Dissertation

Entwicklung einer Methode zur Bestimmung der Ressourceneffektivität von Kreislaufwirtschaftsstrategien

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Doctoral Thesis

Towards a measuring tool for the resource effectiveness of circular economy strategies

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Kurzfassung

Ressourcen bilden eine wichtige Grundlage für die Wertschöpfung einer Gesellschaft. Mit dem Wirtschaftswachstum des vergangenen Jahrhunderts erreichte der Ressourcenverbrauch ein noch nie dagewesenes Ausmaß, mit der Folge von erheblichen Umweltauswirkungen, sodass die menschliche Aktivität einen dominanten und erdgeschichtlich relevanten Einflussfaktor auf das Erdsystem darstellt. Vor diesem Hintergrund werden große Anstrengungen unternommen, um das derzeitige Wertschöpfungsmodell, das nicht nur große Mengen an Rohstoffen verbraucht, sondern auch große Mengen von Abfällen und Emissionen produziert, hin zu einem stärker kreislaufwirtschaftlich orientierten Wirtschaftsmodell umzugestalten. Eine Kreislaufwirtschaft zielt darauf ab, den Wert und die Funktionalität von Produkten, deren Komponenten und Stoffe über einen möglichst langen Zeitraum zu erhalten. Angesichts der Vielfalt möglicher Kombinationen von Kreislaufwirtschaftsstrategien, die auf der Produktebene (z.B. Produktdesign, Verlängerung der Lebensdauer), der Komponentenebene (z.B. Wiederaufarbeitung, Reparatur), oder der Stoffebene (z.B. Recycling) Anwendung finden können, bleibt die Messung der Transformation hin zu einem Kreislaufwirtschaftsmodell eine Herausforderung. In dieser Hinsicht erweitert die vorliegende Arbeit die Methode der Statistischen Entropie Analyse (SEA), die darauf basiert Konzentrations- und Verdünnungsaktivitäten in einem Stoffflusssystem zu bewerten. Die erweiterte Methode ermöglicht es zusätzliche Komplexitätsebenen, angefangen von der Stoff-, Komponenten-, bis hin zu der Produktebene zu berücksichtigen. Dadurch ermöglicht die Methode die Bewertung verschiedener Kombinationen von Kreislaufwirtschaftsstrategien und die Quantifizierung der damit verbundenen Aufwände in Form von Verdünnungs- und Konzentrationsaktivitäten, die im System durchgeführt werden. Des Weiteren wird die Methode um eine zeitlich-dynamische Perspektive erweitert, sodass eine Bewertung längerfristiger Systemtransformationen und der damit verbundenen Kreislaufwirtschaftsszenarien ermöglicht wird.

Im ersten Schritt der Arbeit wird eine Bestandsaufnahme durch eine strukturierte Analyse von 63 Kreislaufwirtschaftsindikatoren durchgeführt, die zur Identifizierung von Indikatoren-Clustern und der jeweils beteiligten Bewertungsperspektiven führt. Unter Anwendung einer Mehrfachkorrespondenzanalyse (MKA) werden die Indikatoren in Bezug zueinander, sowie in Bezug auf die 24 abgeleiteten kreislaufwirtschaftlich relevanten Bewertungsperspektiven strukturiert. Beispiele für einige Bewertungsperspektiven sind die Verfügbarkeit von (Ressourcen-)Lagern, die Verweildauer von Produkten, Komponenten und Stoffen, das Recyclingpotenzial und die Recyclingeffizienz. Darüber hinaus ermöglichen die Ergebnisse eine Beurteilung der Zusammenhänge zwischen den verschiedenen Bewertungsperspektiven, inwiefern diese gemeinsam herangezogen werden sollten bzw. welche von ihnen komplementär zueinander sind. Die Ergebnisse zeigen die wichtigsten Indikatoren-Cluster, einschließlich der bestehenden Bewertungslücken und der sich daraus ergebenden Möglichkeiten für die Entwicklung von Kreislaufwirtschaftsindikatoren, die in diesem Fall bei der Erweiterung der SEA mitberücksichtigt wurden.

