Statistical entropy opens a new way to assess the recyclability of products

Introduction

The European Union forces the transition towards a Circular Economy (CE), where products and materials should be recirculated to the greatest possible extent. To monitor the CE transition, assessment methods are needed that evaluate progress along the whole value chain. With respect to recycling, it is evident that decisions on product design impact the recyclability of products. Fundamental product information, like material composition and product structure, can be considered to express this effect. Thus, the research presented deals with the assessment of product recyclability at the stage of product design, where relevant product information is expressed by statistical entropy (SE).

Material and Methods

Modern products consist of manifold materials that are distributed in different product elements (e.g. electronic components). The here presented *Relative product-inherent recyclability* (RPR) uses SE to evaluate the distribution of materials (expressed as concentrations) in all product elements that can be disassembled. The SE increases the more materials are dispersed in similar concentrations in the product elements considered.
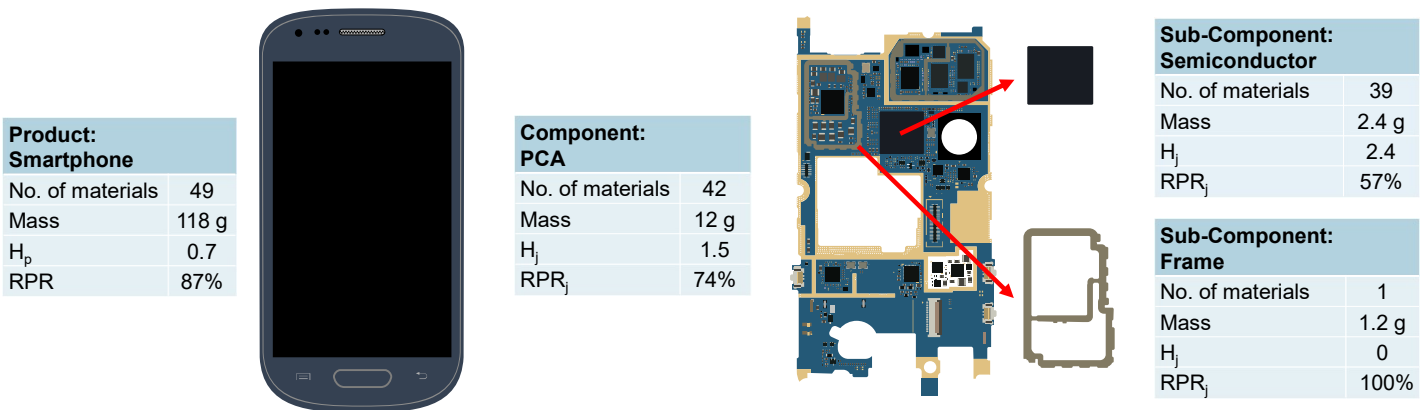
$$\text{(1)} \quad H_j = -\sum_{i=1}^{N_m} c_{i,j}\, ld(c_{i,j}) \qquad \text{(2)} \quad H_p = \frac{1}{M_p}\sum_{j=1}^{N_e} M_j H_j \qquad \text{(3)} \quad RPR = 1 - \frac{H_p}{H_{max}}$$

(1) The SE of the individual product elements (H_j) is calculated from its N_m material concentrations ($c_{i,j}$). (2) The SE of the total product (H_p) is calculated as the mass weighted average of the individual H_j (M_j … mass of product element; M_p … mass of total product). (3) The final RPR is computed based on the relative SE, which is the ratio between H_p and the maximum SE of the product ($H_{max} = ld(N_m)$; when all $c_{i,j}$ are equal and no disassembly is possible). Note: The same scheme can be used to compute the RPR_j of the individual product elements by replacing H_p with H_j in (3).

RPR is a value between 0 and 1; RPR = 0 represents the case where the product cannot be disassembled and all materials are present in the same concentration ($H_p = H_{max}$), while RPR = 1 represents the case where each product element disassembled consists of a single material only ($H_p = 0$). RPR increases the better the product can be disassembled into product elements with concentrated materials. Note that RPR = 0 does not mean that the product cannot be recycled in downstream processes; it is only the worst situation from the product design perspective.

To demonstrate the application of the developed RPR assessment method, a smartphone is considered that was modelled based on literature data.

Case Study: Smartphone

Product: Smartphone	
No. of materials	49
Mass	118 g
H_p	0.7
RPR	87%

Component: PCA	
No. of materials	42
Mass	12 g
H_j	1.5
RPR_j	74%

Sub-Component: Semiconductor	
No. of materials	39
Mass	2.4 g
H_j	2.4
RPR_j	57%

Sub-Component: Frame	
No. of materials	1
Mass	1.2 g
H_j	0
RPR_j	100%

The modelled Smartphone consists of 49 materials that are distributed in 11 components and 32 sub-components. The following results focus on the component "printed circuit assembly" (PCA), which is generally one of the most complex product elements of smartphones. The PCA consists of 42 materials and 6 sub-components. Some materials only occur in traces, whereas others are highly concentrated. The RPR of the modelled Smartphone is relatively high (87%) because the Smartphone contains several product elements that consist of pure or highly concentrated materials. The RPR might be smaller if less disassembly was possible and vice versa. The RPR_j of the PCA accounts for 74%, reflecting the relatively strong dispersion of materials in this component. Considering the PCA's sub-components, semiconductor and frame, material compositions vary greatly, and so does H_j. The H_j of the frame is zero (and thus RPR_j a maximum) as it only consists of one pure material.

The RPR assessment helps to improve product design with regard to recyclability, thus promoting products of concentrated materials and optimal disassembly. Overall, products of high RPR could contribute to an increased recirculation of products and materials.

TECHNISCHE UNIVERSITÄT WIEN

Caroline Roithner, MSc.
Dr. Oliver Cencic
Prof. Dr. Helmut Rechberger

TU Wien, Institute for Water Quality and Resource Management
Contact: caroline.roithner@tuwien.ac.at