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MULTIPLE APPLICATION OF STATISTICAL ENTROPY: ASSESSMENT OF RECYCLING PROCESS EFFECTIVENESS AS WELL AS PRODUCT-INHERENT RECYCLABILITY

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ABSTRACT: Statistical entropy (SE) appears to be a feasible metric to assess manifold conditions and activities in waste management. The core idea of SE is that the stronger the mixing of materials, the higher is the (statistical) entropy generation and vice versa. Such effects can be described by material flow analysis (MFA), which provides the basis for the SE calculation. With regard to recycling processes, concentrating efforts are omnipresent, e.g. the aim of sorting plants is to separate specific target materials from a mixed waste input. Recycling processes have to be evaluated not only with respect to the quantities of recycled materials produced, but also regarding the concentration (quality) of target materials in the recycling output. Both aspects, quantity and quality, can be expressed by the combination of MFA and SE. The effectiveness of a recycling process increases the more target material is concentrated in the recycling output, corresponding to a SE decrease. Another recycling-relevant fact is the composition of products with regard to material distribution and product structure. It is evident that products of high complexity are associated with high recycling efforts and low recyclability. In terms of SE, complex products show high SE if the product cannot be disassembled into product parts with concentrated materials. Hence, SE can also be used to express the inherent recyclability of products. To demonstrate these different SE approaches, two case studies are presented. In the first case study, the effectiveness of plastic packaging recycling, and in the second, the product-inherent recyclability of a smartphone are analyzed. The results of the case studies show that the SE assessment enables valid insights into the performance of recycling processes and the recyclability of products, respectively. These findings could be of relevance for recyclers and product designers, but also for the implementation of the European Circular Economy Package.

Keywords: Recycling effectiveness; Recycling rate; Recyclability; Product design; Statistical Entropy; Circular Economy

1. INTRODUCTION

The European Union (EU) implemented the Circular Economy (CE) Package that aims to establish a more sustainable production and consumption of products and materials, respectively (European Commission 2014a, b, 2018a, b; European Union 2020). The CE concept involves various processes along the supply chain, like product design or recycling. It is evident that the transition towards a CE represents a complex undertaking that needs appropriate monitoring and evaluation. Aware of this necessity, the EU has set different strategies to promote new assessment methods and indicators, respectively. On the one hand, existing indicators are expanded or improved (e.g. Ecodesign, recycling rate), and, on the other hand, new indicators need to be defined (e.g. resource footprints).

Regarding the improvement of the recycling rate calculation, the EU neglected to include qualitative recycling aspects, thus still bases purely on quantitative aspects. Concerning CE goals, this represents a weakness because an effective CE significantly depends on the quality of recycling outputs. Thus, there exists a weakness in the actual calculation method.

In view of new indicators, the assessment of product recyclability is receiving more and more attention. Products should be designed to enable the best possible recycling and thus ensure high circulation of materials. Hence, the focus has shifted from recycling (performances) to product design and manufacturing. Design trends, like increasing material variety, show a significant impact on recycling; thus, products and their inherent recyclability should be assessed already at the design stage to allow timely design adaptations.

The presented research aims to meet these outlined issues by establishing new assessment methods based on statistical entropy (SE) that enable an advanced assessment of concepts like recycling and product design. The new assessment methods should allow relevant insights into the different processes and help to deduce meaningful optimization measures.

2. METHODS

2.1 Statistical entropy analysis

SE, which has its origins in thermodynamics, has been further developed and applied in various areas over the past few decades. SE is a measure of the order or disorder of a system. The greater the disorder of the system under consideration, the higher the SE. In most applications, the goal is to keep the SE low and avoid a higher level of disorder. Claude Shannon made a significant contribution to the further development of SE by introducing SE to information theory and defining it as the mean information content of a message (Shannon 1948). The information content of a character (expressed in the unit bit) is low the more frequently the character occurs in a message (expressed by the probability of occurrence p_i). Shannon's approach can be represented in a simplified manner with equation (1) (where ld is the logarithm to base 2; ld (0) = 0).

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

Rechberger and Brunner used Shannon's approach in order to investigate the concentrating or diluting effects of processes on specific substances and thus to be able to evaluate material flow systems (Rechberger 1999; Rechberger and Brunner 2002). Very simplified and shortened one can say that if a substance is present in the same concentration (c) in all output flows after passing through a process, this would be the worst-case in terms of SE (H = maximum). If the substance is maximally concentrated in a single output flow of the process, this corresponds to the best-case (H = minimum; H = 0 if c = 1). In practice, the substance distribution lies between these two SE extremes.

