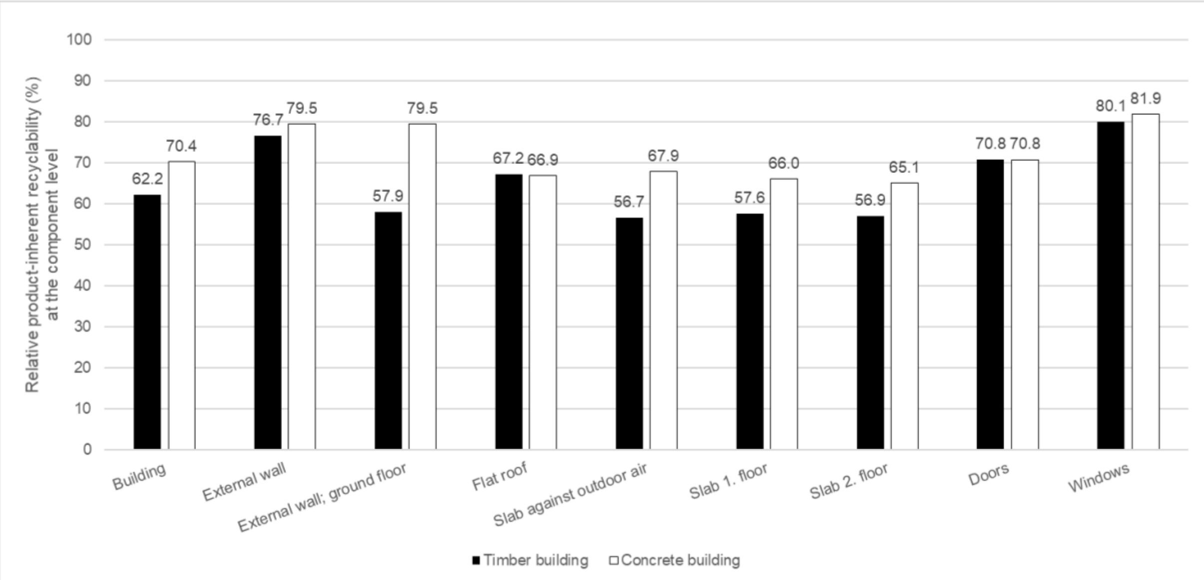

Figure 14 RPR_j of the individual timber and concrete building components at the component level. (Roithner et al., submitted)

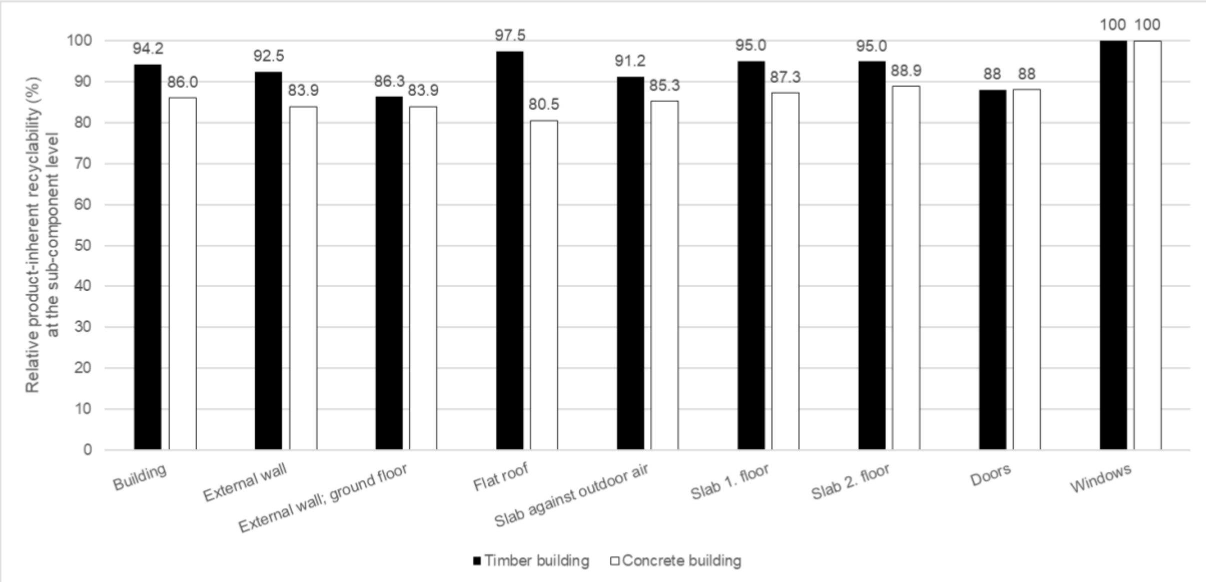

Figure 15 RPR_j of the individual timber and concrete building components at the SC level. (Roithner et al., submitted)

Table 7 lists the mass weights (m_j), H_j and RPR_j of the buildings' components calculated at the component level and the component's contribution to the building's total RPR. The components' m_j vary significantly between the different building variants. As mentioned before (cf. Chapters 2.2 and 4.2.2), the component-specific m_j defines the impact of RPR_j on the building's final RPR. For both buildings, the highest m_j can be observed for the "slab of the first floor" and the smallest m_j for the "doors" (= <0.1). Further, the other slabs and the "external wall" show a relatively high m_j. For the timber building, the three highest H_j values can be observed for all slabs, while for the concrete building, the slab of the first and second floor and the "flat roof" show the highest H_j. The "external wall" and the "windows" achieve the lowest two H_j values in both buildings. Subsequently, the contribution of the individual components to the total RPR varies too (see m_j RPRj $\%_{abs}$ and $\%_{rel}$ in Table 7). The timber buildings' components "slab first floor", "external wall" and "slab against outdoor air" show the highest contributions to the total RPR. For the concrete building, the slabs of the first and second floor and the "external wall" show the highest contributions. The differences between the building components' contributions to the total RPR are listed in the last column of Table 7. The three most significant differences can be observed for the "external wall" (-8.7$\%_{abs}$), the "slab against outdoor air" (+3.1$\%_{abs}$) and the "windows" (+2.4$\%_{abs}$).

Table 7 Mass weight (m_j), H_j and RPR_j of the individual timber and concrete building components at the component level.

	Timber building					Concrete building					Δ
Component	m_j	H_j	RPR_j ($\%_{abs}$)	m_j RPR_j ($\%_{abs}$)	m_j RPR_j ($\%_{rel}$)	m_j	H_j	RPR_j ($\%_{abs}$)	m_j RPR_j ($\%_{abs}$)	m_j RPR_j ($\%_{rel}$)	m_j RPR_j ($\%_{abs}$)
External wall	0.13	1.14	76.7	10.2	16.3	0.24	0.98	79.5	18.9	26.9	-8.7
External wall; ground floor	0.04	2.06	57.9	2.3	3.7	0.04	1.00	79.5	2.8	4.0	-0.5
Flat roof	0.10	1.61	67.2	6.5	10.4	0.11	1.63	66.9	7.5	10.7	-1.0
Slab against outdoor air	0.18	2.13	56.7	10.0	16.1	0.10	1.57	67.9	6.9	9.8	3.1

Slab 1. floor	0.37	2.08	57.6	21.1	33.9	0.34	1.67	66.0	22.8	32.4	-1.7
Slab 2. floor	0.13	2.11	56.9	7.3	11.8	0.14	1.71	65.1	9.0	12.8	-1.7
Doors	<0.01	1.43	70.8	<0.1	<0.1	<0.01	1.43	70.8	0.0	<0.1	<0.0
Windows	0.06	0.98	80.1	4.8	7.8	0.03	0.89	81.9	2.5	3.5	2.4
Total	1			62.2	100	1			70.4	100	

4.3 Suitability of the RPR metric as product recyclability indicator

The SE-based RPR indicator represents a new possibility to evaluate the recyclability of products consistently and could pose a new recyclability indicator. The RPR assessment is based on fundamental decisions of the design phase that significantly impact the recyclability of products, namely the material composition and the product structure with its associated separability of product parts. The SE measure is suited to express the complexity of product design in a simple and comprehensible way, thus contributing to a new understanding of recyclability. The product-inherent recyclability increases the more concentrated the materials in the product (and its parts) are and if these materials can be recovered separately through possible disassembly.

The consideration of fundamental product information allows an unbiased and reliable assessment of product recyclability. The data necessary for the RPR method may be extensive but should be available as it forms the basis of any product design or manufacturing process. It seems reasonable that all materials are evaluated equally and only according to their concentration and disassembly level. Otherwise, a focus on specific materials (e.g. valuable metals) could arise and thus drive the assessment in one direction. However, there might be cases where material characteristics require a specific consideration, e.g. if products comprise hazardous or critical materials, which is currently not foreseen in the RPR assessment method.

With the RPR indicator, product comparisons are easy to draw as the product‘s recyclability result is reflected by one value. However, meaningful product comparisons should be established by applying product group-specific material catalogues (cf. product comparison in Chapter 4.2); these material catalogues should be marked by an index, e.g. the year issued, since product developments are progressing rapidly.

The Case studies illustrate the extensive application of the new assessment method using products of different product groups (see the modelled smartphone in Chapters 4.1 and building variants in Chapter 4.2). The Case studies’ results show that products (parts) with a high material mix perform worse than those with concentrated materials. Further, the positive effect of product disassembly on product recyclability is demonstrated that promotes the recovery of individual materials. The additional RPR assessment of individual product parts helps identify specific design weaknesses and their contribution to the recyclability of the entire product.

It must be highlighted that the RPR assessment method is founded only on two design decisions selected; however, there exist other potentially recyclability-relevant aspects in design that could be introduced too, e.g. product lifetime or energy efficiency. Nevertheless, these aspects cannot be expressed with SE, so other assessment methods are required. Further, the RPR method considers disassembly only in a binary system (yes or no) and thus excludes disassembly efforts (e.g. time or costs). Though, combining the RPR results with data on disassembly effort seems feasible, e.g. in the form of specific RPRs per cost of disassembly.

5. Conclusions

The last decades have shown that the high global resource consumption is becoming an increasing burden for humankind, the environment, and the climate. The EU has drafted a Circular Economy Action Plan (CEAP) to counteract this development, defining measures and strategies to reduce these environmental and social impacts by establishing a CE (European Commission, 2014b, 2014a). The CEAP also promotes the implementation of metrics and indicators for assessing and monitoring CE transformations. One focus lies in developing indicators for recycling-relevant conditions because recycled (secondary) materials are essential in a CE to, among other things, reduce primary resource demand directly. The contribution of this thesis lies in the development of indicators based on statistical entropy (SE), which allow assessing recycling-relevant conditions. These indicators aim to provide significant results and comparisons and enable widespread application. Furthermore, optimization potentials should be derivable from the indicators' results.

The SE assessment approach was chosen because it can express phenomena occurring in recycling and associated processes. Expressed in SE, a waste flow consisting of mixed materials shows a higher entropy than a waste flow consisting of one material. This principle can also be applied to recycling, where the recycling effort increases with higher material mixing. Therefore, the recycling industry's task to effectively separate waste materials can be described with an entropy reduction. A similar phenomenon can be observed for product design in connection with recycling: the more complex the material composition of a product is, the more difficult the recycling. In terms of entropy, the goal of product design should be to create products with low entropy. The SE assessment method is based on material concentrations of the investigated system, which allows evaluating material distributions mentioned before. In order to implement the objectives of this thesis, the SE assessment approach was further developed and extended to new applications.

The first assessment method developed based on the SE approach outputs the *Recycling Effectiveness* (RE) indicator that evaluates recycling processes' quantitative and qualitative performance. The starting point for this work was the current European recycling rate calculation that represents a purely quantitative recycling performance evaluation (recycling output compared to the waste input), therefore lacking to cover qualitative recycling aspects (purity of recycled materials). Given the qualitative requirements for recycling outputs in a CE, developing a complementary assessment method that combines both recycling aspects seems necessary. The RE assessment method considers the recycling process's total and target material mass balances, therefore evaluating the quantity and quality of the recycling process's target material in addition to the total performance. The RE result increases the more effectively the recycling process concentrates target materials in the recycling output. The final RE result is expressed by a single value, suitable for meaningful comparisons due to the calculation steps provided. The RE indicator allows identifying significant differences in the concentrating power of different recycling processes and is further suitable for evaluating internal process optimizations.

A case study on two hypothetical plastic packaging recyclers was conducted to prove the significance of the RE assessment method compared to the conventional recycling rate of the EU. Further, different recycling cases were analysed to show the sensitivity of the RE metric in incorporating qualitative differences. The results of the Case study show that the RE assessment method can express qualitative differences in the recycling performance and thus reveal significant differences between recycling processes; the recycling rate's results do not reflect these qualitative recycling differences. The Case study illustrates that the sole consideration of the recycling processes' total mass balance can be misleading and should be complemented by considering the qualitative recycling performance to assess and monitor the recycling industry's performance holistically.

It must be noted that the recycling processes illustrated in the Case Study follow a simplified scheme; however, the RE assessment method does not preclude its application to more complex recycling systems. Currently, the RE assessment method does not cover chemical recycling processes (involving substance transformations), thus focusing on mechanical or physical recycling steps only.

The second indicator is the *Relative product-inherent recyclability* (RPR) that aims to assess the recyclability of products. In order to achieve a CE with products whose materials are kept in circulation to the highest possible extent, a product design is required that enables high product recyclability. Developing an assessment method that evaluates product design impacts on recyclability is necessary. Therefore, the RPR assessment method evaluates fundamental product design decisions, namely the material composition and product structure with its associated separability of product parts with SE. For the RPR assessment, the material concentrations of the product (parts) are considered at the disassembly level provided. The RPR increases the more concentrated materials occur in the different product parts, provided these materials can be separated. For product comparisons, it is relevant to define product group-specific material catalogues that specify the maximum number of materials as N_m determines H_{max}. The RPR of individual product parts can also be assessed and thus could form the basis for product part-specific design optimizations.

The RPR indicator was tested on products referring to different product groups: a smartphone and two building variants. Smartphones are considered because they consist of various materials that occur in small and large concentrations, while large material masses usually dominate buildings. In the Smartphone Case study, an additional scenario was adopted in which certain product parts (components) were considered a single unit that could not be disassembled. The aim was to demonstrate the impact of a disassembly-unfriendly product design on recyclability. The results of the Case studies show that the recyclability increases the more concentrated materials occur in the product parts and the more disassembly-friendly the product is designed. The aggregated design of the component reduces the smartphone's recyclability. In the Case study on buildings, it can be shown that with progressing disassembly, the RPR of the timber building increases more than for the concrete building. The building comparison demonstrates that the RPR indicator can delineate significant differences between products of the same product group.

Currently, the RPR assessment method does not consider material characteristics, like hazardousness or criticality, thus representing a purely mass-based approach. However, future research might focus on implementing such material characteristics in the RPR assessment method. Furthermore, it must be highlighted that the RPR assessment is based only on two design aspects (material composition and product structure with its associated separability) to assess product recyclability. It is a fact that there exist other aspects in product design that could be included in the recyclability assessment, such as energy consumption or product lifetime. However, addressing additional design aspects would go beyond the target of this thesis to develop a fundamental but well-founded recyclability indicator. Nevertheless, combining the RPR method with assessment approaches covering other design aspects should be possible and recommended for more comprehensive product evaluations.

Finally, it should be noted for both indicators that the results should be interpreted carefully like for any other indicator or assessment method. A 100% result should not be seen as the default target. In specific situations, it cannot be ignored that, e.g. the recycling process's input strongly depends on the collection behaviour, or certain product functions depend on specific materials irreplaceable. In this respect, the results should always be considered in context. To enable a better orientation for individual performances, it seems feasible to define specific value ranges for the RE and RPR results, respectively, e.g. for certain recycling sectors or product groups. Both assessment methods aim to generate an increased sensitivity for the qualitative performance of recycling processes and the recyclability of products. In addition, it must be noted that the meaningfulness of the RE and RPR results strongly depends on the quality of the input data. Especially for the RPR indicator, precise data on the material concentrations in the individual product parts is necessary, which will not always be easy to achieve. As in the Case study on the smartphone, it might, in some cases, not be possible to avoid defining material groups, like "Others", that aim to close the data gap on specific material concentrations.

6. Outlook

In general, the thesis shows that SE is a suitable metric to assess different conditions relevant to recycling and thus CE due to its fundamental principles and high flexibility in application. The indicators developed already cover essential processes and conditions in a CE (cf. Figure 16); however, different areas in the CE exist for which new SE applications could be defined. The indicators presented in this thesis could serve as a template for future developments.

As already mentioned at the beginning of this thesis, different indicators should not be seen as opponents but as contributions to completing a puzzle. Thus, the developed RE and RPR indicators are to be placed in the existing series of indicators and, depending on the problem, should be used in or without combination with other indicators, e.g. covering environmental impacts (e.g. LCA) or ease of disassembly.

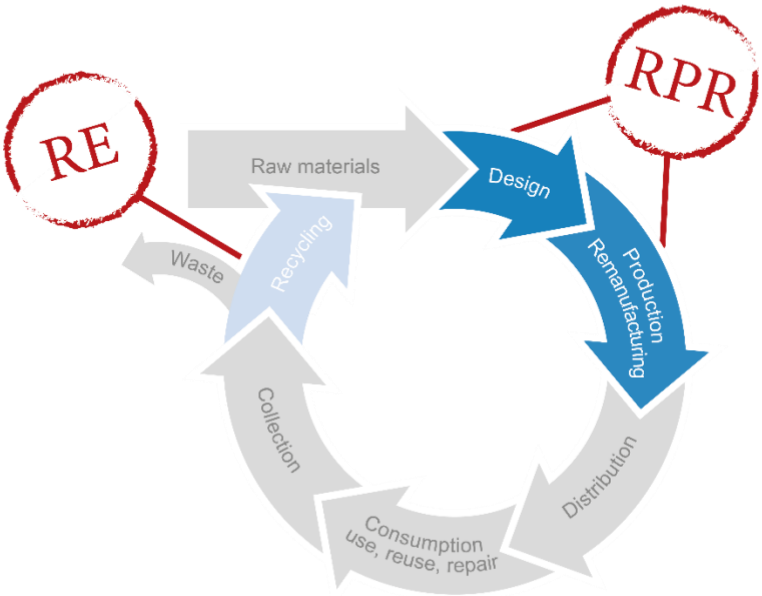

Figure 16 Value chain in a Circular Economy complemented with the RE and RPR indicators developed.

6.1 RE indicator

Implementing the RE indicator at the EU level could improve the European recycling performance evaluation significantly because it would enable assessing and identifying qualitative differences in the Member States' recycling performance for the first time. The RE indicator could act complementary to the existing recycling rate. The RE assessment method would allow relevant insights into the Member States' implementation of the new recycling rate targets and thus whether these attainments are more qualitative or quantitative. The definition of specific RE targets should best accompany the implementation of the RE assessment. Such RE targets could also be interpreted as quality standards if certain target material concentrations in the recycling output are achieved. This could positively affect the secondary materials market, which might promote their products through such quality information.

It should be noted that although the RE assessment method is structured similarly to the recycling rate calculation, it is accompanied by an additional data effort (in terms of target material concentrations). However, with the new rules concerning the EU recycling rate calculation, which provide for more extensive recording of material mass flows (e.g. for composite packaging materials), as well as the systematic data basis of recycling companies, the widespread implementation of the RE assessment method seems practicable.

