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EVALUATION OF RESOURCE EFFECTIVENESS OF CIRCULAR ECONOMY STRATEGIES THROUGH MULTI-LEVEL STATISTICAL ENTROPY ANALYSIS

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Statistical Entropy Analysis of materials, components and products

In a circular economy (CE), materials, components and products should be kept at the highest level of functionality, while their loss and dilution should be avoided. Recycling, remanufacturing and reuse are examples of established CE strategies which aim to minimise the loss of materials and substances from anthropogenic metabolic systems. One method that assesses the performance of systems to concentrate or dilute substances is Statistical Entropy Analysis (SEA). The method has been applied on the substance level (elements and compounds), at different scales and on a variety of systems (Rechberger & Graedel, 2002; Rechberger & Brunner 2002; Sobańtka & Rechberger, 2013; Laner et al. 2017). Nevertheless, the current method does not allow for an integrated evaluation of recycling, reuse or remanufacturing systems, which consist of multiple materials and components. Through the extension of the method we are able to combine all three hierarchical levels consisting of the substance/material, component and product level. Additionally, we establish a baseline for resource effectiveness, which represents an ideal state of a CE system. In that ideal state, the dilution of substances/materials, components and products is avoided. Through a simple hypothetical case study we demonstrate how the baseline for resource effectiveness can be used to measure the distance of any system configuration to the ideal circular system state.

Simple MFA system

A simple Material Flow Analysis (MFA) system is developed to demonstrate the multi-level SEA method. It consists of four processes and represents a simplified production and end-of-life treatment system of an average car (Figure 1). The car composition data is aggregated on six material groups and four component groups (Table 1) as described by Modaresi et al., (2014a).

Table 2 **Average car composition, divided into four main component (vertical) and six material groups (horizontal) (based on an average US car, downscaled to global average) (Modaresi et al., 2014b).**

Group name	Standard steel (kg)	High strength steel (HSS) (kg)	Cast Iron (kg)	Wrought Al (kg)	Cast Al (kg)	Others (kg)	Total (kg)
Body and closures	222	182	0	8	0.3	45	457.3
Chassis and suspension	203	41	17	10	23	37	331
Powertrain	99	0	94	4	41	108	346
Interior and misc	61	0	0	12	2	173	248
Total (kg)	585	223	111	34	66.3	363	1382.3

The car composition data is employed to construct two different reuse scenarios, each with two recycling configurations (Figure 2).

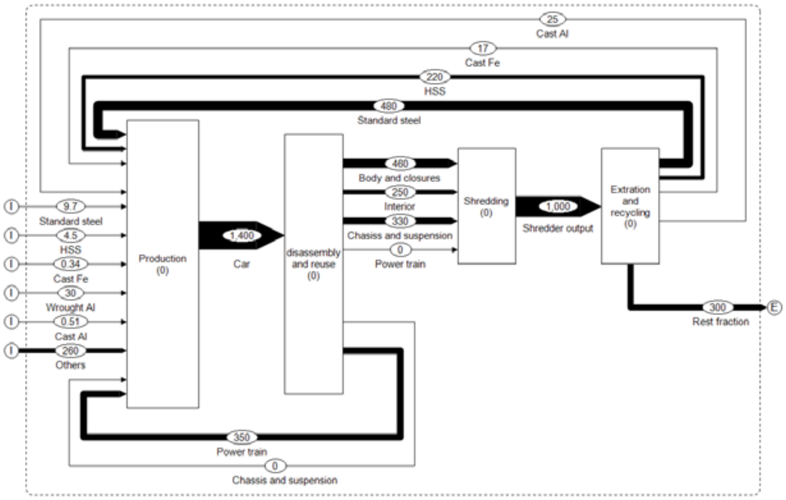
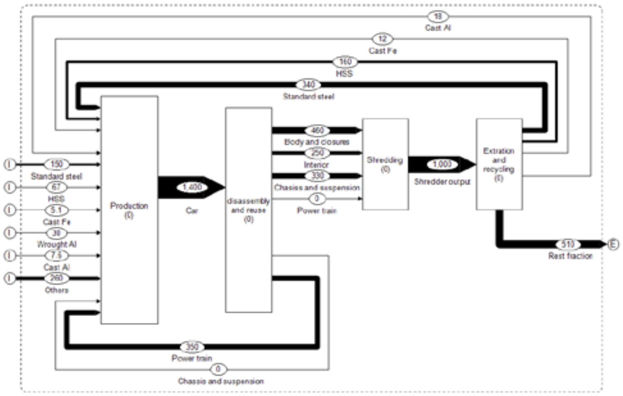
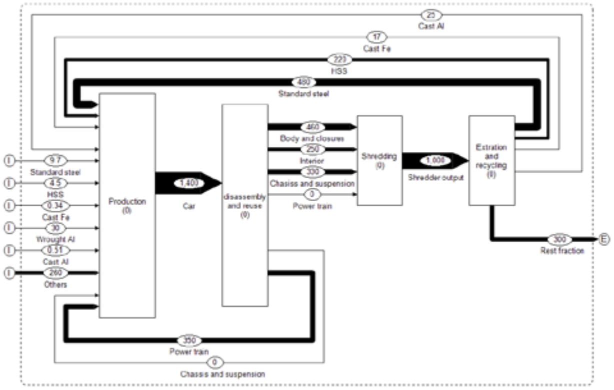