Im zweiten Schritt wird die SEA auf die genannten Komplexitätsebenen erweitert und an einem Fallbeispiel eines vereinfachten Fahrzeuglebenszyklus demonstriert. Dadurch wird sowohl die Funktionsweise der Methode, als auch ihr Einsatz und der damit zusammenhängende mögliche

Erkenntnisgewinn dargestellt, z.B. hinsichtlich der Identifizierung von kritischen Ressourcen- und Funktionalitätsverlusten, die durch ihre Anwendung identifiziert und ggf. vermieden werden können. Darüber hinaus wird gezeigt wie unterschiedliche Kreislaufwirtschaftsstrategien, einzeln oder in Kombination, zu einem Systemzustand beitragen. Durch die Möglichkeit der Definition eines idealen kreislaufwirtschaftlichen Systemzustands, bei dem z.B. die Funktionalität eines Produktes auf dem höchstmöglichen Niveau erhalten bleibt, kann die Leistungsfähigkeit verschiedener Systeme als Abstand zum Idealzustand gemessen werden. Auf der Grundlage der Ergebnisse wird ein Beurteilungsrahmen für Ressourceneffektivität abgeleitet, in dem Verdünnungs- und Konzentrationseffekte von Kreislaufwirtschaftsstrategien quantifiziert werden können. Dies ermöglicht eine Vielzahl von Systemen und in Bezug zu einem System größter Ressourceneffektivität darzustellen. Dabei beschreibt Ressourceneffektivität einen Zustand der maximalen Erhaltung von Funktionalität über einen möglichst langen Zeitraum unter minimalen Aufwänden, die in diesem Fall als Änderungen von statistischer Entropie quantifiziert werden.

Im dritten Schritt wird die erweiterte Methode um eine zeitliche Dimension erweitert, und auf eine komplexere Fallstudie eines generischen europäischen Automobilsystems angewendet. Für die Betrachtung der zeitlichen Dimension wird die Methode mit einem dynamischen Bestandsmodell der Fahrzeugflotte und einer damit verbundenen Stoffflussanalyse kombiniert. Durch die Fallstudie wird verdeutlicht, wie die weiterentwickelte Methode zur Beurteilung von Szenarien und Systemveränderungen verwendet werden kann. In diesem Fall wird die Elektrifizierung des Fahrzeugbestandes bis zum Jahr 2050 modelliert, wobei je nach Szenario verschiedene Kombinationen von Kreislaufwirtschaftsstrategien zur Anwendung kommen. Unter anderem ermöglicht die Berücksichtigung von zeitlich-dynamischen Systemveränderungen weitere Systemelemente, wie die Veränderung der Lebensdauer, oder eine Änderung des Fahrzeugbestandes aufgrund einer veränderten Nutzung der Fahrzeugflotte, mithilfe der SEA zu bewerten. Als Ergebnis der Fallstudie ist festzuhalten, dass Kombinationen von Kreislaufwirtschaftsstrategien die Aufwände, die ansonsten eine steigende Tendenz beim Übergang hin zu einem höheren Anteil von Elektrofahrzeugen bis zum Jahr 2050 aufweisen, durch Kombinationen von Kreislaufwirtschaftsstrategien minimiert werden können. Dadurch wird außerdem gezeigt, wie die Nutzung der weiterentwickelten Methode zu einer Bewertung bzw. Entscheidungsfindung beim Übergang zu einer Kreislaufwirtschaft beitragen kann.