2.2 Recycling effectiveness of recycling processes

Roithner and Rechberger apply the SE approach to assess recycling processes’ performance in concentrating specific target materials at the end of a recycling process (e.g. valuable materials of a mixed waste input) (Roithner and Rechberger 2020). Thereby, effective separation of unwanted materials (e.g. impure or contaminated materials) is essential. The more dilute or contaminated the recycled target material is, the lower the recycling performance and quality. Similar to Rechberger and Brunner’s approach, this circumstance can be described by considering material distributions and concentrations, respectively. In order to capture the quantitative and qualitative recycling aspects in combination with the

SE approach, two different mass balances must be drawn up: the total mass balance (= quantitative aspect; e.g. total plastic packaging) (see the top of Figure 1) and the target material mass balance (= qualitative aspect; e.g. polyethylene terephthalate (PET) packaging) (see bottom of Figure 1). If the recycling process handles more than one target material, separate target material mass balances have to be established.

As shown in Figure 1, these mass balances are composed of specific mass flows (input and output mass flows). The input mass flow represents the collected waste and the output mass flows comprise at least one recycled mass flow and one discard mass flow. The target material mass flows ($X_{out,i}$) are calculated by applying the target material concentrations ($c_{out,i}$) to the output mass flows ($M_{out,i}$) of the total mass balance, thus reflecting the qualitative recycling aspect.

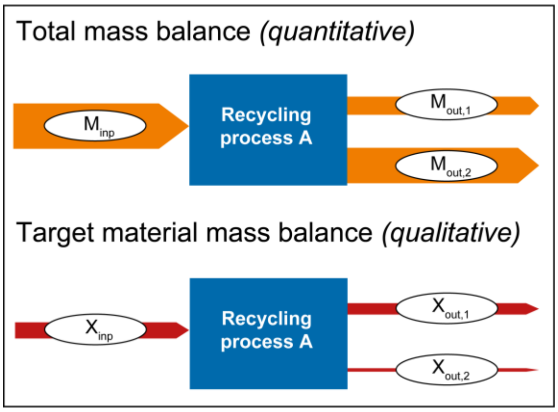

Figure 1 Quantitative and qualitative consideration of a recycling process. The input mass flow (left side) is processed by the Recycling process A, resulting in two output mass flows (right side). Top figure: Total mass balance; Bottom figure: Target material mass balance. Source: (Roithner and Rechberger 2020).

The calculation of the processes' SE is based on Equation (2), where $m_{out,i}$ represents a specific mass fraction (= $M_{out,i}$ / X_{inp}; e.g. kg plastic per kg PET input). In a subsequent step (cf. Equation (3)), the relative SE ($H_{out,rel}$) is determined (a value between 0 and 1), which enables comparison to other recycling processes. H_{max} results if the concentration of the target material in each output flow would remain the same as in the input flow (c_{inp} = $c_{out,i}$).

$$H_{out}\ (c_{out,i}, m_{out,i}) = -\sum_{i=1}^{k} m_{out,i} * c_{out,i} * ld(c_{out,i}) \tag{2}$$

$$H_{out,rel} = \frac{H_{out}}{H_{max}} \tag{3}$$

Finally, the *Recycling Effectiveness* (RE) is expressed as RE = 1 – $H_{out,rel}$ because, in general, 100% is interpreted as the best result (which is reached if $H_{out,rel}$ = 0). The goal is to achieve a maximum RE. The RE increases, the more effective the investigated recycling process can concentrate target materials.

2.3 Product-inherent recyclability

The latest publication of Roithner and colleagues deals with the SE-based assessment of products and their product design inherent recyclability (Roithner et al. 2021). They assume that product information, like material distribution and product structure, which is defined in the phase of product design, has a significant impact on the recyclability of a product and it thus the base of the developed approach. The recyclability decreases the more materials are present in similar concentrations in the product or the more difficult the product is to be disassembled in individual product parts. The calculation of the *Relative product-inherent recyclability* (RPR) metric bases on Equations (4) and (5). It is essential to calculate the product part-specific SE (H_j) for those N_e product parts reflecting the highest disassembly depth (cf. Equation (4)). The SE of the entire product (H_p; see Equation (5)) is the mass-weighted mean of all H_j (M_j ... mass of the product part; M_p ... mass of the entire product). For the final RPR result (see Equation (6)), the relative SE is used, which sets H_p in ratio to H_{max} (= ld (N_m)). In this application of SE, H_{max} represents the case where all N_m materials in the product occur in the same concentration and no disassembly is possible. According to Equation (6), the RPR of the individual product parts (RPR_j) can also be calculated, whereby H_p has to be replaced by H_j. In order to enable profound comparisons between different products, Roithner et al. recommend establishing a typical product-specific material catalog with N_m materials, which then defines H_{max} for the comparison (see Equation (6)).