Due to the flexible method of the RE assessment, the evaluation question can refer to various substances. For example, the assessment method could also be used to monitor the occurrence of toxic substances occurring in, e.g. recycling processes, and thus also take up another strategy of the EU concerning the monitoring of toxic substances (European Commission, 2019b). Of course, such an application only allows for simplified monitoring that does not consider other effects caused by the toxic substance (e.g., substance transformations) but could still provide general insights into the residues of toxic substances in the CE. In the long term, the SE assessment approach could be extended for more extensive applications that might also consider other media such as air and soil or allow transnational observations.

Besides the large-scale implementation at the EU level, also recyclers could profit from the application of the RE indicator concerning internal process evaluations. Thus, it could act as a planning and evaluation tool for qualitative process adjustments, tracking whether process changes increase the quality of the recycling output. Further, voluntary quality standards of recyclers could be checked with the RE assessment and thus bring more transparency in the market for secondary materials.

6.2 RPR indicator

The introduction of the RPR indicator at the EU level could significantly promote a rethinking in product design and thus result in the design of (more) recyclable and circular products. Product designers and manufacturers should use the RPR assessment method to identify potential design impacts on recyclability and improve the product's material composition and structure. Such product design optimizations should ensure that materials are used more efficiently and intelligently, and that product structure enables optimal disassembly. Thus, high product-inherent recyclability is achieved independent of the recycling technologies that will be available in the future. The triggered transition in product design could bring the EU closer to establishing a CE with circular products and materials.

Moreover, improved product design could also impact the European resource demand and consumption because efficient material use and high recyclability could lead to lower primary resources demand. This might further relieve the EU's dependence on certain producing countries concerning the demand for critical raw materials (see (European Commission, 2020b)). Generally speaking, product design optimisations might also positively influence environmental impacts in processes ahead of design, like mining and production of raw materials.

The RPR indicator could be easily included in existing product certification systems of the EU (e.g. EU Ecolabel) or other recognized institutions. Especially in the construction sector, there already exists a large number of established certification systems (such as the British “BREEAM” certification (Building Research Establishment Ltd, 2021)) that aim to assess the sustainability of buildings; however, they (currently) lack to assess the building’s recyclability. This gap could be filled with the RPR indicator, as its application could already be demonstrated in the buildings’ Case study.

However, the RPR assessment method should be implemented with a high degree of transparency and minimum requirements for consideration of product information (e.g., materials and connection types) to prevent incorrect or improper application. Therefore, the development of product group-specific guidelines should be realised and accompanied by the expertise of scientists and stakeholders. In this context, existing product (part) standards could be considered (e.g. CEN standards or Eurocodes) or further developed in this respect. These guidelines should be uniformly valid and best coordinated directly by the EU.

The RPR indicator aims to provide designers and manufacturers with a tool to assess the product's inherent recyclability in the design stage prior to construction. Decisions on material composition and product structure negatively impacting the product's recyclability can thus directly be reconsidered. The new indicator could give designers and manufacturers a new approach to product recyclability and further motivate them to apply existing design concepts such as "Design for recycling" or “Design for disassembly”.

In the future, the RPR results of products could also serve as a basis for decision-making for other stakeholders. For example, green investments could be related to the product’s RPR result or, if directly attached to products as a label, could also be a decision basis for citizens. All in all, this could trigger a more sustainable movement in investments and consumption. However, it should always be noted here that the RPR assessment does not cover all design aspects necessary for the comprehensive assessment of product recyclability.

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Appendices

A. Smartphone material composition

List of materials

Table 8 Smartphone: List of materials.

Material no.	Material ID	Material description
Material 1	M1	ABS
Material 2	M2	PC
Material 3	M3	PE
Material 4	M4	PP
Material 5	M5	PVC
Material 6	M6	Ag
Material 7	M7	Al
Material 8	M8	As
Material 9	M9	Au
Material 10	M10	B
Material 11	M11	Ba
Material 12	M12	Be
Material 13	M13	Bi
Material 14	M14	C (Graphite)
Material 15	M15	Ca
Material 16	M16	Cd
Material 17	M17	Co
Material 18	M18	Cr
Material 19	M19	Cu
Material 20	M20	Fe
Material 21	M21	Ga
Material 22	M22	Ge
Material 23	M23	Hf
Material 24	M24	In
Material 25	M25	Li
Material 26	M26	Mg
Material 27	M27	Mn
Material 28	M28	Mo
Material 29	M29	Na
Material 30	M30	Nb
Material 31	M31	Ni
Material 32	M32	Pa
Material 33	M33	Pb
Material 34	M34	Pd
Material 35	M35	Pt

Material 36	M36	Rb
Material 37	M37	Sb
Material 38	M38	Si
Material 39	M39	Sn
Material 40	M40	Sr
Material 41	M41	Ta
Material 42	M42	Ti
Material 43	M43	V
Material 44	M44	W
Material 45	M45	Zn
Material 46	M46	Zr
Material 47	M47	REE
Material 48	M48	Others
Material 49	M49	Glass

Material distribution at the product level

Table 9 Smartphone: Material distribution at the product level.

Material ID	Mass (g)
M1	2.4
M2	33.31
M3	2.6
M4	0.52
M5	0.02
M6	0.03
M7	2.35
M8	<0.01
M9	0.03
M10	0.01
M11	0.08
M12	<0.01
M13	<0.01
M14	6.24
M15	0.05
M16	<0.01
M17	0.51
M18	0.02
M19	5.22
M20	6.72
M21	0.02
M22	<0.01
M23	<0.01
M24	23.04
M25	0.57

M26	<0.01
M27	0.51
M28	<0.01
M29	<0.01
M30	0.01
M31	4.1
M32	0.02
M33	<0.01
M34	0.06
M35	<0.01
M36	<0.01
M37	<0.01
M38	1.05
M39	4.56
M40	<0.01
M41	0.38
M42	0.64
M43	<0.01
M44	<0.01
M45	0.16
M46	<0.01
M47	0.42
M48	10.82
M49	11.16
Total mass (g)	117.65

Material distribution at the component and sub-component level

Table 10 Smartphone: Material distribution of the component "PCA" and its sub-components.

	Mass (g) in sub-components						Mass (g) in component
Material ID	Circuit board	Capacitors	Semiconductors	Buttons	Frames	Solder	PCA
M1							
M2				0.27			0.27
M3							
M4							
M5							
M6		0.03	<0.01				0.03
M7		0.02	0.09	0.03			0.14
M8			<0.01				0.00
M9		0.01	<0.01				0.01
M10							
M11		<0.01	0.08				0.08

M12			<0.01				<0.01
M13		<0.01	<0.01				<0.01
M14							
M15		<0.01	0.04				0.04
M16			<0.01				<0.01
M17			<0.01				<0.01
M18			<0.01				<0.01
M19	0.61	0.03	1.35			<0.01	1.99
M20		0.03	0.23		1.22		1.48
M21			<0.01				<0.01
M22			<0.01				<0.01
M23			<0.01				<0.01
M24			<0.01				<0.01
M25			<0.01				<0.01
M26		<0.01	<0.01				<0.01
M27		0.02	<0.01				0.03
M28			<0.01				<0.01
M29			<0.01				<0.01
M30			<0.01				<0.01
M31		0.02	0.17				0.19
M32							
M33		<0.01	<0.01				<0.01
M34		0.05	0.02				0.06
M35			<0.01				<0.01
M36			<0.01				<0.01
M37		<0.01	<0.01				<0.01
M38		0.12	0.21				0.33
M39		<0.01	0.05			0.61	0.66
M40			<0.01				<0.01
M41		0.38	<0.01				0.38
M42		0.49	0.14				0.64
M43			<0.01				<0.01
M44			<0.01				<0.01
M45		<0.01	0.02				0.02
M46			<0.01				<0.01
M47			<0.01				<0.01
M48	2.19			0.30			2.49
M49	3.28						3.28
Total mass (g)	6.08	1.22	2.43	0.61	1.22	0.61	12.15

Table 11 Smartphone: Material distribution of the component “Housing”.

	Mass (g) in component
Material ID	Housing
M1	
M2	20.00

M3
M4
M5
M6
M7
M8
M9
M10
M11
M12
M13
M14
M15
M16
M17
M18
M19
M20
M21
M22
M23
M24
M25
M26
M27
M28
M29
M30
M31
M32
M33
M34
M35
M36
M37
M38
M39
M40
M41
M42
M43
M44
M45
M46
M47

M48	
M49	
Total mass (g)	20.00

Table 12 Smartphone: Material distribution of the component “Screen”.

Material ID	Mass (g) in component Screen
M1	
M2	
M3	
M4	
M5	
M6	
M7	
M8	
M9	
M10	
M11	
M12	
M13	
M14	
M15	
M16	
M17	
M18	
M19	
M20	
M21	
M22	
M23	
M24	23.04
M25	
M26	
M27	
M28	
M29	
M30	
M31	
M32	
M33	
M34	
M35	
M36	
M37	
M38	

M39	2.56
M40	
M41	
M42	
M43	
M44	
M45	
M46	
M47	
M48	
M49	6.40
Total mass (g)	20.00

Table 13 Smartphone: Material distribution of the component “Battery” and its sub-components.

	Mass (g) in sub-components					Mass (g) in component
Material ID	Cathode	Anode	Coating	Separator	Electrolyte	Battery
M1						
M2						
M3			0.52	2.08		2.60
M4				0.52		0.52
M5						
M6						
M7			2.08			2.08
M8						
M9						
M10						
M11						
M12						
M13						
M14		6.24				6.24
M15						
M16						
M17	0.46					0.46
M18						
M19		1.56				1.56
M20						
M21						
M22						
M23						
M24						
M25	0.57					0.57
M26						
M27	0.46					0.46
M28						
M29						

M30						
M31	3.70					3.70
M32						
M33						
M34						
M35						
M36						
M37						
M38						
M39						
M40						
M41						
M42						
M43						
M44						
M45						
M46						
M47						
M48	2.61				5.2	7.81
M49						
Total mass (g)	7.80	7.80	2.60	2.60	5.20	26.00

Table 14 Smartphone: Material distribution of the component “Speaker” and its sub-components.

	Mass (g) in sub-components				Mass (g) in component
Material ID	Magnets	Casing	Solder	Others	Speaker
M1					
M2		0.30			0.30
M3					
M4					
M5					
M6					
M7	<0.01				<0.01
M8					
M9					
M10	<0.01				<0.01
M11					
M12					
M13					
M14					
M15					
M16					
M17				0.01	0.01
M18					
M19			<0.01	0.23	0.23
M20	0.50			0.04	0.54

M21					
M22					
M23					
M24					
M25					
M26					
M27				<0.01	<0.01
M28					
M29					
M30	<0.01				<0.01
M31				0.03	0.03
M32					
M33					
M34					
M35					
M36					
M37					
M38					
M39			0.07	0.03	0.10
M40					
M41					
M42					
M43					
M44					
M45				0.02	0.02
M46					
M47	0.23			<0.01	0.23
M48				<0.01	<0.01
M49					
Total mass (g)	0.75	0.30	0.08	0.38	1.50

Table 15 Smartphone: Material distribution of the component “Cameras” and its sub-components.

	Mass (g) in sub-components				Mass (g) in component
Material ID	Housing	Lens	Solder	Others	Cameras
M1	2.00				2.00
M2					
M3					
M4					
M5					
M6				<0.01	<0.01
M7				<0.01	<0.01
M8					
M9				<0.01	<0.01
M10					
M11					

M12					
M13					
M14					
M15				<0.01	<0.01
M16					
M17				0.01	0.01
M18				0.02	0.02
M19			<0.01	0.92	0.93
M20				0.27	0.27
M21					
M22					
M23					
M24					
M25					
M26					
M27				<0.01	<0.01
M28					
M29					
M30					
M31				0.10	0.10
M32					
M33				<0.01	<0.01
M34					
M35					
M36					
M37					
M38					
M39			0.50	0.07	0.57
M40					
M41					
M42				<0.01	<0.01
M43					
M44					
M45				0.08	0.08
M46					
M47					
M48				<0.01	<0.01
M49		1.00			1.00
Total mass (g)	2.00	1.00	0.50	1.50	5.00

Table 16 Smartphone: Material distribution of the component “SIM tray”.

	Mass (g) in component
Material ID	SIM tray
M1	
M2	

M3	
M4	
M5	
M6	
M7	
M8	
M9	
M10	
M11	
M12	
M13	
M14	
M15	
M16	
M17	
M18	
M19	
M20	2.00
M21	
M22	
M23	
M24	
M25	
M26	
M27	
M28	
M29	
M30	
M31	
M32	
M33	
M34	
M35	
M36	
M37	
M38	
M39	
M40	
M41	
M42	
M43	
M44	
M45	
M46	
M47	

M48	
M49	
Total mass (g)	2.00

Table 17 Smartphone: Material distribution of the component “Back cover” and its sub-components.

	Mass (g) in sub-components		Mass (g) in component
Material ID	Casing	Glue	Back cover
M1			
M2	12.74		12.74
M3			
M4			
M5			
M6			
M7			
M8			
M9			
M10			
M11			
M12			
M13			
M14			
M15			
M16			
M17			
M18			
M19			
M20			
M21			
M22			
M23			
M24			
M25			
M26			
M27			
M28			
M29			
M30			
M31			
M32			
M33			
M34			
M35			
M36			
M37			
M38			

M39			
M40			
M41			
M42			
M43			
M44			
M45			
M46			
M47			
M48		0.26	0.26
M49			
Total mass (g)	12.74	0.26	13.00

Table 18 Smartphone: Material distribution of the component “Vibration motor” and its sub-components.

	Mass (g) in sub-components					Mass (g) in component
Material ID	Magnets	Casing	Glue	Solder	Others	Vibration motor
M1		0.40				0.40
M2						
M3						
M4						
M5					<0.01	<0.01
M6						
M7	<0.01					<0.01
M8						
M9		<0.01				<0.01
M10	<0.01					<0.01
M11						
M12						
M13						
M14						
M15						
M16						
M17					0.01	0.01
M18						
M19				<0.01	0.25	0.26
M20	0.40				0.03	0.44
M21						
M22						
M23						
M24						
M25						
M26						
M27					<0.01	<0.01
M28						
M29						

M30	<0.01					<0.01
M31					0.02	0.02
M32						
M33						
M34						
M35						
M36						
M37						
M38						
M39				0.40	0.03	0.43
M40						
M41						
M42						
M43						
M44						
M45					0.02	0.02
M46						
M47	0.19				<0.01	0.19
M48			0.20		<0.01	0.21
M49						
Total mass (g)	0.60	0.40	0.20	0.40	0.40	2.00

Table 19 Smartphone: Material distribution of the component “Buttons” and its sub-components.

	Mass (g) in sub-components				Mass (g) in component
Material ID	Semiconductors	Button material	Solder	Others	Buttons
M1					
M2					
M3					
M4					
M5				<0.01	<0.01
M6					
M7		0.12			0.12
M8					
M9	<0.01				<0.01
M10					
M11					
M12					
M13					
M14					
M15					
M16					
M17				0.01	0.01
M18					
M19			<0.01	0.25	0.26
M20				0.03	0.03

M21	0.02				0.02
M22					
M23					
M24					
M25					
M26					
M27				<0.01	<0.01
M28					
M29					
M30					
M31	0.03			0.02	0.06
M32	0.02				0.02
M33					
M34					
M35					
M36					
M37					
M38	0.72				0.72
M39			0.20	0.03	0.23
M40					
M41					
M42					
M43					
M44					
M45				0.02	0.02
M46					
M47				<0.01	<0.01
M48				<0.01	<0.01
M49		0.48			0.48
Total mass (g)	0.80	0.60	0.20	0.40	2.00

Table 20 Smartphone: Material distribution of the component “Screws” and its sub-components.

	Mass (g) in sub-components		Mass (g) in component
Material ID	Screw material	Glue	Screws
M1			
M2			
M3			
M4			
M5			
M6			
M7			
M8			
M9			
M10			
M11			

M12			
M13			
M14			
M15			
M16			
M17			
M18			
M19			
M20	1.96		1.96
M21			
M22			
M23			
M24			
M25			
M26			
M27			
M28			
M29			
M30			
M31			
M32			
M33			
M34			
M35			
M36			
M37			
M38			
M39			
M40			
M41			
M42			
M43			
M44			
M45			
M46			
M47			
M48		0.04	0.04
M49			
Total mass (g)	1.96	0.04	1.96

B. Building variants' material composition

List of materials

Table 21 Timber building: List of materials.

Material no.	Material ID	Material description
Material 1	M1	Acrylic
Material 2	M2	Binding agent
Material 3	M3	Bitumen
Material 4	M4	Cardboard
Material 5	M5	Glue
Material 6	M6	Mineral oil
Material 7	M7	Nylon
Material 8	M8	Paraffin
Material 9	M9	Polyethylene
Material 10	M10	Polyurethane
Material 11	M11	Silicone
Material 12	M12	Styrene-butadiene-styrene
Material 13	M13	Timber
Material 14	M14	Wood stain
Material 15	M15	Adhesive agent
Material 16	M16	Cement
Material 17	M17	Fluxing agent
Material 18	M18	Glass
Material 19	M19	Gravel
Material 20	M20	Gypsum
Material 21	M21	Lime
Material 22	M22	Rock wool
Material 23	M23	Sand
Material 24	M24	Shale
Material 25	M25	Split
Material 26	M26	Aluminium
Material 27	M27	Chromium
Material 28	M28	Nickel
Material 29	M29	Steel
Material 30	M30	Zinc

Table 22 Concrete building: List of materials.

Material no.	Material ID	Material description
Material 1	M1	Acrylic
Material 2	M2	Binding agent
Material 3	M3	Bitumen
Material 4	M4	Expanded polystyrene
Material 5	M5	Glue

Material 6	M6	Mineral oil
Material 7	M7	Nylon
Material 8	M8	Polyethylene
Material 9	M9	Polyurethane
Material 10	M10	Silicone
Material 11	M11	Styrene-butadiene-styrene
Material 12	M12	Synthetic resin
Material 13	M13	Timber
Material 14	M14	Wood stain
Material 15	M15	Cement
Material 16	M16	Glass
Material 17	M17	Glass wool
Material 18	M18	Gravel
Material 19	M19	Gypsum
Material 20	M20	Rock wool
Material 21	M21	Sand
Material 22	M22	Shale
Material 23	M23	Silicates
Material 24	M24	Split
Material 25	M25	Aluminium
Material 26	M26	Chromium
Material 27	M27	Nickel
Material 28	M28	Steel
Material 29	M29	Zinc

Material distribution at the product level

Table 23 Timber building: Material distribution at the product level.

Material ID	Mass (kg)
M1	20
M2	5,622
M3	2,907
M4	3,710
M5	3,650
M6	80
M7	4,334
M8	1,134
M9	5,485
M10	41
M11	348
M12	444
M13	741,531
M14	396
M15	10

M16	43,504
M17	1,178
M18	82,532
M19	64,572
M20	70,496
M21	16,333
M22	21,321
M23	280,735
M24	740
M25	323,092
M26	2,048
M27	18
M28	10
M29	17,921
M30	104
Total mass (kg)	1,694,319

Table 24 Concrete building: Material distribution at the product level.

Material ID	Mass (kg)
M1	23
M2	13,725
M3	3,397
M4	10,834
M5	2,006
M6	52
M7	606
M8	2,271
M9	46
M10	387
M11	871
M12	619
M13	73,493
M14	264
M15	571,313
M16	92,233
M17	1,087
M18	2,307,366
M19	21,411
M20	8,909
M21	29,451
M22	1,452
M23	9,470
M24	25,829
M25	18,303
M26	18

M27	10
M28	573,225
M29	3,813
Total mass (kg)	3,772,482

Material distribution at the component and sub-component level

Table 25 Timber building: Material distribution of the component "external wall" and its sub-components.