Abstract

Resources represent an important basis for the value creation of a society. With the economic growth of the past century, resource consumption reached an unprecedented scale, leading to severe environmental effects that made human activity a force of geologic importance. Given this background, large efforts are undertaken to transform the current production-consumption system that produces vast amounts of waste and emissions into a more Circular Economy (CE) that aims to preserve functionality and value of products, parts, and materials over a maximum period of time. However, measuring the transition towards a more circular system remains a challenge, especially in the light of the diversity of possible combinations of CE strategies that can be applied on the level of the product (e.g. product design, lifetime extension), component (e.g. remanufacturing, repair), or the material level (e.g. recycling). Employing the method of Statistical Entropy Analysis (SEA) that evaluates the concentration and dilution activities in a material flow system for single substances (elements and compounds), this thesis extends the method to a Multilevel SEA that considers additional material, component and product levels. As a result, the Multilevel SEA allows evaluating different combinations of CE strategies, quantifying the related efforts in terms of dilution and concentration activities performed in the system, while the extension of the method by a time-dynamic perspective allows assessing long term system transitions and related CE scenarios.

In the first step, a structured analysis of 63 CE metrics is performed, leading to the identification of methodology clusters and related assessment perspectives. Applying the method of Multiple Correspondence Analysis (MCA), the metrics are structured in relation to each other as well as to the 24 assessment perspectives that are relevant to the CE, such as the availability of stocks, retention of products, parts and materials, the potential for recycling and recycling efficiency. Further, the MCA results are employed to assess how the different CE perspectives are associated with each other, and what CE perspectives are most commonly assessed in combination. The analysis identifies main metric clusters, including gaps and potentials to integrate CE perspectives or complementary CE metrics. Thereby, the results provide guidance for the development of CE metrics, which has also been considered to develop the SEA method further.

In the second step, the SEA method is extended to the Multilevel SEA method that allows considering information on the product, component and material levels. The method is demonstrated on a case example of a simplified vehicle life cycle. The case example serves as a demonstrator to provide insights into how the method can identify critical stages of resource and functionality losses. Moreover, it demonstrates how different CE strategies, on their own or in combination, contribute to a system performance that can be measured as a distance to an ideal system state that preserves functionality on the highest level possible. Based on the results, a framework for resource effectiveness is derived in which diluting and concentrating effects of CE strategies are quantified and which allows to relate a variety of systems to a resource-effective system that maintains the product functionality over a maximum period of time, with minimal efforts that are measured in terms of changes of statistical entropy.

In the third step, the Multilevel SEA method is extended by a time dimension and is applied to a more complex case study of a generic European automotive system. For the consideration of the time dimension, the method is applied in combination with a stock-driven model and a material flow analysis (MFA). The case study demonstrates how the Multilevel SEA method can be employed to assess system transitions and scenarios, in this case, the transition towards a higher share of electric vehicles (EV) until the year 2050 while being employed in combination with different combinations of CE strategies. The consideration of the time dimension further allows assessing CE strategies that affect the lifetime of vehicles or the overall size of the vehicle stock. As a result of the case study, it is shown, among other things, how CE strategies and their different combinations can minimise the efforts in the transition to an increasing share of electric vehicles by 2050, thereby demonstrating how the refined method can contribute to the assessment and decision-making in the transition to a more circular economy.

Published articles and author's contributions

Results of the present doctoral thesis have also been published in (or submitted to) peer-reviewed scientific journals in the form of the following three articles:

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Author's contributions:

In all three papers, formal analysis, investigation, data curation, visualisation and writing – original draft preparation were undertaken by the author of the present thesis.

Conceptualisation, methodology development, validation and writing – review and editing were performed in cooperation with the respective co-authors.