$$H_j = -\sum_{i=1}^{N_m} c_{i,j} \,\mathrm{ld}\,(c_{i,j}) \tag{4}$$

$$H_p = \frac{1}{M_p} \sum_{j=1}^{N_e} M_j \, H_j \tag{5}$$

$$RPR = 1 - \frac{H_p}{H_{max}} = 1 - \frac{H_p}{\mathrm{ld}(N_m)} \tag{6}$$

An RPR result of 1 (= 100%) reflects maximum recyclability based on product design. The goal is to achieve the highest possible RPR. The RPR increases, the more concentrated the individual materials are in the product parts, which is favored by extensive disassembly.

An RPR of 0 does not mean that the product cannot subsequently be recycled, but it is the worst situation in terms of product design.

3. RESULTS AND DISCUSSION

Two different case studies are presented to demonstrate the developed assessments. The first case study shows the application of the RE assessment method on hypothetical plastic packaging recycling. In the second case study, the RPR of a modeled smartphone is evaluated.

3.1 Case study 1: Plastic packaging recycling

The observed plastic packaging recycling processes are reduced to the absolute minimum level of complexity to demonstrate the application of the developed RE method. The term *Recycling process* may include sub-processes like washing, sorting, shredding, etc., but no chemical treatment. The target material of both recycling processes is PET. The results of the RE assessment are compared to the purely quantitative recycling rate (RR) assessment (following the EU's calculation approach).

3.1.1 Scenario 1

Figure 2 shows the recycling performance of two different plastic packaging recyclers. Both recycling processes achieve 70 t / d of recycled plastic from a purely quantitative perspective, which corresponds to a RR of 0.70 (= $M_{out,1}$ / M_{inp}). When considering the PET mass balance, it becomes apparent that Recycling process 2 sorts more PET (= 58 t PET / d) and thus has a higher PET concentration in the target stream. This fact has a positive effect on the RE. Recycling process 2 achieves a higher RE than Recycling process 1 (0.47 > 0.23).

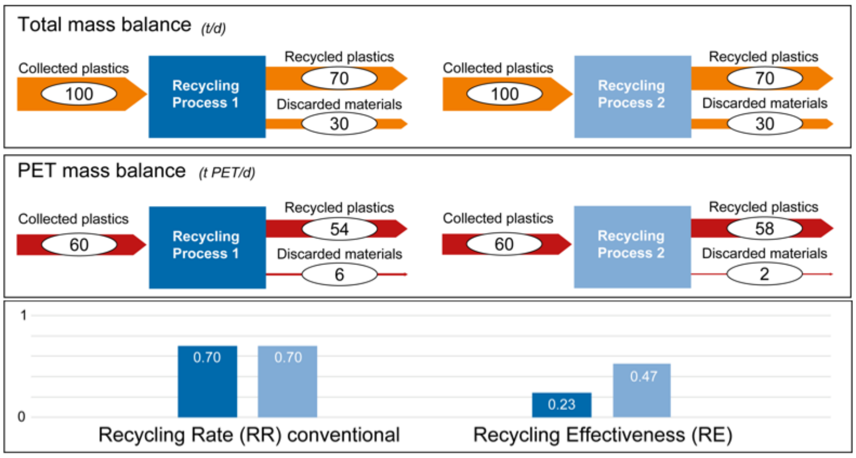

Figure 2. Scenario 1: Total mass (top) and PET mass balance (second row) of two different recycling processes and results of the RR and RE calculation (bottom). Source: (Roithner and Rechberger 2020)

The results of Scenario 1 show that the initial quantitative assumption on the recycling processes' performances (cf. RR values in Figure 2) has to be reconsidered because of the significant differences in the concentrating of PET that reflects a different purity of recycled plastics. The scenario shows that the conventional RR method can be significantly misleading if the recycling performance regarding target materials is not considered together with the total mass balance.