	Mass (kg) in sub-components									Mass (kg) in component
Material ID	Cross laminated timber	Sawn timber	Nails/ Screws	Wood fibreboard	Wood fibreboard insulation	Cross laminated timber	Sawn timber	Rockwool	Gypsum plasterboard	External wall
M1										
M2				1,023	2,385			72		3,479
M3										
M4									1,814	1,814
M5	20			31		80				131
M6								14		14
M7	40			73	486	159		169	806	1,733
M8				205	596					801
M9										
M10										
M11										
M12										
M13	19,813	4,057		8,998	56,633	78,425	6,085			174,011
M14										
M15										
M16										
M17										
M18										
M19										
M20									34,467	34,467
M21										
M22								2,787		2,787
M23										
M24										
M25										
M26										
M27										
M28										
M29	159	41	41	104	603	630	61	336	3,202	5,135
M30	1	<1	<1	1	4	4	<1	2	23	36
Total mass (kg)	20,033	4,098	41	10,434	60,706	79,298	6,147	3,381	40,313	224,409

Table 26 Concrete building: Material distribution of the component “external wall” and its sub-components.

Material ID	Mass (kg) in sub-components				Mass (kg) in component
	Silicate plaster	Expanded polystyrene	Armoured concrete	Spatula	External wall
M1					
M2	324				324
M3					
M4		5,665			5,665
M5					
M6					
M7					
M8					
M9					
M10					
M11					
M12	324	49			373
M13					
M14					
M15		486	172,786		173,271
M16					
M17					
M18			691,143		691,143
M19				10,244	10,244
M20					
M21		1,894			1,894
M22					
M23	5,839				5,839
M24					
M25					
M26					
M27					
M28			8,727		8,727
M29					
Total mass (kg)	6,488	8,093	872,655	10,244	897,480

Table 27 Timber building: Material distribution of the component “external wall; ground floor” and its sub-components.

Material ID	Mass (kg) in sub-components							Mass (kg) in component
	Plaster	Wood fibreboard	Wood fibreboard insulation	Cross laminated timber	Sawn timber	Insulation	Gypsum plasterboard	External wall; ground floor
M1								
M2		152	355			11		518
M3								
M4							270	270
M5		5		16				21
M6						2		2

M7		11	72	32		25	120	260
M8		30	89					119
M9								
M10								
M11								
M12								
M13		1,339	8,429	15,728	906			26,403
M14								
M15								
M16	2,502							2,502
M17								
M18								
M19								
M20							5,130	5,130
M21	5,004							5,004
M22						415		415
M23	25,022							25,022
M24								
M25								
M26								
M27								
M28								
M29		15	90	126	9	50	477	767
M30		<1	1	1	<1	<1	3	5
Total mass (kg)	32,529	1,553	9,036	15,903	915	503	6,000	66,439

Table 28 Concrete building: Material distribution of the component "external wall; ground floor" and its sub-components.

Material ID	Mass (kg) in sub-components Silicate plaster	 Expanded polystyrene	 Armoured concrete	 Spatula	Mass (kg) in component External wall; ground floor
M1					
M2	48				48
M3					
M4		843			843
M5					
M6					
M7					
M8					
M9					
M10					
M11					
M12	48	7			56
M13					
M14					

M15		72	25,718		25,790
M16					
M17					
M18			102,872		102,872
M19				1,525	1,525
M20					
M21		282			282
M22					
M23	869				869
M24					
M25					
M26					
M27					
M28			1,299		1,299
M29					
Total mass (kg)	966	1,205	129,890	1,525	133,585

Table 29 Timber building: Material distribution of the component “flat roof” and its sub-components.

	Mass (kg) in sub-components									Mass (kg) in component
Material ID	Gravel fill	Geo-membrane	Bituminised board	Insulation wool	Geo-membrane	Cross laminated timber	Sawn timber	Insulation	Gypsum plasterboard	Flat roof
M1										
M2				101				14		114
M3			1,130							1,130
M4									343	343
M5						82				82
M6				20				3		23
M7				237		164		32	152	585
M8										
M9		613			1,022					1,636
M10										
M11										
M12										
M13						81,175	1,151			82,326
M14										
M15										
M16										
M17										
M18										
M19	64,572									64,572
M20									6,518	6,518
M21										
M22				3,904				527		4,431
M23										

M24										
M25										
M26										
M27										
M28										
M29		32		470	53	652	12	63	606	1,888
M30		<1		3	<1	5	<1	<1	4	13
Total mass (kg)	64,572	646	1,130	4,735	1,076	82,079	1,162	639	7,623	163,663

Table 30 Concrete building: Material distribution of the component “flat roof” and its sub-components.

	Mass (kg) in sub-components								Mass (kg) in component
Material ID	Sand-gravel-split fill	Geo-membrane	Vapour pressure equalising layer	Expanded polystyrene	Bituminised board	Vapour pressure equalising layer	Armoured concrete	Spatula	Flat roof
M1									
M2		246			44				290
M3		2,955			442				3,397
M4				2,742					2,742
M5									
M6									
M7									
M8			1,069			1,202			2,271
M9									
M10									
M11		739			133				871
M12				24					24
M13									
M14									
M15				235			65,347		65,582
M16		985			177				1,162
M17									
M18	25,829						261,389		287,218
M19								2798	2,798
M20									
M21	25,829			917					26,746
M22		1,231			221				1,452
M23									
M24	25,829								25,829
M25					88				88
M26									
M27									
M28			56			63	3,300		3,419
M29			<1			<1			1
Total mass (kg)	77,487	6,156	1,125	3,917	1,105	1,266	330,036	2,798	423,890

Table 31 Timber building: Material distribution of the component “slab against outdoor air” and its sub-components.

Material ID	Mass (kg) in sub-components										Mass (kg) in component
	Parquet floor	Cement floor	Bituminised board	Floor impact protection	Split fill	Trickle protection	Cross laminated timber	Geo-membrane	Insulation	Plaster	Slab against outdoor air
M1											
M2			30	72					857		959
M3			360								360
M4											
M5	614						78				692
M6				4							4
M7							156		175		331
M8									214		214
M9						583		972			1,554
M10											
M11											
M12			90								90
M13	6,926						77,138		20,353		104,418
M14	79										79
M15				2							2
M16		7,159								5,664	12,823
M17		239									239
M18			120								120
M19											
M20											
M21										11,328	11,328
M22				1,968							1,968
M23		40,328								56,641	96,969
M24			150								150
M25					65,452						65,452
M26											
M27											
M28											
M29						30	620	51	217		917
M30						<1	4	<1	2		6
Total mass (kg)	7,619	47,725	750	2,045	65,452	614	77,997	1,023	21,817	73,633	298,675

Table 32 Concrete building: Material distribution of the component “slab against outdoor air” and its sub-components.

Material ID	Mass (kg) in sub-components							Mass (kg) in component
	Parquet floor	Sawn timber	Insulation	Distance pieces	Armoured concrete	Expanded polystyrene	Silicate plaster	Slab against outdoor air
M1								
M2		2,553	19				153	2,725
M3								

M4						1,584		1,584
M5	406							406
M6			4					4
M7			44					44
M8								
M9								
M10								
M11								
M12						14	153	167
M13	4,586	10,210						14,797
M14	52							52
M15					62,097	136		62,233
M16								
M17			729					729
M18					248,390			248,390
M19								
M20								
M21						529		529
M22								
M23							2,761	2,761
M24								
M25								
M26								
M27								
M28		1,408	88	42,246	3,136			46,878
M29		10	1	298				308
Total mass (kg)	5,045	14,181	884	42,544	313,623	2,262	3,068	381,607

Table 33 Timber building: Material distribution of the component “slab 1. floor” and its sub-components.

	Mass (kg) in sub-components										Mass (kg) in component
Material ID	Parquet floor	Cement floor	Bituminised board	Floor impact protection	Split fill	Trickle protection	Cross laminated timber	Sawn timber	Insulation	Gypsum plasterboard	Slab 1. floor
M1											
M2			88	210					38		336
M3			1,057								1,057
M4										957	957
M5	1,802						230				2,032
M6				12					8		20
M7							458		89	425	973
M8											
M9						1,712					1,712
M10											
M11											
M12			264								264

M13	20,337						226,504	3,211			250,052
M14	233										233
M15				6							6
M16		21,021									21,021
M17		701									701
M18			352								352
M19											
M20										18,187	18,187
M21											
M22				5,778					1,471		7,248
M23		118,416									118,416
M24			440								440
M25					192,188						192,188
M26											
M27											
M28											
M29						89	1,819	32	177	1,690	3,808
M30						1	13	<1	1	12	27
Total mass (kg)	22,372	140,137	2,202	6,006	192,188	1,802	229,024	3,243	1,784	21,271	620,029

Table 34 Concrete building: Material distribution of the component “slab 1. floor” and its sub-components.

	Mass (kg) in sub-components								Mass (kg) in component Slab 1. floor
Material ID	Parquet floor	Sawn timber	Insulation	Distance pieces	Armoured concrete	Steel battens	Insulation	Spatula	
M1									
M2		7,495	7				126		7,629
M3									
M4									
M5	1,193								1,193
M6			1				25		27
M7			16				297		314
M8									
M9									
M10									
M11									
M12									
M13	13,467	29,981							43,449
M14	154								154
M15					182,339				182,339
M16									
M17			267						267
M18					729,354				729,354
M19								5,105	5,105
M20							4,902		4,902
M21									

M22									
M23									
M24									
M25									
M26									
M27									
M28		4,135	32	155,060	9,209	155,060	590		324,086
M29		29	<1	1,093		1,093	4		2,220
Total mass (kg)	14,815	41,641	324	156,153	920,902	156,153	5,946	5,105	1,301,038

Table 35 Timber building: Material distribution of the component “slab 2. floor” and its sub-components.

	Mass (kg) in sub-components										Mass (kg) in component
Material ID	Parquet floor	Cement floor	Bituminised board	Floor impact protection	Split fill	Trickle protection	Cross laminated timber	Sawn timber	Insulation	Gypsum plasterboard	Slab 2. floor
M1											
M2			30	72					65		166
M3			360								360
M4										326	326
M5	614						78				692
M6				4					13		17
M7							156		152	145	453
M8											
M9						583					583
M10											
M11											
M12			90								90
M13	6,926						77,138	5,467			89,532
M14	79										79
M15				2							2
M16		7,159									7,159
M17		239									239
M18			120								120
M19											
M20										6,194	6,194
M21											
M22				1,968					2,504		4,472
M23		40,328									40,328
M24			150								150
M25					65,452						65,452
M26											
M27											
M28											
M29						30	620	55	302	575	1,582
M30						<1	4	<1	2	4	11

Total mass (kg)	7,619	47,725	750	2,045	65,452	614	77,997	5,522	3,037	7,244	218,006

Table 36 Concrete building: Material distribution of the component “slab 2. floor” and its sub-components.

	Mass (kg) in sub-components								Mass (kg) in component
Material ID	Parquet floor	Sawn timber	Insulation	Distance pieces	Armoured concrete	Steel battens	Insulation	Spatula	Slab 2. floor
M1									
M2		2,553	2				103		2,658
M3									
M4									
M5	406								406
M6			<1				21		21
M7			6				243		249
M8									
M9									
M10									
M11									
M12									
M13	4,586	10,210							14,797
M14	52								52
M15					62,097				62,097
M16									
M17			91						91
M18					248,390				248,390
M19								1,739	1,739
M20							4,007		4,007
M21									
M22									
M23									
M24									
M25									
M26									
M27									
M28		1,408	11	52,807	3,136	126,738	483		184,583
M29		10	<1	372		893	3		1,279
Total mass (kg)	5,045	14,181	110	53,180	313,623	127,631	4,860	1,739	520,369

Table 37 Timber building: Material distribution of the component “doors” and its sub-components.

	Mass (kg) in sub-components				Mass (kg) in component
Material ID	Doors	Handles	Hinges	Screws	Doors
M1					
M2	51				51
M3					

M4					
M5					
M6					
M7					
M8					
M9					
M10					
M11					
M12					
M13	450				450
M14	5				5
M15					
M16					
M17					
M18					
M19					
M20					
M21					
M22					
M23					
M24					
M25					
M26					
M27		18			18
M28		10			10
M29		73	54	13	140
M30			<1	<1	<1
Total mass (kg)	506	101	54	13	675

Table 38 Concrete building: Material distribution of the component “doors” and its sub-components.

	Mass (kg) in sub-components				Mass (kg) in component
Material ID	Doors	Handles	Hinges	Screws	Doors
M1					
M2	51				51
M3					
M4					
M5					
M6					
M7					
M8					
M9					
M10					
M11					
M12					

M13	450				450
M14	5				5
M15					
M16					
M17					
M18					
M19					
M20					
M21					
M22					
M23					
M24					
M25					
M26		18			18
M27		10			10
M28		73	54	13	140
M29			<1	<1	<1
Total mass (kg)	506	101	54	13	675

Table 39 Timber building: Material distribution of the component “windows” and its sub-components.

	Mass (kg) in sub-components										Mass (kg) in component
Material ID	Frames	Glass	Handles	Fittings	Steel reinforcement	Screws	Seal	Joint outside	Joint middle	Joint inside	Windows
M1										20	20
M2											
M3											
M4											
M5											
M6											
M7											
M8											
M9											
M10									41		41
M11							328	20			348
M12											
M13	14,339										14,339
M14											
M15											
M16											
M17											
M18		81,939									81,939
M19											
M20											
M21											
M22											

M23											
M24											
M25											
M26			2,048								2,048
M27											
M28											
M29				203	3,073	407					3,683
M30				1		3					4
Total mass (kg)	14,339	81,939	2,048	205	3,073	410	328	20	41	20	102,424

Table 40 Concrete building: Material distribution of the component “windows” and its sub-components.

	Mass (kg) in sub-components										Mass (kg) in component
Material ID	Frames	Glass	Handles	Fittings	Steel reinforcement	Screws	Seal	Joint outside	Joint middle	Joint inside	Windows
M1										23	23
M2											
M3											
M4											
M5											
M6											
M7											
M8											
M9									46		46
M10							364	23			387
M11											
M12											
M13											
M14											
M15											
M16		91,071									91,071
M17											
M18											
M19											
M20											
M21											
M22											
M23											
M24											
M25	15,937		2,277								18,214
M26											
M27											
M28				226	3,415	452					4,093
M29				2		3					5
Total mass (kg)	15,937	91,071	2,277	228	3,415	455	364	23	46	23	113,839

Material distribution at the sub-component and sub-sub-component level

Table 41 Timber building: Material distribution of the sub-sub-components of the “external wall” and its sub-components (values rounded).

	Mass (kg) of sub-component																						
	Cross laminated timber 20,033			Sawn timber 4,098		Wood fibreboard 10,434				Wood fibreboard insulation 60,706			Cross laminated timber 79,298			Sawn timber 6,147		Rockwool 3,381			Gypsum plasterboard 40,313		
	Mass (kg) of sub-sub-component																						
Material ID	Timber	Nails/Screws	Dowels	Timber	Nails/Screws	Timber fibreboard	Nails/Screws	Dowels	Glue	Timber fibreboard	Nails/Screws	Dowels	Timber	Nails/Screws	Dowels	Timber	Nails/Screws	Rock wool	Nails/Screws	Dowels	Gypsum plasterboard	Nails/Screws	Dowels
M1																							
M2						1,023				2,385								72					
M3																							
M4																					1,814		
M5	20								31				80										
M6																		14					
M7			40					73				486			159					169			806
M8						205				596													
M9																							
M10																							
M11																							
M12																							
M13	19,813			4,057		8,998				56,633			78,425			6,085							
M14																							
M15																							
M16																							
M17																							
M18																							
M19																							
M20																					34,467		
M21																							
M22																		2,787					
M23																							
M24																							
M25																							
M26																							
M27																							

M28																							
M29		159			41		104				603			630			61		336			3,202	
M30		1			<1		1				4			4			<1		2			23	
Total mass (kg)	19,833	160	40	4,057	41	10,225	104	73	31	59,614	607	486	78,505	634	159	6,085	61	2,874	338	169	36,282	3,225	806

Table 42 Concrete building: Material distribution of the sub-sub-components of the “external wall” and its sub-components (values rounded).

	Mass (kg) of sub-component					
	Silicate plaster	Expanded polystyrene		Armoured concrete		Spatula
	6,488	8,093		872,655		10,244
	Mass (kg) of sub-sub-component					
Material ID		Expanded polystyrene	Adhesive spatula	Concrete	Reinforcing steel	
M1						
M2						
M3						
M4		5,665				
M5						
M6						
M7						
M8						
M9						
M10						
M11						
M12			49			
M13						
M14						
M15			486	17,2786		
M16						
M17						
M18				691,143		
M19						
M20						
M21			1,894			
M22						
M23						
M24						
M25						
M26						
M27						

M28					8,727	
M29						
Total mass (kg)		5,665	2,428	863,928	8,727	

Table 43 Timber building: Material distribution of the sub-sub-components of the “external wall; ground floor” and its sub-components (values rounded).

	Mass (kg) of sub-component																		
	Plaster	Wood fibreboard				Wood fibreboard insulation			Cross laminated timber			Sawn timber		Insulation			Gypsum plasterboard		
	32,529	1,553				9,036			15,903			915		503			6,000		
	Mass (kg) of sub-sub-component																		
Material ID		Timber fibreboard	Nails/Screws	Dowels	Glue	Timber fibreboard	Nails/Screws	Dowels	Timber	Nails/Screws	Dowels	Timber	Nails/Screws	Rock wool	Nails/Screws	Dowels	Gypsum plasterboard	Nails/Screws	Dowels
M1																			
M2		152				355								11					
M3																			
M4																	270		
M5					5				16										
M6														2					
M7				11				72			32					25			120
M8		30				89													
M9																			
M10																			
M11																			
M12																			
M13		1,339				8,429			15,728			906							
M14																			
M15																			
M16																			
M17																			
M18																			
M19																			
M20																	5,130		
M21																			
M22														415					
M23																			
M24																			
M25																			
M26																			
M27																			
M28																			

M29			15				90			126			9		50			477	
M30			<1				1			1			<1		<1			3	
Total mass (kg)		1,522	16	11	5	8,873	90	72	15,744	127	32	906	9	428	50	25	5,400	480	120

Table 44 Concrete building: Material distribution of the sub-sub-components of the “external wall; ground floor” and its sub-components (values rounded).

	Mass (kg) of sub-component					
	Silicate plaster	Expanded polystyrene		Armoured concrete		Spatula
	966	1,205		129,890		1,525
	Mass (kg) of sub-sub-component					
Material ID		Expanded polystyrene	Adhesive spatula	Concrete	Reinforcing steel	
M1						
M2						
M3						
M4		843				
M5						
M6						
M7						
M8						
M9						
M10						
M11						
M12			7			
M13						
M14						
M15			72	25,718		
M16						
M17						
M18				102,872		
M19						
M20						
M21			282			
M22						
M23						
M24						
M25						
M26						
M27						
M28					1,299	

M29					
Total mass (kg)		843	361	128,591	1,299

Table 45 Timber building: Material distribution of the sub-sub-components of the “flat roof” and its sub-components (values rounded).