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1. Motivation and Outline

Human development is fundamentally linked to the use of natural resources. During the 20th century, the global anthropogenic material stocks increased 23-fold (Krausmann et al., 2017), while the rate of resource consumption continuous rising (Streeck et al., 2020). For the time period between the years 2000 – 2010 resource use increased by around 20 billion tons annually, which is three times the rate of any previous decade between 1950 and 2000 (Duro et al., 2018). This expansion of the socio-economic system and the related extraction of resources comes at the cost of waste generation, emissions and other externalities leading global ecosystems to recede (e.g. Korhonen et al., 2018a). As a consequence, some critical planetary boundaries such as the level of atmospheric CO_2-concentration, biodiversity loss, ocean acidification are approached, indicating that the current system trajectory cannot be continued (Rockström et al., 2009; Steffen et al., 2015), without risking qualitative, sudden and possibly irreversible changes in the earth system (Wunderling et al., 2020). Therefore, it is apparent that the current system of production and consumption with its material throughput and quantities of waste and emissions cannot be sustained in the long term and the commonly applied strategy of system boundary expansion begins reaching its limits. Given this background, the European Union (EU) intends to make a transition towards a more circular economy (CE) (European Commision, 2015; European Commission, 2018a, 2019a, 2020), representing a system in which the value of products, parts, and materials is maintained over a maximum period of time (European Commision, 2015). The CE concept aims to reverse the logic of system boundary expansion by the preservation of value and functionality, employing CE strategies such as product reuse, repair, extension of product lifetime, component remanufacturing, and material recycling.

It is noteworthy, that many of the ideas related to the CE are not as novel as the recent framing around the CE might suggest (e.g., Saavedra et al., 2018). First signs appear as early as 1928 with W. Leontief's article on 'The Economy as a Circular Flow' in 1928 (Leontief, 1991). Further conceptualisations followed by Boulding (1966), formulating the idea of a `closed economy', that aims at maintaining capital stocks. Latest with the Stockholm Protocol (1972) when environmental ideas began percolating into various disciplines including engineering and economics, emerging research fields such as Industrial Ecology and Ecological Economics actively shaped the CE concept without necessarily referring to it as such (e.g. Frosch and Gallopoulos, 1989; Georgescu-Roegen, 1971; Pearce and Turner, 1990; Stahel and Reday-Mulvey, 1981). With the relatively recent formulation of the CE as a concept, it took a catalyst role in the resource management debate which, among others, can be observed from the number of related academic publications that increased from around 100 in the years between 2001 – 2008, to almost 5000 until the year 2020 (Calisto Friant et al., 2020).

The recent success of the CE concept can be related to external and its internal characteristics. Two external elements were especially helpful in establishing the CE concept. First, CE legislations such as the 'Closed Substance Cycle and Waste Management Act' in Germany (1996), the 'Recycling-Based-Society' in Japan (2002) (Heshmati, 2015), and the 'Circular Economy Promotion Law' of China (2005) (Smol et al., 2017; Wu et al., 2014), allowed the CE concept to enter institutions that helped its initial dissemination. Second, the active advocation of the CE concept by influential economic actors, e.g. Ellen MacArthur Foundation, (2013) and

McKinsey, (2016), who stressed its value proposition and its role as a new path to economic growth, established the concept in a wider policy and business community. On the other hand, internal characteristics provide the CE concept its function as an umbrella concept, representing a cognitive unit that appeals to a large and diverse group of actors (Blomsma and Brennan, 2017), while being perceived as intuitively positive, which results from its aim to maintain value and functionality, recirculate resources, and reduce waste and resource extraction (Harris et al., 2020). Being perceived as a potential solution to interconnected problems such as resource scarcity, waste management, and environmental pollution, while incorporating the goal of sustaining a viable economy, the transition towards a more CE is also pursued as a development strategy (Lieder and Rashid, 2016), explaining its support by the various economic actors and multilateral organisations, including the OECD, (2015) and the United Nations (e.g., UNIDO, 2017). With the high expectations that are communicated in terms of cost savings, higher disposable incomes, employment and profits (e.g. EMF, 2013; McKinsey, 2016), the transition towards a more CE provides an attractive and powerful narrative, that increasingly facilitates the mobilisation of resources, mainstreams policy and research agendas and is employed to coordinate action at various political levels (European Commission, 2019b).