3.2 Case study 2: Smartphone

A smartphone put on the market around 2012 was modeled based on literature data (cf. Figure 3) (Roithner et al. 2021). Three levels were chosen to describe the structure of the smartphone: the product level (= entire smartphone), the component level (e.g. battery), and the sub-component level (e.g. the casing of a battery). The modeled smartphone consists of 11 components and 32 sub-components. It comprises 49 materials distributed in the different product parts (components and sub-components).

The RPR calculation follows a theoretical disassembly order, where the individual product parts are disassembled stepwise. At each disassembly step, the RPR is calculated; the remaining product parts are assumed to be combined.

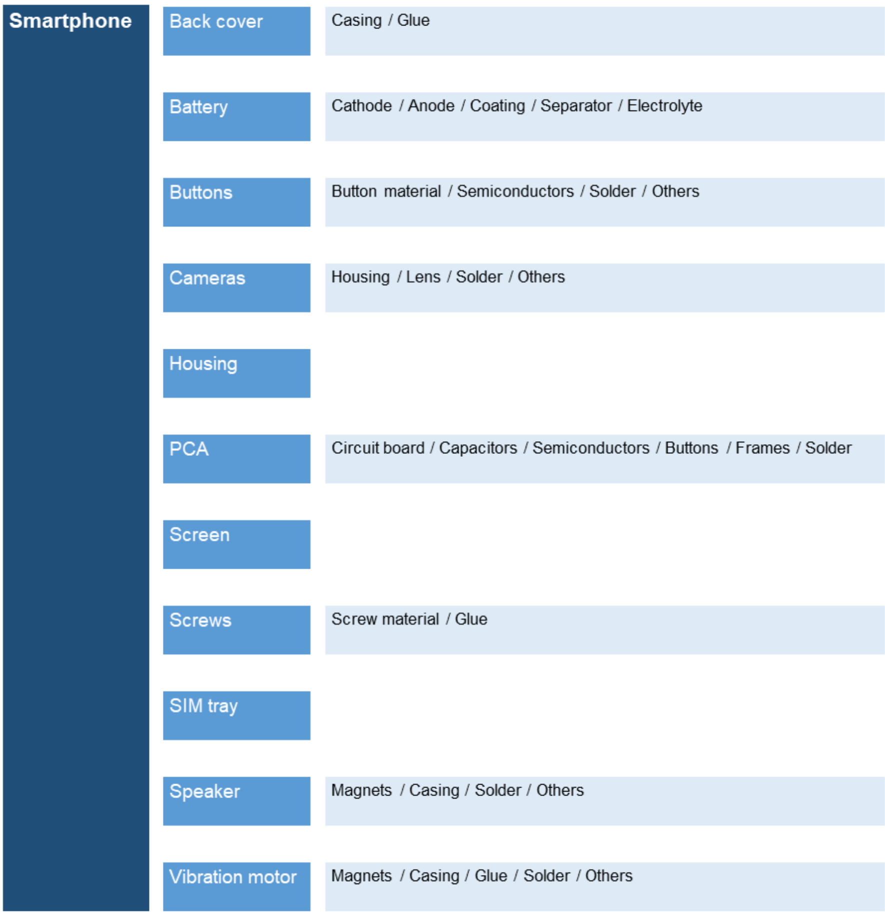

Figure 3. Structure of the modeled smartphone (left column: product level; middle column: component level; right column: sub-component level).

3.2.1 Scenario 1

Figure 4 shows the RPR results of the modeled smartphone in Scenario 1 if components are disassembled into sub-components (w/) or not (w/o). The RPR at the product level accounts for 40.8%, representing the case if the product is not disassembled at all. With the advancing disassembly steps, the RPR of the smartphone rises. The final RPR is reached when the last product part (in this case, the PCA (Printed circuit assembly)) is disassembled, resulting in 87.3% if sub-components are considered and 74.1% if not. It becomes evident that the RPR is higher if the components are disassembled into sub-components.