	Mass (kg) of sub-component																			
	Gravel fill	Geomembrane		Bituminised board	Insulation wool			Geomembrane		Cross laminated timber			Sawn timber		Insulation			Gypsum plasterboard		
	64,572	646		1,130	4,735			1,076		82,079			1,162		639			7,623		
	Mass (kg) of sub-sub-component																			
Material ID		Geomembrane	Nails/Screws		Rock wool	Nails/Screws	Dowels	Geomembrane	Nails/Screws	Timber	Nails/Screws	Dowels	Timber	Nails/Screws	Rock wool	Nails/Screws	Dowels	Gypsum plasterboard	Nails/Screws	Dowels
M1																				
M2					101										14					
M3																				
M4																		343		
M5										82										
M6					20										3					
M7							237					164					32			152
M8																				
M9		613						1,022												
M10																				
M11																				
M12																				
M13										81,175			1,151							
M14																				
M15																				
M16																				
M17																				
M18																				
M19																				
M20																		6,518		
M21																				
M22					3,904										527					
M23																				
M24																				
M25																				
M26																				
M27																				
M28																				
M29			32			470			53		652			12		63			606	
M30			<1			3			<1		5			<1		<1			4	

Total mass (kg)		613	32			4025	474	237	1,022	54	81,258	657	164	1,151	12	543	64	32	6,861	610	152			

Table 46 Concrete building: Material distribution of the sub-sub-components of the “flat roof” and its sub-components (values rounded).

	Mass (kg) of sub-component													
	Sand-gravel-split fill 77,487			Geomembrane 6,156	Vapour pressure equalising layer 1,125		Expanded polystyrene 3,917		Bituminised board 1,105	Vapour pressure equalising layer 1,266		Armoured concrete 330,036		Spatula 2,798
	Mass (kg) of sub-sub-component													
Material ID	Sand	Gravel	Split	Geomembrane	Geomembrane	Nails/Screws	Expanded polystyrene	Adhesive spatula		Geomembrane	Nails/Screws	Concrete	Reinforcing steel	
M1														
M2														
M3														
M4							2,742							
M5														
M6														
M7														
M8					1,069					1,202				
M9														
M10														
M11														
M12								24						
M13														
M14														
M15								235				65,347		
M16														
M17														
M18		25,829										261,389		
M19														
M20														
M21	25,829							917						
M22														
M23														
M24			25,829											
M25														
M26														
M27														
M28						56					63		3,300	
M29						<1					<1			
Total mass (kg)	25,829	25,829	25,829		1,069	56	2,742	1,175		1,202	63	326,736	3,300	

Table 47 Timber building: Material distribution of the sub-sub-components of the “slab against outdoor air” and its sub-components (values rounded).

	Mass (kg) of sub-component																
	Parquet floor		Cement floor	Bituminised board	Floor impact protection	Split fill	Trickle protection		Cross laminated timber			Geomembrane		Insulation			Plaster
	7,619		47,725	750	2,045	65,452	614		77,997			1,023		21,817			73,633
	Mass (kg) of sub-sub-component																
Material ID	Timber	Glue					Geomembrane	Nails/Screws	Timber	Nails/Screws	Dowels	Geomembrane	Nails/Screws	Timber fibreboard	Nails/Screws	Dowels	
M1																	
M2														857			
M3																	
M4																	
M5		614							78								
M6																	
M7											156					175	
M8														214			
M9							583					972					
M10																	
M11																	
M12																	
M13	6,926								77,138					20,353			
M14	79																
M15																	
M16																	
M17																	
M18																	
M19																	
M20																	
M21																	
M22																	
M23																	
M24																	
M25																	
M26																	
M27																	
M28																	
M29								30		620			51		217		
M30								<1		4			<1		2		
Total mass (kg)	7,005	614					583	31	77,217	624	156	972	51	21,425	218	175	

Table 48 Concrete building: Material distribution of the sub-sub-components of the “slab against outdoor air” and its sub-components (values rounded).

	Mass (kg) of sub-component													
	Parquet floor 5,045		Sawn timber 14,181		Insulation 884			Distance pieces 42,544		Armoured concrete 313,623		Expanded polystyrene 2,262		Silicate plaster 3,068
	Mass (kg) of sub-sub-component													
Material ID	Timber	Glue	Timber	Nails/Screws	Glass wool	Nails/Screws	Dowels	Distance pieces	Nails/Screws	Concrete	Reinforcing steel	Expanded polystyrene	Adhesive spatula	
M1														
M2			2,553		19									
M3														
M4												1,584		
M5		406												
M6					4									
M7							44							
M8														
M9														
M10														
M11														
M12													14	
M13	4,586		10,210											
M14	52													
M15										62,097			136	
M16														
M17					729									
M18										248,390				
M19														
M20														
M21													529	
M22														
M23														
M24														
M25														
M26														
M27														
M28				1,408		88		33,797	8,449		3,136			
M29				10		1		238	60					
Total mass (kg)	4,639	406	12,763	1,418	751	88	44	34,035	8,509	310,487	3,136	1,584	679	

Table 49 Timber building: Material distribution of the sub-sub-components of the “slab 1. floor” and its sub-components (values rounded).

	Mass (kg) of sub-component																		
	Parquet floor		Cement floor	Bituminised board	Floor impact protection	Split fill	Trickle protection		Cross laminated timber			Sawn timber		Insulation			Gypsum plasterboard		
	22,372		140,137	2,202	6,006	192,188	1,802		229,024			3,243		1,784			21,271		
	Mass (kg) of sub-sub-component																		
Material ID	Timber	Glue					Geomembrane	Nails/Screws	Timber	Nails/Screws	Dowels	Timber	Nails/Screws	Rock wool	Nails/Screws	Dowels	Gypsum plasterboard	Nails/Screws	Dowels
M1																			
M2														38					
M3																			
M4																	957		
M5		1,802							230										
M6														8					
M7											458					89			425
M8																			
M9							1,712												
M10																			
M11																			
M12																			
M13	20,337								226,504			3,211							
M14	233																		
M15																			
M16																			
M17																			
M18																			
M19																			
M20																	18,187		
M21																			
M22														1,471					
M23																			
M24																			
M25																			
M26																			
M27																			
M28																			
M29								89		1,819			32		177			1,690	
M30								1		13			<1		1			12	
Total mass (kg)	20,570	1,802					1,712	90	226,734	1,832	458	3,211	32	1,516	178	89	19,144	1,702	425

Table 50 Concrete building: Material distribution of the sub-sub-components of the “slab 1. floor” and its sub-components (values rounded).

	Mass (kg) of sub-component																
	Parquet floor		Sawn timber		Insulation			Distance pieces		Armoured concrete		Steel battens		Insulation			Spatula
	14,815		41,641		324			156,153		920,902		156,153		5,946			5,105
	Mass (kg) of sub-sub-component																
Material ID	Timber	Glue	Timber	Nails/Screws	Glass wool	Nails/Screws	Dowels	Distance pieces	Nails/Screws	Concrete	Reinforcing steel	Steel battens	Nails/Screws	Rock wool	Nails/Screws	Dowels	
M1																	
M2			7,495		7									126			
M3																	
M4																	
M5		1,193															
M6					1									25			
M7							16									297	
M8																	
M9																	
M10																	
M11																	
M12																	
M13	13,467		29,981														
M14	154																
M15										182,339							
M16																	
M17					267												
M18										729,354							
M19																	
M20														4,902			
M21																	
M22																	
M23																	
M24																	
M25																	
M26																	
M27																	
M28				4,135		32		124,048	31,012		9,209	139,554	15,506		590		
M29				29		<1		874	219			984	109		4		
Total mass (kg)	13,621	1,193	37,477	4,164	276	32	16	124,922	31,231	911,693	9,209	140,538	15,615	5,054	595	297	

Table 51 Timber building: Material distribution of the sub-sub-components of the “slab 2. floor” and its sub-components (values rounded).

	Mass (kg) of sub-component																		
	Parquet floor		Cement floor	Bituminised board	Floor impact protection	Split fill	Trickle protection		Cross laminated timber			Sawn timber		Insulation			Gypsum plasterboard		
	7,619		47,725	750	2,045	65,452	614		77,997			5,522		3,037			7,244		
	Mass (kg) of sub-sub-component																		
Material ID	Timber	Glue					Geomembrane	Nails/Screws	Timber	Nails/Screws	Dowels	Timber	Nails/Screws	Rock wool	Nails/Screws	Dowels	Gypsum plasterboard	Nails/Screws	Dowels
M1																			
M2														65					
M3																			
M4																	326		
M5		614							78										
M6														13					
M7											156					152			145
M8																			
M9							583												
M10																			
M11																			
M12																			
M13	6,926								77,138			5,467							
M14	79																		
M15																			
M16																			
M17																			
M18																			
M19																			
M20																	6,194		
M21																			
M22														2,504					
M23																			
M24																			
M25																			
M26																			
M27																			
M28																			
M29								30		620			55		302			575	
M30								<1		4			<1		2			4	
Total mass (kg)	7,005	614					583	31	77,217	624	156	5,467	55	2,582	304	152	6,520	580	145

Table 52 Concrete building: Material distribution of the sub-sub-components of the “slab 2. floor” and its sub-components (values rounded).

	Mass (kg) of sub-component																
	Parquet floor		Sawn timber		Insulation			Distance pieces		Armoured concrete		Steel battens		Insulation			Spatula
	5,045		14,181		110			53,180		313,623		127,631		4,860			1,739
	Mass (kg) of sub-sub-component																
Material ID	Timber	Glue	Timber	Nails/Screws	Glass wool	Nails/Screws	Dowels	Distance pieces	Nails/Screws	Concrete	Reinforcing steel	Steel battens	Nails/Screws	Rock wool	Nails/Screws	Dowels	
M1																	
M2			2,553		2									103			
M3																	
M4																	
M5		406															
M6					<1									21			
M7							6									243	
M8																	
M9																	
M10																	
M11																	
M12																	
M13	4,586		10,210														
M14	52																
M15										62,097							
M16																	
M17					91												
M18										248,390							
M19																	
M20														4,007			
M21																	
M22																	
M23																	
M24																	
M25																	
M26																	
M27																	
M28				1,408		11		42,246	10,561		3,136	114,064	12,674		483		
M29				10		<1		298	74			804	89		3		
Total mass (kg)	4,639	406	12,763	1,418	94	11	6	42,544	10,636	310,487	3,136	114,868	12,763	4,131	486	243	

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Implementing the dimension of quality into the conventional quantitative definition of recycling rates

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ABSTRACT

With the proposed Circular Economy Package, the European Union is striving to play a leading role in the implementation of recycling goals. The significantly increased recycling targets are just some of the defined objectives. However, to assess the Member States' attainment of the new recycling targets, the European Union still builds on a purely quantitative recycling rate assessment procedure that neglects to include qualitative recycling aspects. This circumstance could lead to additional quality losses in recycling processes because recyclers might tend to focus exclusively on higher quantities to achieve the stricter recycling targets on time. To prevent such a development, the aim of this study is to establish a complementary recycling indicator that combines quantitative and qualitative recycling aspects in one single metric. The basis of this assessment method is the statistical entropy approach, which enables the concentrating or diluting effect of a recycling process brought about through the separation or mixing of materials to be measured. The results of the statistical entropy metric will provide greater insight into recycling processes (or systems) and thereby yield enhanced information on the quantity and purity of recycling outputs. The simple structure of the new approach will allow enhanced comparisons between technologies as well as national recycling performance. A case study on plastic packaging recycling demonstrates that the new recycling indicator provides multifaceted findings relative to the hitherto purely quantitative recycling assessment data, hence enriching conclusions on the recycling performance.

1. Introduction

In 2018 the European Union (EU) launched the ambitious Circular Economy (CE) Package, which aims at maximizing the recycling and re-use of waste, while at the same time ensuring benefits for the environment and the economy (European Commission, 2018a, 2018b, 2018c). Further, the long awaited revision of the European waste framework entered into force in January 2018 (European Parliament and European Council, 2018a, 2018b), thus tightening existing waste targets. The cornerstone of these amendments was set back in 2015 when the European CE Action Plan was introduced (European Commission, 2015a, 2015b). Since then CE has been put on the agenda of numerous strategies within the EU that inter alia intend to establish quality standards for plastics, raise the quality of recycled materials or improve the traceability of materials and hazardous substances (European Commission, 2018a, 2018b, 2018d, 2018c).

Since recycling has always been an integral part of European waste legislation, strong commitments have been set in the field of recycling targets. For example, the recycling target for all packaging waste has been raised from 55% to 75% by 2030 (European Parliament and European Council, 2018b, 2004). With respect to plastic packaging, it has been more than doubled - from 22.5% to 55% by 2030 (see Table 1).

To assess the attainment of the European recycling targets, the EU established a simple, mass based method to measure the different recycling rates of the Member States (European Commission, 2005; European Parliament and European Council, 1994), thereby relating the quantity of total recycled waste to the quantity of total waste generated. Every Member State is obligated to submit its specific recycling rates on an annual basis, to provide a continuous evaluation of its recycling performance and to enable comparisons between Member States.

Differences in the recycling performance of Member States do not only originate from different waste management regimes, but also from inconsistent implementation of state-specific waste data into the recycling rate method. A study carried out for the Directorate-General for Environment of the European Commission

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Table 1
Minimum recycling targets (%) for specific packaging materials (European Parliament and European Council, 2018b, 2004).

	Minimum recycling targets (%)				
	Glass	Paper and board	Metals	Plastic	Wood
no later than 2008	60	60	50	22,5	15
	Glass	Paper and cardboard	Ferrous metals; Aluminium	Plastic	Wood
no later than 2025	70	75	70; 50	50	25
no later than 2030	75	85	80; 60	55	30

(Eunomia Research & Consulting et al., 2017) analyzed the European waste statistics and discussed relevant issues, calling for improvements in European waste legislation. One of the greatest criticisms of the study is that the requirements for the data reporting are too imprecise, thus affecting the accuracy of the input data for the recycling rate calculation. Furthermore, the study authors criticize that the recording of sorting qualities and packaging types are not required. These identified issues show that current recycling rates might be subject to significant overestimations. However, they also demonstrate the difficulty in establishing a simple recycling rate definition that guarantees, on the one hand, a comprehensive assessment of the recycling performance and, on the other hand, easy application by the Member States.

Consequently, the new amendments of Directive 2018/852 (European Parliament and European Council, 2018b) and the Commission Implementing Decision of the European Commission (European Commission, 2019) aim at overcoming weaknesses in the current recycling rate method. Among others amendments, the EU has changed the rules concerning the recycling rate calculation with regard to the definition of recycled packaging waste: the calculation point for the recycled packaging waste amount has been shifted from the input to the output of the recycling process, resulting in lower recycling rates as the losses are now excluded. Hence, a direct comparison with the previous recycling targets is not possible. Concerning composite packaging that consists of more than one material, the calculation of the recycling rate should be carried out for each material, except for materials that only account for an insignificant proportion of the total packaging unit (<5%). Moreover, the recording of loss rates and the production of quality check reports are required (European Commission, 2019). However, the proposed adaptation of the recycling rate method does not involve a reconsideration of the purely quantitative assessment approach and thus neglects the consideration of qualitative recycling aspects, such as the purity of the recycling outputs. This is despite the fact that such an additional assessment focus would be of direct benefit for the attainment of the CE objectives that aim to enhance the quality and standards of recycled materials. The entry into force of the increased recycling targets should be particularly supported by taking into account qualitative recycling aspects. This would help to prevent a predominantly mass based realization of the recycling targets that might, in turn, entail additional impurities in recycled materials (e.g. due to hazardous substances) and declining qualities (=down-cycling). The recycling market's capacity to absorb recycling materials of low quality is bounded because the areas of application are limited (Eriksen et al., 2019), even though some recyclers attempt to increase the material quality by dilution with e.g. virgin or high quality recycled material (Haupt et al., 2017). Here it is important to stress that the generation of low quality materials causes irreversible material losses in a CE, inter alia due to their finite recyclability, thereby creating additional environmental and economic expenses for the following cycles (Haupt et al., 2017; Kral et al., 2013). Further, the new CE requirements might risk that recyclers mainly focus on recycling materials of large quantities (like e.g. steel or polyethylene) and high monetary value that are simple and efficient to recycle (Dahmus and Gutowski, 2007; Velázquez Martínez et al., 2019). On the downside, this narrow recycling focus could result in a decrease in the recovery of rare or minor materials (like e.g. molybdenum or polypropylene) (Reck and Graedel, 2012; Van Eygen et al., 2017), although several of these materials are of significant ecological and economic importance (cf. (European Commission, 2017)). Therefore, the necessity of introducing an indicator that includes qualitative recycling aspects is well grounded. Several authors (Eriksen et al., 2019; Haupt et al., 2017; Huysman et al., 2017) have already addressed the inclusion of qualitative aspects into CE assessment methods. They consequently applied different assessment approaches (Life Cycle Assessment, Material Flow Analysis), which is partially due to the varying interpretations of quality. Unfortunately, most of the indicators proposed are based on certain assumptions (e.g. quality classifications), which give rise to striking uncertainty regarding the reliability of the indicators' results. Hence, it seems necessary to find an alternative metric that expresses qualitative aspects in a more self-evident manner. Statistical entropy might meet such requirements because it takes into account the concentration of specific materials, which can also be interpreted as a quality indicator.

The aim of this study is to introduce a statistical entropy-based recycling indicator that integrates quantitative and qualitative recycling aspects. It should act as a significant metric for the assessment of recycling processes or technologies. This new recycling indicator incorporates existing waste data in a consistent way to ensure a simple and transparent application. The statistical entropy approach is demonstrated with straightforward recycling process cases to prove the sensitivity and applicability of the metric. The results enable advanced comparisons between different recycling processes, and are proposed to serve as a complementary method for the EU's recycling assessment.

2. Method

2.1. Statistical entropy

Statistical entropy measures the concentrating or diluting effect of a process on a specific material (Rechberger, 1999; Rechberger and Brunner, 2002). This effect can be exemplified with a simplified material flow system consisting of one process (e.g. recycling technology) transforming one input flow (e.g. waste) into three output flows of equal size. The input flow contains a specific target material (e.g. plastics), which should be maximally recovered, and hence the distribution pattern of the target material after passing through the process is of interest (see Fig. 1). In the case that the target material content (c) is equally distributed among the output flows, no separation process has occurred and the statistical entropy (H) for such a distribution is a maximum (=Max; H = 1) (Fig. 1 left). However, when the target material is entirely concentrated in one output flow (c = 1), the statistical entropy is a minimum (=Min; H = 0) (Fig. 1 right). This simple example demonstrates that a process produces distribution patterns of the content of a target material in its output flows; these patterns can be expressed through statistical entropy. All real distribution

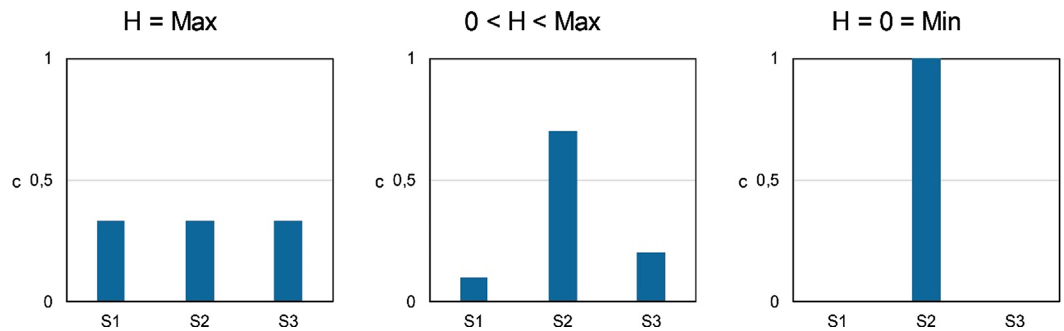

Fig. 1. Distribution of a target material into different output flows (S1–S3) after passing through a process. Statistical entropy (H) quantifies the distribution patterns of the target material content (c).

patterns appear in between these extremes (Fig. 1 middle) (Rechberger and Brunner, 2002).