Figure 17 **Simple MFA system, consisting of a car production, disassembly and reuse, shredding, recycling processes (flows in kg/car).**

Low recycling level (70% of metals recycled) | High recycling level (98% of metals recycled)

Scenario 1: Reuse of one component group





Scenario 2: Reuse of none of the component groups

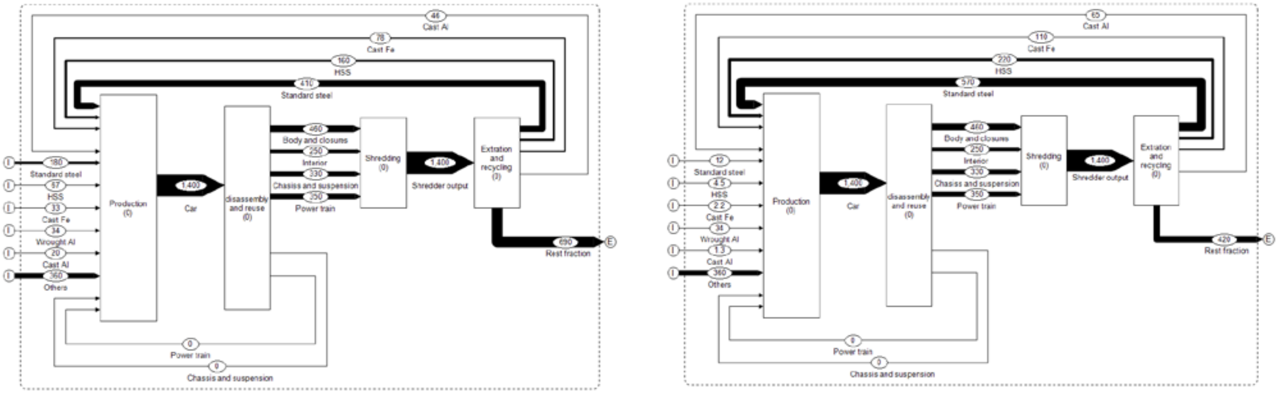


Figure 2 Two reuse scenarios with a higher and a lower level of recycling (low recycling level means 70%, high level recycling means 98% of metallic fraction of shredder output is recycled).

Method

The extended SEA method consists of two parts. First, the component SEA is calculated. Second, the component SEA is aggregated for the product. The component SEA calculation is similar to the original approach by Rechberger & Brunner (2002), with the difference that a component C_i consists of multiple substances *j* through their concentrations in the component *i*. In total, the sum of the substance concentrations $\sum c_{ij}$ adds up to one, resulting in the sum of substances $\sum X_{ij}$, which can fully describe the component *i*. The normalised mass fractions m_{ij} are calculated for the set *k* of induced material flows for the respective component by dividing each material flow rate by the sum of all induced substance flow rates $\sum\sum X_{ij}$ within the full set of material flows at a system stage (a stage representing a set of material flows between two processes) (1). Thereby, the normalised mass fractions take into account the relative contribution of each substance to the overall set of material flows at a system stage.