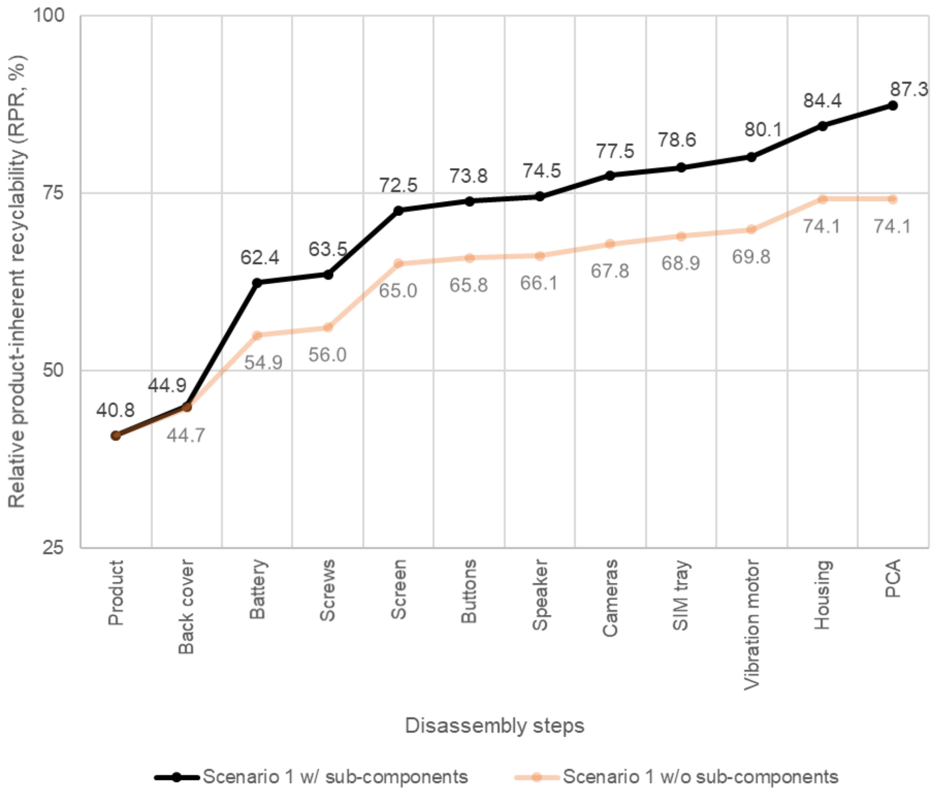

Figure 4. Scenario 1: RPR of the modeled smartphone as a function of disassembly steps with (w/) and without (w/o) consideration of sub-components.

The RPR_j of the individual components with consideration of sub-components are listed in Table 1 (see the second column). It shows that some components are 100% recyclable due to their uniform material composition (Housing, SIM tray) or possible disassembly into pure materials (Back cover, Screws). The lowest RPR_j achieves the PCA with 74%, caused by its highly complex material composition. Further, the relative contribution of the individual RPR_j to the product RPR is shown in columns 3-4 of Table 1. These values are computed with the average mass weight ($m_j = M_j / M_p$) of the individual components (= M_j / M_p) in relation to RPR. The highest contributions can be observed for the Scree, Battery and Housing.

Table 1. Scenario 1: RPR_j and their mass-weighted (m_j) contribution to the total RPR of the different components with consideration of sub-components.

	RPR_j (%abs)	**m_j RPR_j (%abs)**	**m_j RPR_j (%rel)**
PCA	74.0	7.6	8.8
Housing	100	17.0	19.5
Screen	80.5	21.9	25.1
Battery	84.0	18.6	21.2
Cameras	90.1	3.8	4.4
SIM tray	100	1.7	1.9
Back cover	100	11.0	12.7
Buttons	84.5	1.4	1.6
Screws	100	1.7	1.9
Speaker	82.0	1.0	1.2
Vibration motor	87.0	1.5	1.7
Smartphone		**87.3**	**100**

The smartphone results show that the RPR metric can help to point out product design impacts on recyclability. The RPR increases the more concentrated materials are present in the disassembled product parts of the smartphone. Further, the results of the RPR_j contributions of the individual components show that different prioritization would have to be set to optimize the product design.

4. CONCLUSIONS

Both case studies show that SE is a suitable metric to describe complex context, like the quantitative and qualitative recycling performance and the product-inherent recyclability. The developed assessment methods allow a simple application and profound comparisons. The outcomes of the SE analysis will help contribute to the evaluation of CE strategies.

The RE assessment method uniquely enables the combined assessment of quantitative and qualitative recycling aspects. Significant comparisons between different recyclers are possible and will help outline differences in the quality of recycling outputs. The EU could implement the RE assessment complementary to the purely quantitative recycling rate assessment and allow an advanced comparison between the Member States' recycling performances.

The new RPR metric is aimed primarily at product designers and manufacturers because they could get an enhanced insight into the product-inherent recyclability. The RPR results highlight product design weaknesses and allow the planning of product design optimizations. The new assessment method could promote the European efforts to increase the recyclability of products and establish a more transparent supply chain.

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