The statistical entropy approach was initially introduced for determining the concentrating power of waste incineration plants for specific heavy metals (Rechberger and Brunner, 2002). It was shown that the statistical entropy approach is a valid measure to assess differences in the waste incineration technologies investigated. In different follow-up studies, the hitherto implemented statistical entropy approach was further developed and thereby modified for various applications (Laner et al., 2017; Rechberger and Graedel, 2002; Sobańtka et al., 2014; Zeng and Li, 2016), such as for the consideration of different chemical compounds (Sobańtka et al., 2012).

2.2. Application of statistical entropy to recycling processes

Recycling describes the physical or chemical processing of a separately collected or technically derived waste stream that consists of a mixture of wanted (target materials) and unwanted materials (e.g. impure, contaminated materials, or materials of low economic value). The challenge of recycling lies in effectively separating target material(s) (best with a high material purity) from unwanted materials that should not be recycled or must be treated separately. Accordingly, the objective is to produce (at least) two separated outputs: one that shows a high content of target material, and another one that contains all unwanted materials. Considering the complexity of real recycling systems, the number of inputs, outputs and transforming process steps is usually larger.

In terms of entropy, the role of the recycling industry is to reduce the level of entropy, and hence the transformation of high-entropy flows (mixed, collected waste) into low-entropy flows (recycling output with high content of target material) (Rechberger, 2012; Rechberger and Graedel, 2002; Velázquez Martínez et al., 2019). Moreover, target material losses that can typically occur during recycling processes are entropy-relevant as they constitute an entropy increase. Thus, statistical entropy is a qualified metric to assess the performance of recycling processes, and thereby the quantitative recycling output(s). However, it is evident that recycling performance is not only based on quantitative, but also on qualitative recycling aspects, such as the achieved material purity of specific target material(s). The recycling output can show a low to high level of material purity. This qualitative aspect depends on factors such as the recycling technology applied or the homogeneity of the waste input. These different recycling aspects require a dual consideration of the recycling process, namely: the total mass balance of the recycling process with its general inputs and outputs (=quantitative aspect; see the top of Fig. 2) and the mass balance(s) of target material(s) (=qualitative aspect; see the bottom of Fig. 2) that reflects the target material-

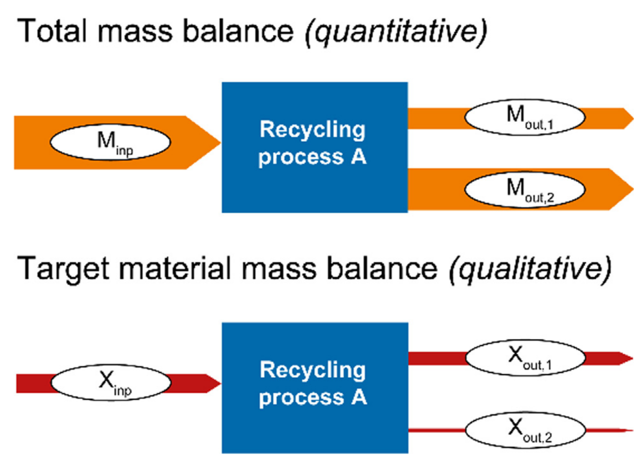

Fig. 2. Quantitative (top figure) and qualitative (bottom figure) consideration of a recycling process. Recycling process A transforms the input mass flow (left side) into two output mass flows (right side).

specific recycling performance. While the structure of the total mass balance corresponds to the existing determination and assessment method of recycling processes (cf. EU's recycling rate method), the mass balance(s) of target material(s) exclusively displays the mass flows of the pure target material in the corresponding recycling process. The data requirements of this dual approach are comparable with the current recycling rate method of the EU (=mass flows), with the sole difference that data for the content of target material(s) in the output mass flows ($M_{out,i}$) is not yet reported.

The total mass balance consists of an input mass flow (M_{inp}) that represents the collected waste mass and different output mass flows ($M_{out,i}$; i = index for output flows). One of these output mass flows represents the mass of recycled materials (with more or less pure target material), while the other output mass flow accounts for the discarded materials (including e.g. different materials, contaminated target material, or target material losses during the process). If there is more than one target material, other output mass flows ($M_{out,i}$) must be introduced in the total mass balance, but this does not affect the subsequent general derivation. The mass balance of the target material is established by applying the concentrations of the target material ($c_{out,i}$) to the output mass flows ($M_{out,i}$) of the total mass balance (see Eq. (1)). Thus, X_{inp} represents the total input mass flow of target material ($X_{inp} = \sum X_{out,i}$), while the output mass flows ($X_{out,i}$) are constituted of one mass flow that represents the recycled target material and one that represents the target material losses.

$$X_{out,i} = M_{out,i} * c_{out,i} \tag{1}$$

Next, the functional unit is defined by the turnover of the target material to enable comparisons between different processes. Otherwise, the impact of different high input mass flows of target material (X_{inp}) would be neglected. Therefore, the output mass flows ($M_{out,i}$) of the total mass balance have to be divided by the input mass flow of the target material (see Eq. (2)), resulting in specific mass fractions, $m_{out,i}$ (e.g. kg plastic per kg PET input) (cf. (Rechberger and Graedel, 2002)). The variables $c_{out,i}$ and $m_{out,i}$ of Eqs. (1)–(2) serve as the main inputs of the statistical entropy (H_{out}) calculation (see Eq. (3)[1]; cf. derivation in (Rechberger and Graedel, 2002)). H_{out} is zero if all target material is separated in a pure fraction (=best recycling performance, quantitatively and qualitatively). In comparison, H_{out} = H_{max} if the target material (X_{inp}) is evenly distributed among the outputs of the recycling process ($c_{out,i}$ = c = $X_{inp}/\Sigma M_{out,i}$) (cf. Eqs. (4)–(5)[1]), and hence the recycling process did not affect the target material concentration at all (=worst case).

$$m_{out,i} = \frac{M_{out,i}}{X_{inp}} \tag{2}$$

$$H_{out}(c_{out,i}, m_{out,i}) = -\sum_{i=1}^{k} m_{out,i} * c_{out,i} * ld(c_{out,i}) \tag{3}$$

However, to allow meaningful comparisons between different recycling processes or systems (e.g. due to different target material mass inputs), the relative statistical entropy ($H_{out,rel}$) is used. Therefore, H_{out} is related to the maximum statistical entropy (H_{max}) (see Eq. (6)). As mentioned before, H_{max} applies if the target material input (X_{inp}) is evenly distributed in the total mass flow (M_{inp}) (see Eqs. (5)–(6)). The result for $H_{out,rel}$ is a dimensionless value between 0 and 1. The higher the result of $H_{out,rel}$ is, the worse the recycling performance is.

$$m_{inp} = \frac{M_{inp}}{X_{inp}} \tag{4}$$

$$H_{max} = ld(m_{inp}) \tag{5}$$

$$H_{out,rel} = \frac{H_{out}}{H_{max}} \tag{6}$$

The final result of the statistical entropy calculation is expressed as the "Recycling Effectiveness" (RE). Since "1" (=100%) is generally linked with a good recycling performance and "0" with poor, Eq. (7) is applied.

$$RE = (1 - H_{out,rel}) \tag{7}$$

In conclusion, the RE describes how effective the observed recycling process could separate and concentrate its recycling input - in a quantitative and qualitative way. Recycling efforts aim at generating a maximum RE.

3. Case Study: Plastic packaging recycling

To demonstrate the use of the statistical entropy approach, the following case study deals with the assessment of the performance of two different recycling processes. The case study is reduced to the absolute minimum level of complexity required in order to illustrate its applicability and to show the main benefits of the statistical entropy metric in comparison to the conventional recycling assessment method (=recycled waste output divided by the total waste input). The term *Recycling process* can be interpreted as a standard recycling service conducted by a recycling operator that includes all relevant pre-recycling steps, like e.g. sorting, shredding and/or washing. The assumed recycling processes will focus on plastic packaging waste recycling; polyethylene terephthalate (PET) is considered as target material. Three recycling cases will be simulated for each recycling process to reveal the sensitivity of the statistical entropy approach in incorporating qualitative recycling aspects. The recycling processes are described by their total and target material (=PET) mass balance (cf. top sections of Fig. 3, Fig. 4, Fig. 5 and Fig. 6) in order to display the quantitative and qualitative recycling perspectives. To ensure a meaningful application of the new approach, the concentration of recycled target material ($c_{out,1}$) should be higher than the concentration of target material losses ($c_{out,2}$) because otherwise target materials would get concentrated in the wrong process output. Furthermore, the Best-case and Worst-case recycling scenario will be covered to show the maximum and minimum statistical entropy generation. The capacities of the recycling processes assumed are fictitious and just for demonstration purposes.

3.1. Case 1

From a purely quantitative perspective (see Total mass balance in top section of Fig. 3), it is obvious that both recycling processes achieve the same conventional recycling rate (RR), namely 70% (=70/100) (see bottom left at the bottom section of Fig. 3). However, if the mass balances of PET (see PET mass balance in the top section of Fig. 3) are considered, it is clear that Recycling process 2 (RP2) reaches a higher recovery of PET, namely 58 t/d of PET (a difference of 4 t/d to Recycling process 1 (RP1)). To express this in terms of statistical entropy, Eqs. (1)–(6) have to be applied to each of the recycling processes. The results at the bottom of Fig. 3 show that RP2 (RE_{RP2} = 0.47) achieves a higher recycling performance than RP1 (RE_{RP1} = 0.23), which is directly deducible from the higher concentrating power of RP2 ($c_{out,1,RP2}$ = 0.83 > $c_{out,1,RP1}$ = 0.77 and $c_{out,2,RP2}$ = 0.07 < $c_{out,2,RP1}$ = 0.20). All in all, the RE results show that the initial quantitative assumption on the processes' recycling performance has to be reconsidered because of the significant differences in the effective concentrating of PET, which correspond to relevant differences in the purity of recycled plastics.

3.2. Case 2

In Case 2, the recycling processes investigated show different total mass balances (see top section of Fig. 4) and therefore achieve different RR, namely, 70% for RP1 (=70/100) and 80% for RP2 (=80/100). From a purely quantitative perspective, RP2 is preferable. Nevertheless, when considering the mass balances of PET, and hence the statistical entropy of both recycling processes, RP1 and RP2 achieve the same RE result (RE_{RP1} = RE_{RP2} = 0.23). This divergent outcome is due to the less effective concentrating of PET in RP2 ($c_{out,1,RP2}$ = 0.72; see bottom section of Fig. 4). RP1 shows a more effective concentrating of PET ($c_{out,1,RP1}$ = 0.77). However, the recycled PET output is smaller than in RP2. In comparison to Case 1, the results of Case 2 demonstrate that a rise in the amount of recycled plastics need not necessarily entail a more effective recycling performance. Therefore, the purely quantitative conclusion has to be refined, as in Case 1, because of the addition of qualitative recycling aspects.

This case covers a potential recycling development where higher RR are achieved by producing more recycling output of lower quality, which would be indicated by higher RR but lower RE results.

[1] ld is the logarithm to the base 2; ld(0) = 0.

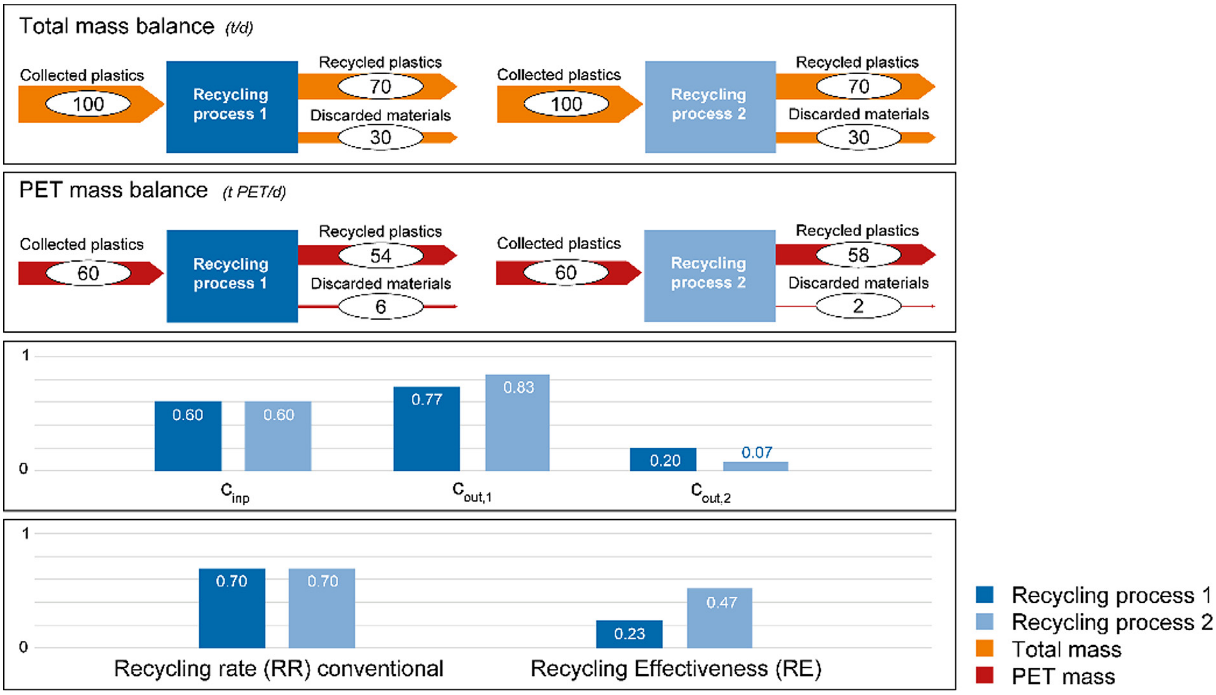

Fig. 3. Case 1) Total and PET mass balances and PET concentrations of two different recycling processes that achieve equally high Recycling rates (RR), but a different Recycling Effectiveness (RE).

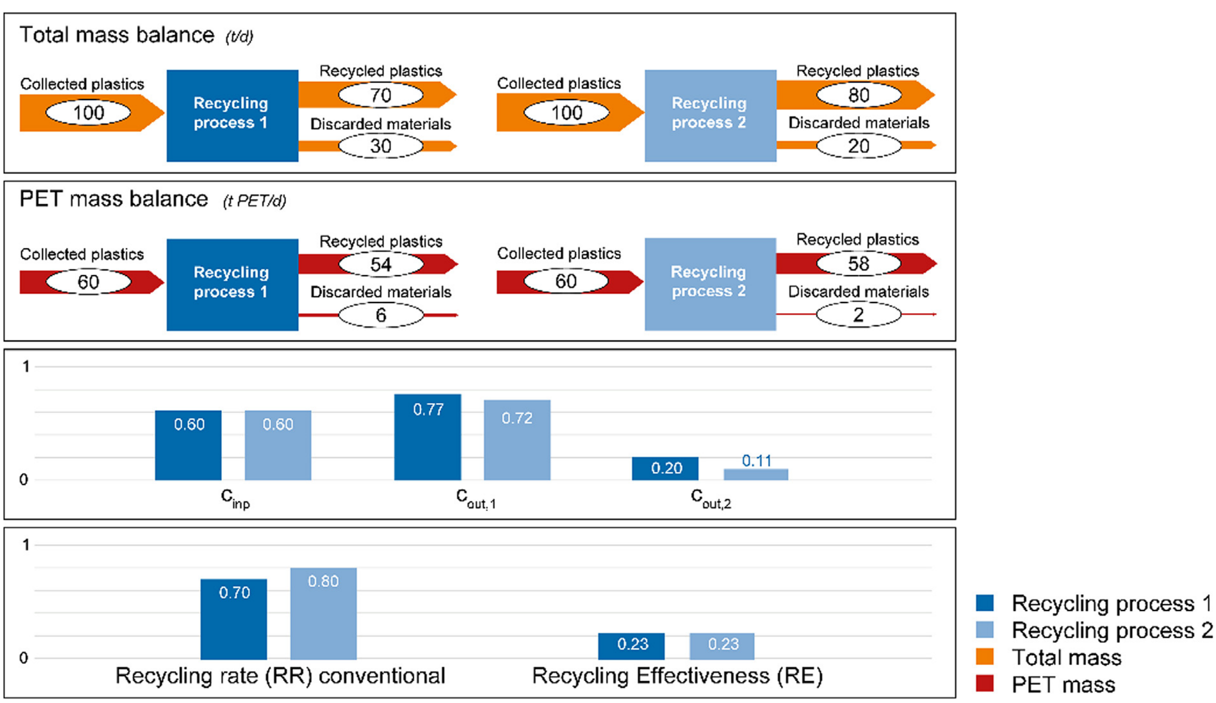

Fig. 4. Case 2) Total and PET mass balances and PET concentrations of two different recycling processes that achieve different RR, but an equally high RE.

3.3. Case 3

Case 3 constitutes a recycling scenario in which the PET input mass flow (X_{inp}) of the recycling processes differ, namely 50 t/d of PET in RP1 and 60 t/d of PET in RP2 (see Fig. 5). However, the output masses of recycled plastics and PET are equally high for both recycling processes (=70 t/d and 46 t PET/d). Obviously, both recycling processes achieve a RR of 70%. However, the difference in the input mass of PET has significant effects on the statistical entropy approach. Although both recycling processes achieve an equally high PET concentration in the output of "Recycled plastics" ($c_{out,1,RP1}$ = $c_{out,1,RP2}$ = 0.66), the considerably higher PET concentration in the "Discarded materials" output of RP2 (compared to RP1) has a significant impact on the final RE result of RP2. Consequently, RP2 (RE_{RP2} = 0.02) achieves a lower RE than RP1 (RE_{RP1} = 0.21).