$$(1)\ \mathrm{m_{ij}} = \frac{\mathrm{M_{ij}}}{\sum\sum \mathrm{X_{ij}}}$$

$$(2)\ \mathrm{H_c}(\mathrm{c_{ij}}, \mathrm{m_{ij}}) = -\sum_{\mathrm{i=1}}^{\mathrm{k}} \mathrm{m_{ij}} \cdot \mathrm{c_{ij}} \cdot \mathrm{ld}(\mathrm{c_{ij}})$$

$$(3)\ \mathrm{H_{max,j}} = \mathrm{ld}(\textstyle\sum \mathrm{m_j})$$

$$(4)\ C_c = \frac{n}{N}$$

$$(5)\ C_m = \frac{m}{M_p}$$

$$(6)\ H_p(C_c, C_m) = -\sum_{i=1}^{k} C_m \cdot ld(C_c) \cdot \frac{H_c}{H_c + 1}$$

$$(7)\ H_{max,\mathrm{p}} = \frac{ld(C_c)}{2}$$

The statistical entropy value is calculated for a component according to Eq. 2 (ld refers to logarithmus dualis). It is further expressed as a dimensionless Relative Statistical Entropy (RSE) value, ranging between [0,1], as it is a ratio between H/H_{max}. The maximum statistical entropy value is calculated for each substance according to Eq. 3. For closed systems, the largest RSE value is reached, when a substance is diluted equally within a *k* set of flows. If a substance is fully concentrated in one flow, the RSE value is zero, representing the highest possible concentration.

For the calculation of the product entropy, the discrete component flows *n* are used to calculate the component concentration C_c. It is expressed as a discrete number of a component within a product over the overall number of components *N* in the product (4). Further, the component mass *m* is standardised by calculating the mass concentration C_m of a component as a fraction of the overall product mass M_p (5). Both terms are combined in the product statistical entropy H_p. The previously calculated component entropy value H_c is included in the entropy term (6). The product entropy value H_p, together with the calculation of $H_{max,p}$ (7), locates the RSE value always in the interval of [0,1], while taking the value of zero or one for the extreme cases.

Results

The SEA results are plotted over their full life-cycle which starts and ends with the product stage (Figure 3). Any increase in the RSE indicates the dilution of substances/materials or components, while any decrease shows a concentrating behaviour of the system. It is important to note that any dilution requires concentrating processes afterwards. For the product and post-disassembly component stage, the relative statistical entropy (RSE) values are identical, as the material flows at these stages are identical for all system configurations. The first deviation for the two scenarios appears at the output flow from the shredder. The RSE is higher for the system with no component reuse, as all components enter the shredder and contribute to an overall larger material dilution. The resource effectiveness baseline as the ideal system state, represents the product which provides functionality and does not require any material inputs, neither does it induce the dilution of substances/materials and components. The system that performs closest to the resource effectiveness baseline is the system 1.2, with the reuse of one component group and a high recycling ratio for metals. Therefore, the worst performing system is the system 2.2, which lacks any reuse and has a low recycling level, requiring a high concentration of materials afterwards, which are again diluted into the functional product in the production stage. For this reason, the number of reused components and the shredder output stage largely determine the system performance. The presented methodology provides an evaluation perspective, which allows to compare systems that involve multiple CE strategies, and compare systems to a resource effectiveness baseline, representing an optimal CE state.

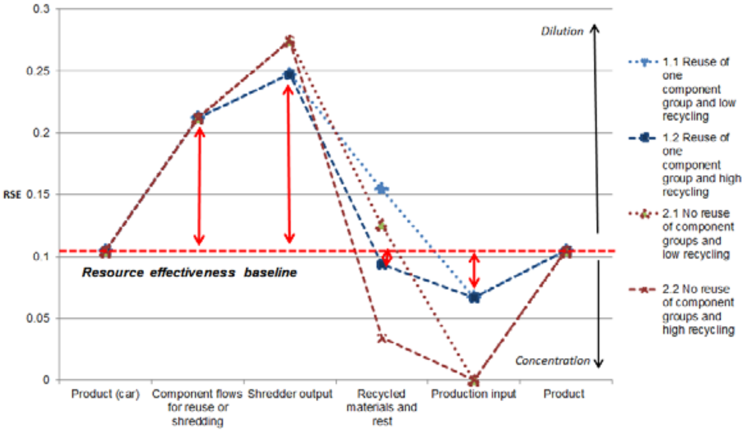


Figure 3 Relative Statistical Entropy (RSE) for two reuse scenarios and two recycling configurations, with indicated distance to the Resource Effectiveness Baseline (red), and exemplary distances to the ideal state of scenario "1.2`Reuse of one component group and high recycling" (red arrows).

Conclusion

In the short case example, we demonstrated that the extended SEA method not only allows to evaluate the degree of circularity in the context of different combinations of CE strategies, but is also able to identify stages with largest contributions to the deviation from the ideal CE state. Thereby, the extended SEA method can guide the choice of CE strategy combinations that minimise product, component and material losses and the distance to the ideal CE state.

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