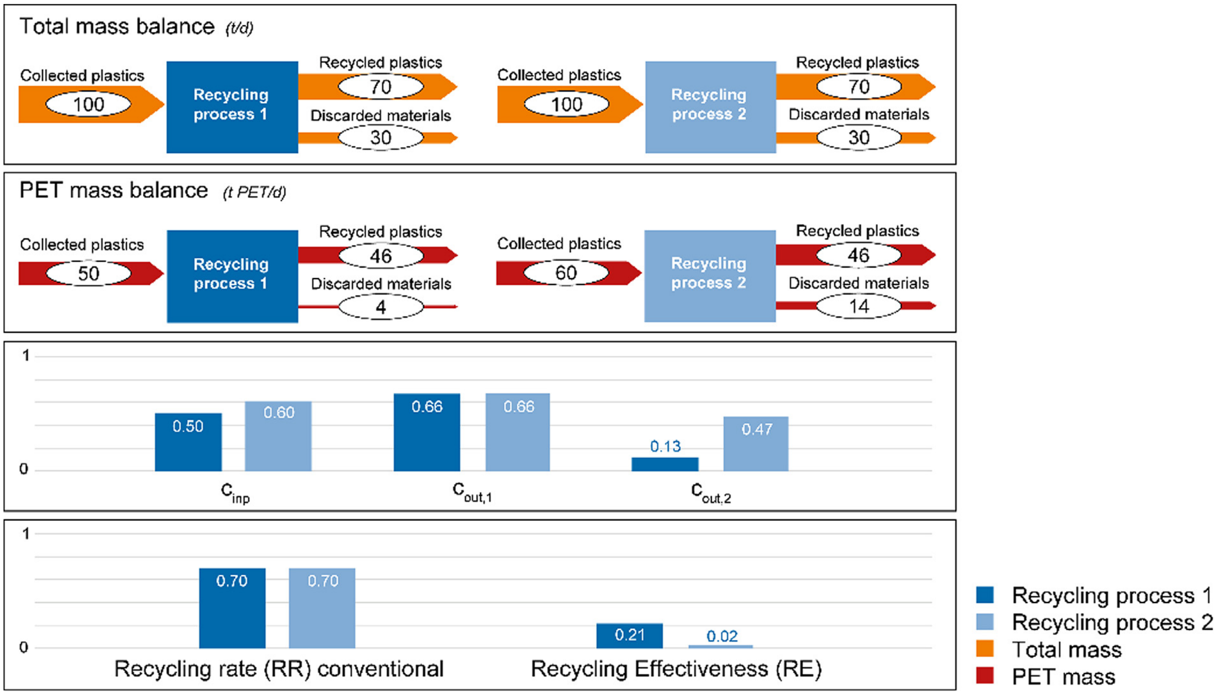

Fig. 5. Case 3) Total and PET mass balances and PET concentrations of two different recycling processes that achieve equally high RR, but a different RE.

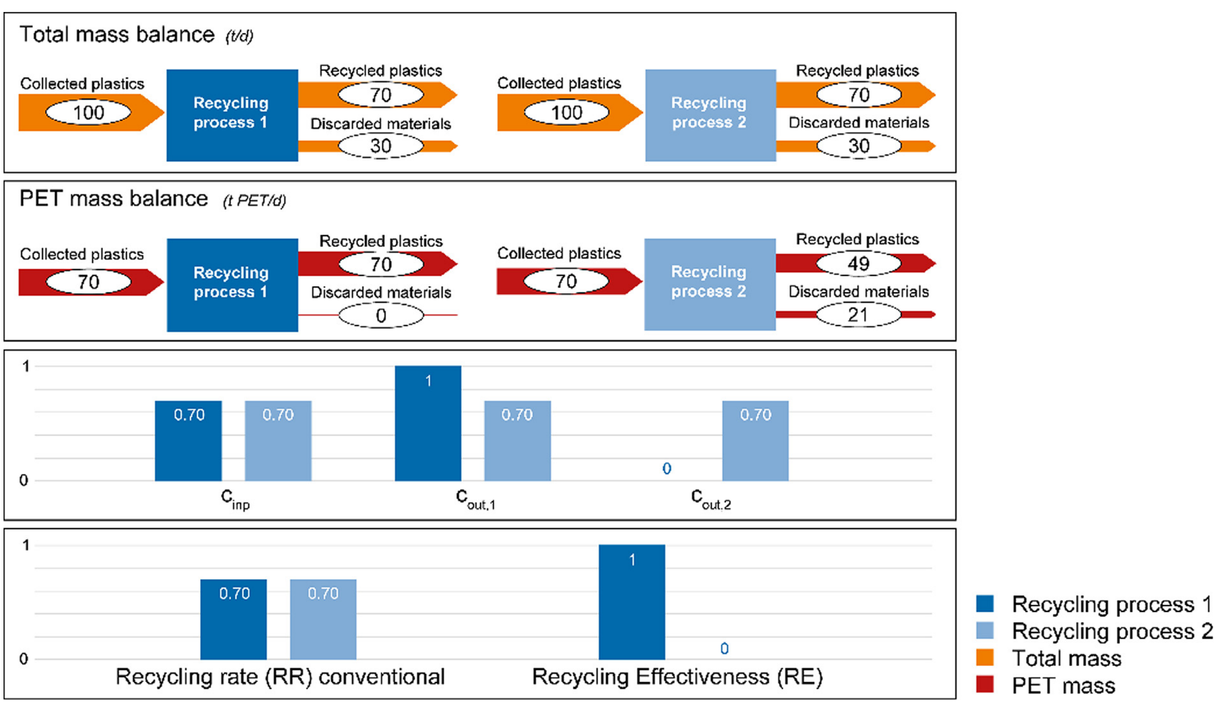

Fig. 6. Best-case, Worst-case) Total and PET mass balances and PET concentrations of two different recycling processes that achieve equally high RR, but a different RE.

3.4. Best-case, Worst-case

The last hypothetical cases demonstrate recycling extremes (Best-case, Worst-case) expressed in statistical entropy that will hardly ever occur in reality, but help to understand the range of real recycling performance. According to statistical entropy, the maximum recycling performance is reached (=Best-case) if the separation of the target material (PET) is at its highest possible point ($c_{out,1}$ = 1 and $c_{out,2}$ = 0). This means that all target material is most effectively concentrated in one pure output mass flow, which is the case for RP1. As a result, the RE of RP1 is maximum (=1; respectively, $H_{out,rel,RP1}$ = 0) (see at the bottom right of Fig. 6). In comparison, the Worst-case outcome results for RP2 because the PET concentrations in the output mass flows are equally high ($c_{out,1,RP2}$ = $c_{out,2,RP2}$ = 0.70; see bottom section of Fig. 6), and hence result in H_{out} = H_{max}. This means that no further separation of PET occurred through RP2. The RE for such a recycling performance is consequently zero. If from that point (equally high

Table 2
Cases 1 to 3, Best-case, Worst-case: Results overview.

	Case 1		Case 2		Case 3		Best-case, Worst-case	
	RP1	RP2	RP1	RP2	RP1	RP2	RP1	RP2
RR	0.70	0.70	0.70	0.80	0.70	0.70	0.70	0.70
RE	0.23	0.47	0.23	0.23	0.21	0.02	1	0
$c_{out,1}$	0.77	0.83	0.77	0.72	0.66	0.66	1	0.70
$c_{out,2}$	0.20	0.07	0.20	0.11	0.13	0.47	0	0.70

$c_{out,i}$), the mass of discarded materials of RP2 would further increase (>21 t/d of PET), the outcome of such a hypothetical scenario could be described as an "inverted recycling process" because more target material is concentrated in the "wrong" output flow.

These cases show (cf. results in Table 2) that the method hitherto applied (=RR) for assessing recycling performance can be significantly misleading if the mass balance of target material is not considered together with the total mass balance, thereby failing to reflect the target material concentrations of the recycling process investigated. In particular, the examination of the target material concentrations ($c_{out,1}$ and $c_{out,2}$) helps to understand the qualitative performance of recycling processes (see Table 2).

4. Conclusions and outlook

The statistical entropy approach presented offers an advanced assessment of recycling processes or systems owing to the fact that quantitative and qualitative recycling aspects are integrated within one single metric, the Recycling Effectiveness (RE) indicator. This implies that the quantity and purity of a specific target material (e.g. PET packaging) are evaluated in addition to the total performance of a recycling process (e.g. total plastic packaging), hence extending the purely quantitatively-based recycling assessment method (cf. EU's recycling rate method). The dual approach enables significant comparisons between different recycling processes and there is good evidence that the RE can be applied to recycling systems of any complexity. The data input of the statistical entropy calculation is based exclusively on mass flows and concentrations, and only considers inputs and outputs of the recycling process investigated. The results of the case studies clearly demonstrate that purely quantitative recycling ambitions should be complemented by qualitative recycling aspects as the effectiveness in concentrating target materials of high purity can vary substantially between different recycling processes.

Taking the European CE objectives and the evaluation of Member State recycling performance into consideration, the statistical entropy approach could serve as a complementary assessment method that evaluates the qualitative recycling performance of Member States. Thus, in a next step, the new assessment approach will be applied on a Member States' level and will thereby offer relevant insights into the divergent strategies of the Member States in attaining the increased recycling targets. Hereby, Member States with a strategic focus on qualitative recycling will score considerably better than Member States that prioritize a predominantly quantitative attainment. In particular, Member States that achieve their recycling rate through significant material dilution (decreasing target material concentration) will perform relatively poorly with the RE indicator. However, it is evident that the values of the RE indicator are usually smaller than the ones calculated with the EU recycling rate method (see Section 3). Therefore, separate RE targets that act complementarily to the existing EU recycling targets should be simultaneously defined. Such RE targets could also be regarded as quality standards if minimum target material concentrations (for specific materials) in the recycling output were to be introduced. Concerning the waste data, statistical entropy assessment only requires additional data for the target material mass balances. It is worth noting that with the new rules concerning the EU recycling rate calculation (European Commission, 2019; European Parliament and European Council, 2018b), more sophisticated reporting of the different material mass flows is required in any case (e.g. for composite packaging materials). Apart from that, the capacity of the recycling industry to measure target material concentrations principally exists because, to maintain high and consistent product standards, most recycling industries have already established their own laboratories or commissioned external services, respectively.

Further, recycling operators could use the statistical entropy approach as a planning and evaluation tool for quantitative process changes in order to verify whether such changes are accompanied by improved quality of the recycled materials. Voluntary recycling quality commitments could be checked by using the RE indicator.

The statistical entropy approach could be further extended to trace the occurrence and concentration of hazardous substances during recycling processes. This would be in line with the European CE strategy to exclude hazardous or critical substances from the recycling chain. Therefore, a possible monitoring application for such substances could be linked to the statistical entropy approach presented. These research topics highlight the great potential of statistical entropy and the wide range of future applications.

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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Product design and recyclability: How statistical entropy can form a bridge between these concepts - A case study of a smartphone

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A B S T R A C T

The concept of Circular Economy has made a crucial contribution to establishing a changed perspective on recycling, one in which recycling is no longer regarded as merely a part of waste management, but rather intimately linked with preceding stages of production, such as product design and manufacturing. It has been shown that recycling achievements significantly depend on the inputs into recycling processes where complex products require higher recycling efforts. To promote transparency with regard to both product design and its impacts on recycling, the assessment of product recyclability is highly relevant. Current recyclability assessment methods neglect to assess product recyclability from the design perspective or are based on parameters that limit comparability between different products. Thus, there is a gap in assessment methods for product recyclability based on design decisions. We developed a recyclability assessment method for products that incorporates fundamental product information on material composition and product structure in a simple and concise way. The assessment approach is based on statistical entropy, which is a well-established metric for the evaluation of material distributions. To demonstrate the applicability of the Relative product-inherent recyclability (RPR) assessment developed, a case study is presented in which a modelled smartphone is investigated. The results show that statistical entropy is a valid measure to assess the recyclability of products at the stage of design and thus helps to identify weaknesses in product design. The new metric is intended to address product designers and manufacturers to enable improvements in product design and comparisons between different products. Overall, it should promote the strategies of the European Circular Economy Action Plan regarding product design and recycling.

1. Introduction

The concept of Circular Economy (CE) implies maintaining the functionality and prolonging the lifetime of materials and products to the greatest possible extent. Therefore, products and materials need to be processed in a way that facilitates reparability and recirculation. The European Union's (EU) implementation of the CE concept had its starting point in the recycling sector (e.g. higher recycling targets). However, it was soon realised that the recycling inputs greatly impact the success and performance of recycling processes. Thus, the latest strategies of the EU focus mainly on upstream stages. It is obvious that decisions on product design and manufacture affect the performance of downstream recycling processes (van Schaik and Reuter, 2010). For example, design trends, like miniaturisation, can significantly impact recycling efforts, as can decisions on materials with regard to recycling strategies, especially in the case of precious metals (Boks et al., 2000; Fontana et al., 2019; Reck and Graedel, 2012; Reuter, 2011). Thus, an exchange of product information (product structure, bill of material, etc.) between manufacturer and recycler could greatly improve the recycling of products and materials, respectively. CE could be further established as a cross-linked network that promotes the exchange of relevant product information.

Following adaptations to the CE Action Plan in 2020 (European Union, 2020), the EU paved the way for more sustainable and transparent product design. Among others, the Ecodesign Directive (European Parliament and European Council, 2012; 2008) will be developed further, as well as the guidelines for the EU Ecolabel (European Union, 2020). The latter will be enhanced by the inclusion of information on the durability and recyclability of products. Different methods for the assessment of these features will be tested. Furthermore, the EU set a target for 2021 to find indicators that assess the use of resources, including footprints for consumption and materials (European Union,

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2020). These strategies should facilitate the transition to a new generation of products with increased recyclability. However, to effectively evaluate these transitions, product-related assessment of recyclability is required.

There are several studies that focus on the assessment of the recyclability and/or circularity of products, where circularity assessments are more systemic and include other processes along the life cycle, such as the primary production or use phases. The intention of such assessments is generally to measure the transition from a linear to a circular state (Ellen MacArthur Foundation, 2015). However, the assessment criteria and approaches selected vary significantly. Several assessment methods are based on (or include) economic data. Linder and colleagues, e.g., established a circularity metric that is solely based on economic values (Linder et al., 2017). Although the approach allows an easy understanding of the results, the consideration of prices might reduce the consistency and validity of the results since prices can fluctuate significantly. A considerable number of assessment methods focus on environmental impacts during recycling (mainly following Life Cycle Assessment principles). For example, Huisman and colleagues worked in several studies (Boks et al., 2000; Huisman et al., 2000, 2001, 2004) on the development of an environmentally weighted recyclability assessment approach for products by incorporating environmental impacts. But, like in Linder et al., their approach might result in the exclusive recycling of the major materials of a product. In a combined approach, Mesa and colleagues assessed the durability (e.g. flammability resistance, fatigue strength) and environmental footprint of materials (Mesa et al., 2020). Their so-called “material durability indicator” (MDI) should help to improve the design and extend the lifespan of products. Certainly, the combination of these product parameters creates a better understanding of product impacts, but it does not specifically address the recyclability. Other assessment approaches that combine environmental impacts with other product characteristics (e.g. material diversity or exergy) to evaluate recyclability have been adopted by Reuter et al. (2018) and Leal et al. (2020) (Leal et al., 2020; Reuter et al., 2018). In 2015, the Ellen MacArthur Foundation presented a comprehensive assessment approach that allows the circularity of material flows of products or even companies to be measured (Ellen MacArthur Foundation, 2015). The proposed “material circularity indicator” (MCI) acts as a decision-making tool for the product designer. The implementation of the indicator can be labour and time intensive as various data (specific raw material use, product use time, etc.) need to be collected and verified first, which could be seen as too complicated. Another interesting assessment approach was presented by Vanegas and colleagues, which is based on disassembly time (Vanegas et al., 2017). The disassembly time depends on product structure and complexity. Possible effects on product lifetime (reuse, repair) and recycling effort can be derived from the ease of disassembly. Especially for reuse strategies, this information could be of great advantage. However, the disassembly time alone does not express how far a product can be disassembled into individual product parts and materials in the end.

Material masses and their spatial distribution in a product is a fundamental piece of product design information that allows an unbiased observation of product recyclability. In this context, the spatial occurrence of materials is particularly relevant as it makes a difference whether materials are dispersed in product parts that can be disassembled or not. For this reason, a metric that has gained importance in the assessment of recycling is statistical entropy (Navare et al., 2021; Nimmegeers et al., 2021; Nimmegeers and Billen, 2021; Parchomenko et al., 2020, 2021; Roithner and Rechberger, 2020; Velazquez Martinez et al., 2021; Velázquez Martínez et al., 2019; Zeng and Li, 2016). Statistical entropy is used to express the complexity of a product through evaluation of its material composition. The more materials there are in a product and the more equal their concentrations are, the higher the statistical entropy and the more complicated recycling is. For example, Dahmus and Gutowski developed an early approach that connects the statistical entropy result of products with the costs of separation (Dahmus and Gutowski, 2007), though their approach does not consider the (spatial) occurrence of materials in specific product parts.

This excerpt of developed assessment methods illustrates the great difficulty in finding an appropriate recyclability metric that simply but comprehensibly describes the recyclability of products based on product-inherent material characteristics. Most assessment methods tend to link product design with recycling aspects (e.g. sorting costs or labour time), or add information that might be relevant only in specific cases (e.g. environmental impacts or physical material characteristics). Thus, it seems appropriate to develop a metric that evaluates product recyclability solely at the stage of design in order to obtain clear and comparable results.

The aim of this study is to develop a recyclability metric based on statistical entropy that describes a product with respect to the material composition of its dismountable parts, thus incorporating fundamental and inherent product design decisions. The metric should be designed in such a way that easy application by various stakeholders is ensured and profound information for product comparisons is provided. A case study on smartphones is conducted to demonstrate the ease of applying the method developed, even though smartphones are highly complex (concerning material composition) and challenging to describe.

2. Material and methods

2.1. Data collection and smartphone modelling

For the following case study, relevant information on the material composition of smartphones was collected from the literature (Bookhagen et al., 2018, 2020; Fontana et al., 2019; Holgersson et al., 2018; Liu et al., 2019; Palmieri et al., 2014; Singh et al., 2018; Smodiš et al., 2018; Tan et al., 2017; Tarantili et al., 2010; Ueberschaar et al., 2017) and online search engines. The literature showed significant differences in the material composition and structure of smartphones, especially depending on the year of smartphone release. For example, in some studies smartphones were composed of six coarse product parts and in others up to a hundred. With the collected data, a hypothetical smartphone, hereinafter referred to as ‘Smartphone’, was modelled that is comparable with smartphones put on the market around 2012. Prior to the Smartphone modelling, different levels of the smartphone structure were defined: product level, component level and sub-component level. Thus, an entire smartphone is represented at the “product level”, whereas the “component level” refers to the different structural product parts of a smartphone that can be regarded as stand-alone (e.g. a battery) (cf. second column in Fig. 1). The distinction might follow functional, technical or other design aspects. For components that consist of sub-parts (e.g. magnets of a vibration motor), the “sub-component level” was defined (cf. third column in Fig. 1). Depending on the complexity of the product observed, further sub-levels might be necessary and are in principle feasible. In contrast, if product parts are connected in a way that makes disassembly practically impossible (due to connecting parts), they are regarded as one product part. Connecting parts require specific consideration as they can appear in products in very different forms and functions. For example, screws are often used to connect specific product parts and can thus be regarded as individual parts that can be disassembled. However, connecting parts like solder might require closer examination. Solder can appear, like screws, as an individual product part (possible to disassemble) or as part of a product part (impossible to disassemble), e.g. if we think of electrical parts.

The finally modelled Smartphone is shown in Fig. 1 and consists of 11 components and 32 sub-components. The sub-component “Others” summarizes electronics and wires. The material composition of the Smartphone is displayed in Table 1 according to the different components. In total, the Smartphone consists of 49 materials. The term “material” includes chemical elements (e.g. copper), chemical compounds (e.g. pure PVC), materials (e.g. plastics with additives) and material groups (e.g. collection of different glass types). Note that the

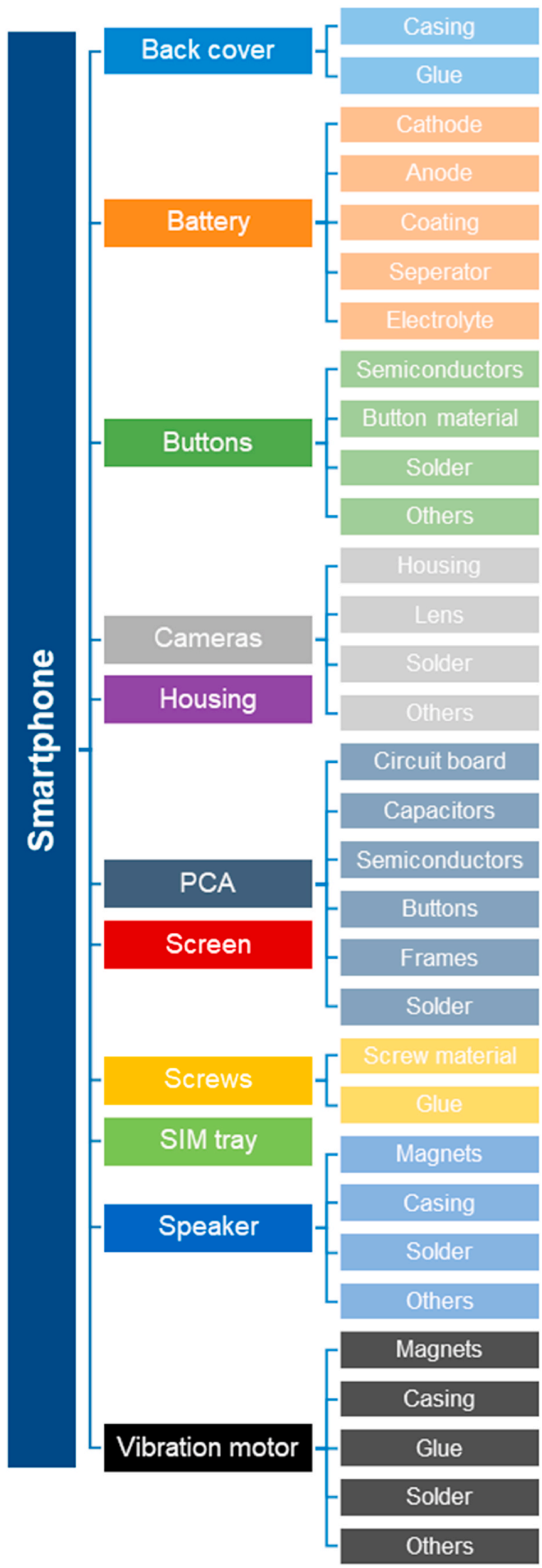

Fig. 1. Structure of Smartphone: Product level, component level and subcomponent level (from left to right) (PCA … Printed circuit assembly).

specific chemical composition of the materials and material groups, which are listed in Table 1, is not considered. The material group "Others" includes materials like liquids, adhesives and epoxy, and "Glass" acts as collective term for all kinds of glasses. The material group "REE" refers to the group of rare earth elements. Both, the structure of the Smartphone and the list of materials, make no claim to be complete. As shown in Table 1, the sum of all material masses equals the total mass of the Smartphone, thus complying with the law of mass conservation.

2.2. *Assessment of product recyclability with statistical entropy*

2.2.1. *Concept of statistical entropy*

Statistical entropy has its origin in thermodynamics but has constantly evolved from its roots in the principles of entropy. A general interpretation of statistical entropy is that it measures the degree of order or disorder, respectively. The higher the degree of disorder/order, the higher/lower is the entropy. Commonly, the aim is to keep the entropy low. For example, a public dustbin with mixed waste represents a state of higher entropy compared to a set of bins with the same waste carefully separated into glass, paper, metals, biomass, plastics and others. Back in the 1940's, Claude Shannon developed the concept of statistical entropy (H) to measure information transfer and its uncertainty (Shannon, 1948). He formulated Equation (1) where p_i is the probability of occurrence of events and ld is the logarithm to the base 2 ($\mathrm{ld}(0) = 0$). The more events there are and the more uniformly distributed their chance of realization is, the higher the statistical entropy is.

$$H = -\sum p_i \mathrm{ld}(p_i) \tag{1}$$

Rechberger and Brunner interpreted the concentration of a substance in a product as a probability and applied statistical entropy to the material balances of processes (Rechberger, 1999; Rechberger and Brunner, 2002). In the latest statistical entropy applications (Laner et al., 2017; Parchomenko et al., 2020; Rechberger, 2012; Rechberger and Graedel, 2002; Sobańtka et al., 2012, 2014; Velázquez Martínez et al., 2019; Zeng and Li, 2016), the focus was on the assessment of material flow systems. The aim was to measure the concentrating or diluting effect of a process/system usually on a single substance/material. Here, we extend statistical entropy to products consisting of a multitude of substances and materials.

2.2.2. *Application of statistical entropy to products*

Products generally consist of different materials that are distributed throughout the product, e.g. in different components. Hence, the distribution and concentration of these materials can vary significantly. It often occurs that specific materials are used only in small amounts (Ciacci et al., 2015; Reck and Graedel, 2012) widely dispersed within the product (e.g. rare earth elements in electronic parts of smartphones). It is recognized that state-of-the-art products are becoming more complex than those of previous generations, e.g. if we think of a printed circuit board of a mobile phone of the 2000s compared to one of a smartphone put on the market in 2014 (cf. Singh et al., 2018). In the end, the inherent design decisions reflected in these products affect the recyclability of products. If the material complexity of products increases, recycling gets more complex or even impractical. The distribution of materials in products can be evaluated with statistical entropy. Similar to Rechberger and Brunner (2002), Equation (1) of Claude Shannon is slightly modified by replacing the term p_i with the concentration of material i (c_i) (i = index for materials; i = 1, …, N_m) in the product (p) investigated. The concentration c_i is the ratio of the mass of material i (M_i) to the total product mass (M_p). In this modification, the concentrations of all N_m materials of the product are investigated. The more materials occur and the more equal the individual concentrations are, the higher the statistical entropy (H_p) is.

If, theoretically, a product consists of one material only, the statistical entropy would be zero, thus representing the best case for

Table 1
Mass (g) of materials and number of materials in the different components of Smartphone.

Material	Back cover	Battery	Buttons	Cameras	Housing	PCA	Screen	Screws	SIM tray	Speaker	Vibration motor	Total
No. of materials (N_m)	2	10	16	17	1	42	3	2	1	13	15	49
ABS				2.00							0.40	2.40
PC	12.74				20.00	0.27				0.30		33.31
PE		2.60										2.60
PP		0.52										0.52
PVC			<0.01								<0.01	0.02
Ag				<0.01		0.03						0.03
Al		2.08	0.12	<0.01		0.14				<0.01	<0.01	2.35
As						<0.01						<0.01
Au			<0.01	<0.01		0.01					<0.01	0.03
B										<0.01	<0.01	0.01
Ba						0.08						0.08
Be						<0.01						<0.01
Bi						<0.01						<0.01
C (Graphite)		6.24										6.24
Ca				<0.01		0.04						0.05
Cd						<0.01						<0.01
Co		0.46	0.01	0.01		<0.01				0.01	0.01	0.51
Cr				0.02		<0.01						0.02
Cu		1.56	0.26	0.93		1.99				0.23	0.26	5.22
Fe			0.03	0.27		1.48		1.96	2.00	0.54	0.44	6.72
Ga			0.02			<0.01						0.02
Ge						<0.01						<0.01
Hf						<0.01						<0.01
In						<0.01	23.04					23.04
Li		0.57				<0.01						0.57
Mg						<0.01						<0.01
Mn		0.46	<0.01	<0.01		0.03				<0.01	<0.01	0.51
Mo						<0.01						<0.01
Na						<0.01						<0.01
Nb						<0.01				<0.01	<0.01	0.01
Ni		3.70	0.06	0.10		0.19				0.03	0.02	4.10
Pa			0.02									0.02
Pb				<0.01		<0.01						<0.01
Pd						0.06						0.06
Pt						<0.01						<0.01
Rb						<0.01						<0.01
Sb						<0.01						<0.01
Si			0.72			0.33						1.05
Sn			0.23	0.57		0.66	2.56			0.10	0.43	4.56
Sr						<0.01						<0.01
Ta						0.38						0.38
Ti				<0.01		0.64						0.64
V						<0.01						<0.01
W						<0.01						<0.01
Zn			0.02	0.08		0.02				0.02	0.02	0.16
Zr						<0.01						<0.01
REE			<0.01			<0.01				0.23	0.19	0.42
Others	0.26	7.81	<0.01	<0.01		2.49		0.04		<0.01	0.21	10.82
Glass			0.48	1.00		3.28	6.40					11.16
Total	13.00	26.00	2.00	5.00	20.00	12.15	32.00	2.00	2.00	1.50	2.00	117.65

recycling. In contrast, the maximum statistical entropy occurs if the concentrations of all materials are the same (they are uniformly distributed) in the product. The latter is assumed to be the worst situation with respect to the product's inherent recyclability.

2.2.3. Implementation of information on the product structure

Concerning the complexity of product structures, the consideration of material concentrations at the product level alone seems inappropriate because relevant information on the (spatial) occurrence of materials in sub-parts is neglected. For example, the copper concentration at the product level might be based on the occurrence of a pure copper coil in a specific product part. Since a pure and stand-alone copper coil can be easily separated and recycled, it would positively affect the recyclability of the total product. Thus, information on the occurrence of materials at the different levels has to be included to improve the estimation of product recyclability. In Fig. 2, the copper concentration (%) in the product parts at the different levels is shown (top: product level; middle: component level; bottom: sub-component). While the copper concentration at the product level is expressed by only one average concentration value (4%), there are 6 and 13 different concentration values at the component and sub-component level, respectively. It shows that in specific product parts copper can be found partly in high concentrations while others do not even contain copper. There is a significant difference in the material concentrations at the different levels, where the most detailed information can be obtained from the "lowest" level (in this case the level of sub-components). It is therefore recommended to trace the product parts to the lowest possible level of disassembly. A statistical entropy approach that tries to combine the material composition of components with the number of components in a product was recently published by Parchomenko et al. and further extended to a multiproduct level by Nimmegeers et al. (Parchomenko et al., 2020; Nimmegeers et al., 2021b). However, we think that their combination of component composition and numbers is to some extent artificial and could be avoided by computing the material-based SE of the product based on the maximum disassembly depth.

In Fig. 3, three theoretical products (P1–P3) are displayed in the form

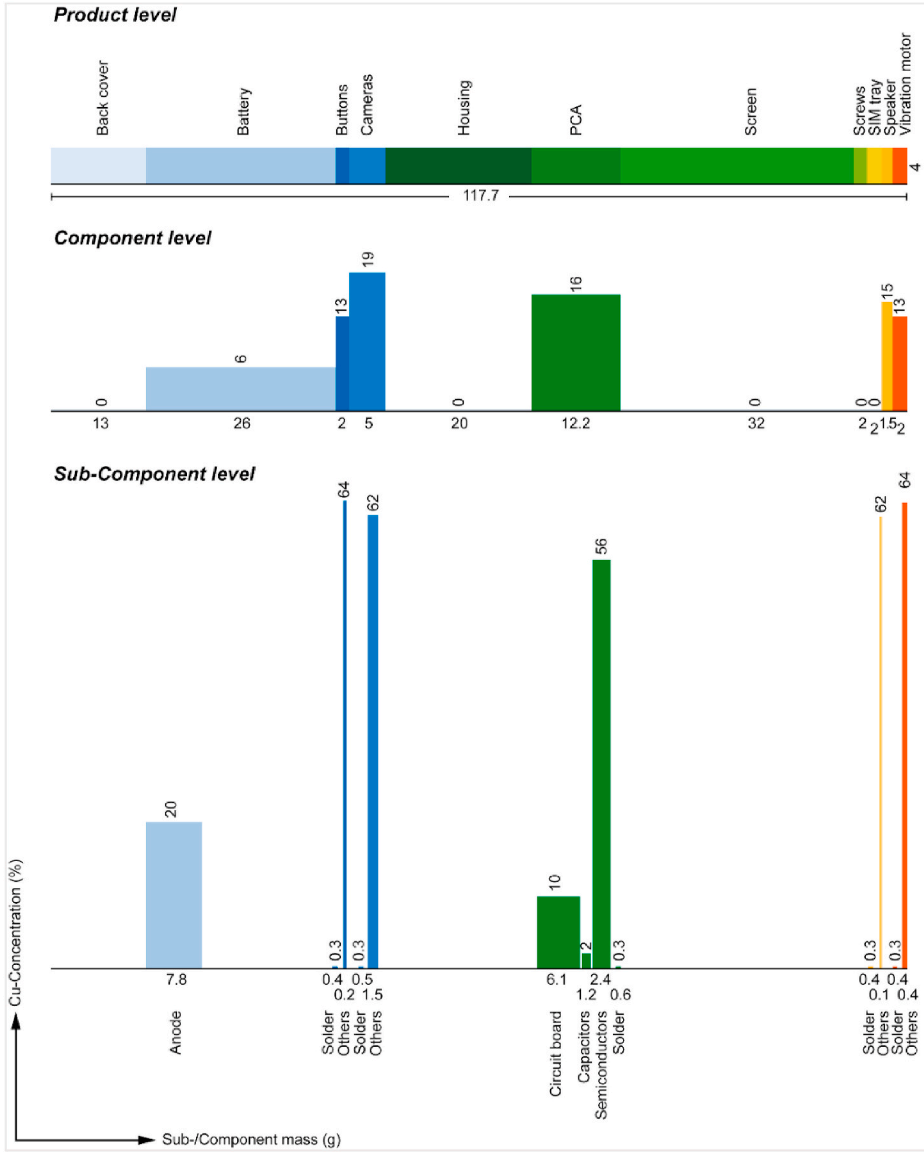

Fig. 2. Product structure information of Smartphone: Copper distribution according to the different product levels (X-axis: Mass of sub-/component (g); Y-axis: Copper concentration (%)). The total mass of the Smartphone is 117.7g.

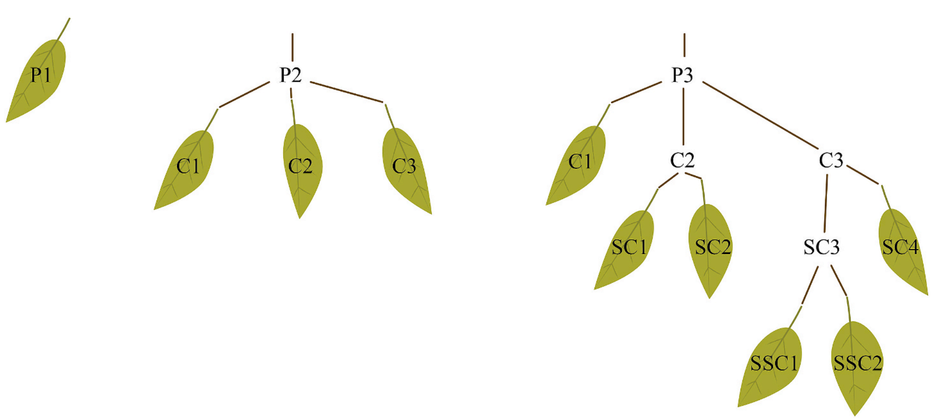

Fig. 3. Product displayed in tree structure: Three theoretical products (P1–P3) and their product parts (C … components; SC … sub-components; SSC … sub-sub-components) are shown.

of a tree structure, where leaves mark the calculation-relevant product parts and levels respectively. The disassembly of the three products varies significantly. Product 1 (P1) cannot be disassembled, thus calculation would be based on the material masses of the total product (P1). In contrast, product 2 (P2) consists of three product parts (C1–C3) that can be individually disassembled, hence the material distributions of these components are considered for the statistical entropy calculation. Product 3 (P3) shows the most complex product structure. It consists of several product parts and levels, respectively. For example, component 3 (C3) can be disassembled into two sub-components (SC3, SC4) where SC3 can be further disassembled into two sub-sub-components (SSC1, SSC2). For P3, the material compositions of C1, SC1, SC2, SSC1, SSC2 and SC4 are taken into account. These product examples show that product structures need to be considered individually (cf. marked leaves). Thus, the following statistical entropy calculation is based on these product structure considerations that aim to reflect product information of highest detail.

As mentioned in Subsection 2.2.2, material concentrations (c_i) are the basis of the statistical entropy calculation. The material concentrations in the different product parts considered ($c_{i,j}$) (j = index for product parts; j = 1, …, N_e) are calculated according to Equation (2), where the mass of material i in product part j ($M_{i,j}$) is divided by the total mass of the observed product part (M_j).

$$c_{i,j} = \frac{M_{i,j}}{M_j} \tag{2}$$

The N_m concentrations are then used to compute the statistical entropy H_j of the product part considered (cf. Equation (3)).

$$H_j = -\sum_{i=1}^{N_m} c_{i,j}\mathrm{ld}(c_{i,j}) \tag{3}$$

The statistical entropy of the complete product (H_p) is computed with the mass weighted average of the N_e statistical entropies (H_j) of the product parts considered (cf. Equation (4)). H_p reflects the statistical entropy of the product that is disassembled into its specific product parts. The lower H_p is, the better the inherent recyclability of the product is. Note that if products cannot be disassembled, they are considered the only product part available. Thus, $N_e = 1$ and $M_j = M_p$.

$$H_p = \sum_{j=1}^{N_e} m_j H_j \tag{4}$$

According to Equation (5), the mass weight m_j is the mass fraction of product part j related to the mass of the product.

$$m_j = \frac{M_j}{M_p} \tag{5}$$

The term m_j times H_j in Equation (4) is the absolute contribution of product part j to the total H_p of the product.

For better comparability, the relative statistical entropy (H_{rel}) is calculated (cf. Equation (7)). H_{rel} relates the H_p of Equation (4) to the maximum statistical entropy (H_{max}) of the product investigated. H_{max} describes the situation where the concentrations of all N_m materials would be equal and no disassembly is possible. The maximum statistical entropy of the product is calculated according to Equation (6). H_{rel} is a dimensionless value between 0 and 1. The higher the value of H_{rel}, the worse the product design inherent recyclability is.

$$H_{max} = \mathrm{ld}(N_m) \tag{6}$$

$$H_{rel} = \frac{H_p}{H_{max}} \tag{7}$$

Finally, the result of H_{rel} is transformed into the *Relative product-inherent recyclability* (RPR) metric by application of Equation (8). This transformation enables an easier interpretation of the statistical entropy result since the best recyclability is usually linked with 100%. Note that RPR = 0 (i.e. $H_p = H_{max}$ or $H_{rel} = 1$) does not mean that the product cannot be recycled; it is only the worst situation from the product design perspective.

$$RPR = 1 - H_{rel} \tag{8}$$

The result of the RPR expresses the inherent recyclability of the product investigated according to its material composition and product structure. The target of product design should be to achieve a high RPR. In the extreme case of a product consisting of one material only ($N_m = 1$, $H_p = 0$), Equations (7) and (8) are not defined because of $H_{max} = \mathrm{ld}(N_m) = 0$ (division by zero problem). However, due to the fact that lim ($N_m \rightarrow 1$) $1-0/\mathrm{ld}(N_m) = 1$ and $H_p = 0$ always represent the best case of product-inherent recyclability, RPR is defined as 1 in this case.

The RPR of the product can also be written as the mass weighted average of the components' RPR (cf. Equation (9)), where the RPRs of the specific components are calculated according to Equation (10).

$$RPR = \sum_{j=1}^{N_e} m_j \, RPR_j \tag{9}$$

$$RPR_j = 1 - \frac{H_j}{H_{max}} \tag{10}$$

The term m_j times RPR_j in Equation (9) is the absolute contribution of component j to the RPR of the product.

3. Case study: smartphone

In the following, the RPR of the Smartphone modelled is calculated according to Equations (2)–(8). Detailed information on the material masses at the different levels is presented in the SI (cf. Tables S–2 to Tables S–13).

The RPR is investigated stepwise by first assuming that the product cannot be disassembled at all (representing the statistical entropy at the product level) and then, step by step, individual components are disassembled from the product in a possible "disassembly order" (see disassembly steps in Fig. 4), assuming the rest remains combined. Thus, the final RPR value of the total Smartphone is reached when the last component is considered, which is, in this case, the PCA (Printed circuit assembly) (cf. Fig. 4). The final results show the possible RPRs of the Smartphone modelled depending on the material distribution and product structure.

3.1. Scenarios

To demonstrate different recyclability situations, two scenarios were considered, namely Scenario 1 and Scenario 2. In Scenario 1, the product structure of the Smartphone is as shown in Fig. 1; the Smartphone consists of 11 components and 32 sub-components. In Scenario 2 the structure of the Smartphone is slightly changed (in comparison to Scenario 1) as it only consists of 6 components. This modification arises from the aggregation of specific components, namely Speaker, Cameras, SIM tray, Vibration motor and Housing. In the following, the aggregated component is called "Component 6". The background for this modelled aggregation is that components are often designed in a way that makes disassembly impossible, thus affecting the material distribution and recyclability, respectively. Hence, this example of aggregated components might stand for various components in modern products that are un-/intentionally designed to impede disassembly. Component 6 does not consist of sub-components, thus the sub-component number is only 19 in Scenario 2. The total material composition of the Smartphone and the other components in Scenario 2 are equal to Scenario 1, but, consequently, the material concentrations of Component 6 are redefined. For both scenarios, the RPR results were calculated with (w/) and without (w/o) consideration of the sub-components to demonstrate the effect of consideration of product structure information, where the latter

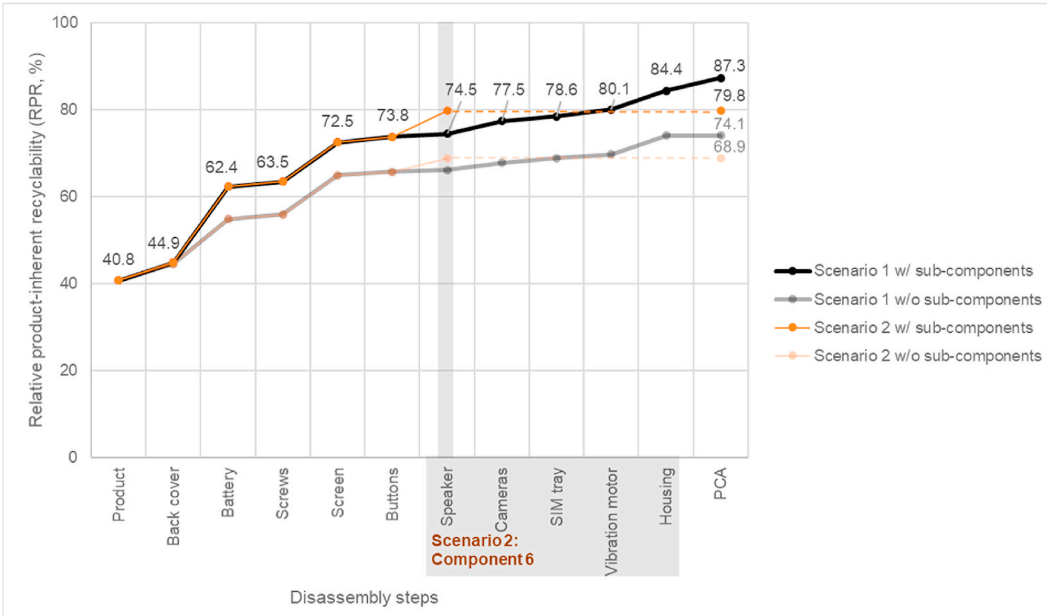

Fig. 4. Scenario 1 and 2: Relative product-inherent recyclability (RPR) of Smartphone as a function of disassembly steps with (w/) and without (w/o) consideration of the sub-components.

can also be interpreted as product design decisions that hinder further disassembly (as mentioned for Component 6).

3.2. Results

Fig. 4 shows the growing RPR due to progressing disassembly of the Smartphone into its individual sub-/components. The hypothetical disassembly order starts with the Back Cover and ends with the PCA. The grey shaded box in Fig. 4 highlights Component 6 of Scenario 2. In addition, the RPR results of each Scenario are also displayed without (w/o) consideration of sub-components (see brighter lines in Fig. 4), thus showing the effects if material concentrations at the component level are considered only. The starting point of all scenarios is a RPR of 40.8%, representing the product's RPR if disassembly is not possible. All scenarios demonstrate that the Smartphone modelled cannot achieve the maximum RPR (= 100%) because it cannot be disassembled into its pure materials. This might be the case for most complex products. However, it is shown that in both scenarios the recyclability increases with progressive disassembly, and thus consideration of more individual sub-/components. The final RPR results of the different scenarios vary significantly (cf. PCA values in Fig. 4). Scenario 1, with consideration of the sub-components, achieves the highest RPR with 87.3%. The counterpart result of Scenario 2 is only 79.8%. Thus, the aggregated consideration of Component 6 shows negative impacts on the recyclability of the Smartphone. Without consideration of the sub-components, the RPR is even less, namely 74.1% for Scenario 1 and 68.9% for Scenario 2, which is a decrease between 10% and 15% compared to the cases with consideration of the sub-components. Further, it should be emphasised that the use of connecting parts that impede disassembly of (sub-) components (e.g. solder) have a negative impact on the RPR

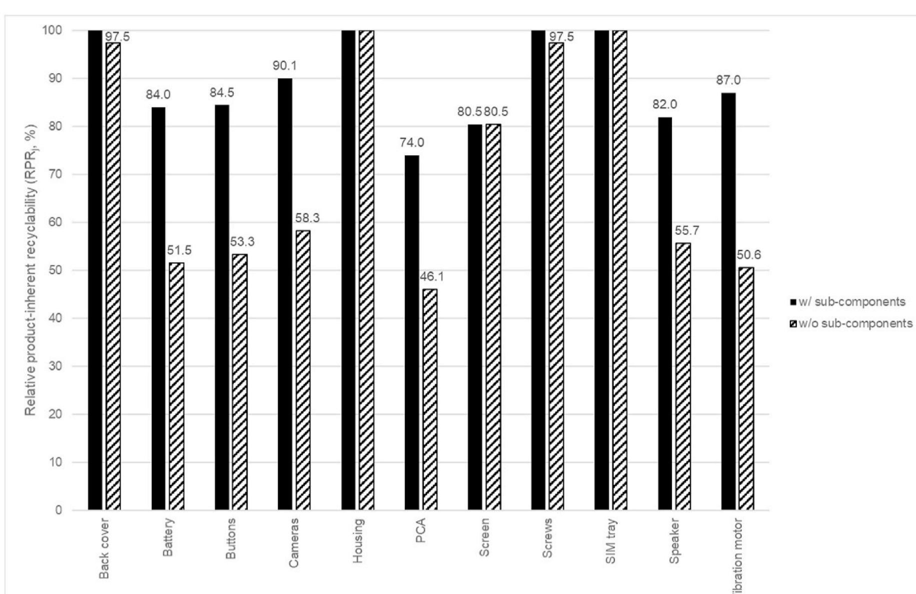

Fig. 5. Scenario 1: RPR_j of the individual Smartphone components with (w/) and without (w/o) consideration of the sub-components.

result, as demonstrated with Component 6 in Scenario 2.

For additional insights into the recyclability of the different Smartphone components, component-specific RPR_js are calculated with Equation (10). The results in Fig. 5 are shown alphabetically and divided into those with or without sub-components. As before, the RPR_j of the single components is higher if the sub-components are considered. Similar to Component 6 of Scenario 2, the component results with/without consideration of the sub-components could be seen as different procedures of design. The components Housing, Screen and SIM tray show the same results with/without consideration of sub-components because they cannot be disassembled into sub-components. The components Back cover, Housing, SIM tray and Screws achieve the maximum RPR_j (100%) with consideration of the sub-components. This is due to the fact that the respective sub-components consist of pure materials (cf. Tables S–4, Tables S–13 and Tables S–9 in the SI). If the sub-components are not considered, the RPR_j of the Back Cover and Screws decrease because of the mixture with glue. Although the Screen consists of only three materials, its RPR_j is lower (80.5%) due to the similar magnitude of the material concentrations involved. The lowest RPR can be observed for the PCA (74.0% and 46.1%, respectively). This result is not surprising as the PCA shows the most complex material composition (cf. Tables S–3 in the SI). Average RPR_js can be observed for the remaining components (82.0%–90.1% and 50.6%–58.3%, respectively). These components show relatively similar results as they all consist of certain sub-components, like magnets, semiconductors and other electronics that partially show a strongly material dilution.

In Table 2, the mass weights of the Smartphone's components, their individual H_j and their individual RPR_j (with and without consideration of the sub-components) in Scenario 1 are listed. Note that the H_j and RPR_j of components with sub-components are computed from the mass weighted average of the respective metrics of its sub-components. The results with sub-components show that the components Screen, Speaker and PCA have an especially high statistical entropy (H_j), while components like the Back cover, Screws, SIM tray and Housing show a minimum H_j (= 0). Further, the mass weights of the individual components vary significantly, thus influencing the impact of the specific H_j and RPR_j on the total H_p and the final RPR, respectively. For example, a relatively high mass weight can be observed for the Back cover, the Battery, the Screen, the Housing or the PCA. Thus, the results for these components show a relatively strong impact on the Smartphone's RPR. The differences between the absolute RPR contributions of the variants with and without sub-components (see last column of Table 2) show the absolute increase in RPR due to the consideration of the sub-components. The top three of these contributions originate from Battery (+7.2%$_{abs}$), PCA (+2.9%$_{abs}$) and Cameras (+1.3%$_{abs}$).

4. Discussion

With the developed statistical entropy approach, relevant information on product design, namely the material composition and product structure, is assessed in a simple and flexible manner, thereby enabling important findings on the inherent recyclability of products. The statistical entropy results are combined in a single metric, namely the *Relative product-inherent recyclability* (RPR). The RPR increases, the more disassembly-friendly the product parts designed with particular materials concentrated in these parts are. The Case Study illustrates the simple application of the new approach with a realistic fictitious smartphone. It is shown that statistical entropy is a suitable metric to express manifold product design decisions and thereby deduce impacts on the inherent recyclability of products. The results of the Case Study demonstrate that the RPR of the smartphone investigated decreases the more the materials are dispersed in product parts and the fewer the levels considered. In particular, the RPR results of the specific components highlight the necessity of intelligent product design as it can offer great material recovery potentials. Thus, for some components significant design improvements could be achieved.

The findings of the RPR metric are highly relevant for product designer and manufacturer as the results of the Case Study show the great impact of fundamental product design decisions on the recyclability of products. The defined RPR could therefore help to detect design weaknesses and recycling potentials. Designer and manufacturer should use the RPR metric as a planning and decision tool to develop products of high RPR. Furthermore, product comparisons between different producers could potentially be based on the new assessment method. Consumers might profit from transparent product comparisons in the form of a RPR product label. Possible comparisons might therefore influence decisions at the end of the supply chain. In the long term, the RPR assessment could contribute to the CE transition by promoting recycling-friendly product design that is based on sustainable resource use.

Conclusions of previous studies underline the results of the RPR assessment. Ciacci and colleagues highlighted more than once the necessity of adjusting product design in a way that reduces loss of materials and thus worse recycling performances (Ciacci et al., 2015, 2016). It is a common position that high dissipation of materials in products is related to complex or worse material recycling (Ciacci et al., 2015; Reck and Graedel, 2012; Reuter, 2011). In this context, Reuter stresses the failure to take advantage of the opportunity to theoretically endlessly recycle metals due to poor product design (Reuter, 2011), further concluding in Reuter et al. (2018) that the recycling of complex products leads to a trade-off between bulk and minor materials.

A similar effect of product disassembly on recyclability can be observed in the Fairphone 2 assessment of Reuter et al. (2018). They also showed that product disassembly improves recyclability. Leal and colleagues, however, claimed in their evaluation of Fairphone 2 that disassembly only shows a minor effect on recyclability (Leal et al., 2020). They attribute higher importance to the variety of materials and material-specific recyclabilities. Interestingly, in both studies the

Table 2
Scenario 1: Mass weight (m_j), H_j and RPR_j of the different components with (w/) and without (w/o) consideration of the sub-components.

		w/sub-components				w/o sub-components				Δ
Component	m_j	H_j	RPR_j (%$_{abs}$)	m_j RPR_j (%$_{abs}$)	m_j RPR_j (%$_{rel}$)	H_j	RPR_j (%$_{abs}$)	m_j RPR_j (%$_{abs}$)	m_j RPR_j (%$_{rel}$)	m_j RPR_j (%$_{abs}$)
Back cover	0.11	0	100	11.0	12.7	0.14	97.5	10.8	14.5	0.3
Battery	0.22	0.90	84.0	18.6	21.2	2.72	51.5	11.4	15.4	7.2
Screws	0.02	0	100	1.7	1.9	0.14	97.5	1.7	2.2	<0.1
Screen	0.27	1.10	80.5	21.9	25.1	1.10	80.5	21.9	29.5	0
Buttons	0.02	0.87	84.5	1.4	1.6	2.62	53.5	0.9	1.2	0.5
Speaker	0.01	1.01	82.0	1.0	1.2	2.49	55.7	0.7	1.0	0.3
Cameras	0.04	0.56	90.1	3.8	4.4	2.34	58.3	2.5	3.3	1.3
SIM tray	0.02	0	100	1.7	1.9	0	100.0	1.7	2.3	0
Vibration motor	0.02	0.73	87.0	1.5	1.7	2.77	50.6	0.9	1.2	0.6
Housing	0.17	0	100	17.0	19.5	0	100.0	17.0	22.9	0
PCA	0.10	1.46	74.0	7.6	8.8	3.03	46.1	4.8	6.4	2.9
Total	1.00	0.71	87.3	87.3	100	1.45	74.1	74.1	100	13.2

recyclability performance of Fairphone 2 is assessed to be relatively low. These findings on material complexity and product disassembly underline the need to find an appropriate metric that assesses product design in fundamental and objective respects.

However, it must be noted that when applying this fundamental assessment approach, other aspects in product design that are equally relevant to recyclability assessment are not considered because they cannot be expressed by means of SE. Therefore, we recommend their inclusion by means of other appropriate assessment methods. For example, the aspect of optimal product lifetime is relevant to design. However, the balance between lifetime and environmental impacts is difficult to define (Bobba et al., 2016; Kara et al., 2008; Richter et al., 2019). A long or even extended product lifetime does not automatically go hand in hand with fewer environmental impacts. Hummen and Desing presented an indicator that measures the environmental performance of products over the lifetime of the product, thus showing the optimal replacement time of products (Hummen and Desing, 2021). The results of their approach could significantly contribute to the recyclability of products. In particular, the energy consumption over the product's lifetime, as targeted by the Ecodesign Directive (European Parliament and European Council, 2012; 2008), plays a relevant role in design. Thus, several studies focused on developing design concepts and aspects that optimize a product's energy consumption (Ibbotson and Kara, 2018a, 2018b; Li et al., 2007, 2019; Seow et al., 2016; Tang and Bhamra, 2008). Another neglected design aspect is the end-of-life treatment of products, which provides relevant planning information for designers and manufacturers. Modern product design should best incorporate this product stage, thus furthering improved product recyclability. In this respect, Leal and colleagues' "RE-CYCLING" design approach might help (Leal et al., 2020). The approach is based on two methodologies that deal with "design-for-recycling" and "design-from-recycling". The assessment approach is founded on several indicators, such as materials' compatibility and recyclability, which ultimately inform recommendations on suitable design guidelines, which designers should then implement. Such design aspects represent only a fraction of possible design principles that have to be taken into account in a comprehensive consideration of recyclability. As for any other assessment method, the RPR results should be carefully interpreted. Accordingly, a 100% RPR should not be seen as a default target. It cannot be ignored that functional progress is accompanied by the use of specific materials. For some materials it might be feasible to move away from their application (e.g. specific materials used in traces or connecting materials), but for many it might not be attainable without losing essential product functions. Hence, the new RPR approach does not automatically imply the removal of specific materials or product parts, but rather helps to identify possible design and recycling weaknesses that might be reconsidered by designers and manufacturers. The approach developed should help to create heightened sensitivity towards products and materials, respectively. Thus, it is probable that establishing RPR value ranges for specific product groups will allow improved and sound comparisons. Therefore, it seems necessary to formulate an agreed-upon material catalogue that is representative for the product group observed. The number of materials considered (N_m) in this catalogue determines H_{max}, thus enabling meaningful comparisons of the RPR values of group associated products. The material catalogue might need regular updates due to the evolution of future product generations. Thus, it might be necessary to add an index to the RPR variable referencing the year the catalogue was issued (e.g. RPR_{2020}).

Meaningful implementation of the new statistical entropy approach significantly depends on precise product data (e.g. bill of materials), which underlines the need to expand data collection and make existing data available and transparent. In following the current CE discussion within the EU and related efforts to initiate transparency regarding product design and material composition, it seems that meeting the concerns of designers and manufacturers poses a great challenge. However, with the implementation of the RPR assessment a first step could be taken regarding product transparency. The overall target should be to convince designers and manufactures of the necessity of designing and producing products that enable disassembly and recycling.

A current restriction of the new approach is that materials are only considered according to their mass, thereby neglecting possible material characteristics such as toxicity, criticality or material source (virgin or recycled). The inclusion of such material information could bring added value and hence enlarge the scope of the RPR assessment. Thus, the possible implementation of additional material characteristics will be a focus of subsequent research. It also has to be mentioned that the RPR assessment does not account for the expenses of disassembly such as associated costs and time. Instead, it follows a binary system: disassembly yes or no. However, disassembly expenses can easily be considered when comparing RPR values of different products in the form of specific RPRs per cost of disassembly (time, energy). Further, the RPR assessment does not evaluate impacts of other product life stages (except design and manufacture). For specific cases, it might be feasible to connect the RPR results to other (socio/ecological) assessments that focus on the remaining product life stages. For example, the connection to a Life Cycle Assessment could be considered.

Finally, it must be underlined that the Case Study presented only focuses on a single product, although, in reality, products usually come along with other product parts (like packaging, battery chargers or other devices to perform the product's function). However, the RPR could also be calculated for such associated product parts, resulting in an extended RPR.

5. Conclusions

The assessment of product recyclability is highly relevant in the transition towards a CE to enable successful and comprehensive implementation. Products should be designed in a way that allows extensive material recovery and easy disassembly. Among the manifold parameters impacting recyclability, material composition and product structure are the fundamental determinants of the recycling path. Existing assessment methods fail to evaluate such product design characteristics in a fundamental way. This paper presents a new assessment method that evaluates product-inherent recyclability based on statistical entropy. Statistical entropy represents an optimal metric to measure these fundamental product characteristics. The case study shows that product design weaknesses can be directly deduced from the RPR results and thus form the basis for design optimizations that increase the recyclability of products and materials, respectively. The calculation of the RPR metric is comparably simple, which enables broad stakeholder application. The method primarily addresses product designers and manufacturers, but should in the long term serve as a decision-making tool for various stakeholders (e.g. governments or consumers).

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.129971.

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