In contrast, it should be noted that the wide use and application of the CE concept has been achieved despite the fact that it is still under debate (e.g. Kirchherr et al., 2017a; Prieto-Sandoval et al., 2018). Even more, the CE has been classified to be in a stage of its validity challenge, from which its full conceptual clarity has yet to emerge, as otherwise it might remain in contention or might finally collapse (Blomsma and Brennan, 2017). Given the lack of conceptual clarity, while being widely used and having the ability to mobilise vast resources, the CE concept is increasingly criticised of being deliberately vague, all-encompassing, and uncontroversial, while focusing on a multitude of win-win situations (Lazarevic and Valve, 2017), therefore being also referred to as an 'essentially contested concept' (Korhonen et al., 2018b).

In the light of the vast amounts of resources that are mobilised to undertake the CE transition (European Commission, 2019b), it is crucial to attain a more objective view on the CE implementation that facilitates a critical analysis of the concept's potentials and limitations. As the development towards a more CE will depend on the derived measures and the applied combinations of CE strategies, it is important to have well-designed and effective assessment methods that can monitor and guide the CE transition (Elia et al., 2017). Therefore, considerable efforts are undertaken to develop assessment methods and metrics (e.g. Corona et al., 2019; Elia et al., 2017; Iacovidou et al., 2017b; Moraga et al., 2019; Saidani et al., 2019). However, given the characteristics of the CE concept and the multitude of contexts it is applied, leads to a large variety of measurement approaches that do not necessarily contribute to a more generally accepted monitoring framework.

Given this situation, Chapter 2 provides a review of 63 CE metrics and evaluates the CE perspectives assessed. Employing the method of Multiple Correspondence Analysis (MCA), the 63 metrics are structured according to their relation to each other, as well as to their relation to the CE perspectives assessed. The assessment perspectives represent characteristics measured by the metrics and include recycling rates, the degree of material retention, longevity, and others. With 24 identified CE perspectives, the analysis provides insights on the most dominant assessment perspectives and how they relate to each other. Based on the results of the analysis, three main clusters of metrics (1) a resource-efficiency cluster, (2) a materials stocks and flows cluster, (3) a product-centric cluster are identified. Some assessment gaps, among others the poor integration of resource-efficiency and product-centric perspectives, the preservation of value and functionality and the predominantly independent macro-, meso- and micro-scale perspectives are identified. The assessment results are considered when extending the method of Statistical Entropy Analysis to a Multilevel SEA method.

With material flows and stocks being at the core of resource management, the method of Material Flow Analysis is employed as the basis for the assessment of CE systems. The strength of the MFA method is based on its systematic assessment of the flows and stocks of arbitrarily complex systems (Brunner and Rechberger, 2016). The result of a MFA is a visualisation of the system structure with its processes and quantified material flows and stocks that provide a comprehensive and systematic account of a physical system, thereby representing a valuable tool to support decision making (Brunner and Rechberger, 2016). The method has been applied to a variety of systems to assess the utilisation pattern of single substances (e.g. Saurat and Bringezu, 2009), goods (e.g. Steubing et al., 2010) or mixtures of substances (e.g. Nakajima et al., 2013) for a defined region and time, or for a time period (e.g. Müller, 2006; Pauliuk et al., 2012). These examples show that the MFA method is versatile, scalable and provides results that help evaluating metabolic production-consumption systems by identifying processes and flows for optimisation and decision making. Nevertheless, MFA results do not explicitly express or quantify the qualitative changes of material flows, so that together with the often inherent complexity of material flow systems, it can be difficult to relate the outcomes of an MFA to the goal of the CE.

In order to better assess the quality dimension of MFA results, and provide an evaluation perspective that allows quantifying the qualitative changes related to the dilution and concentration activities performed in a material flow system the method of SEA has been developed (Rechberger, 1999; Rechberger and Brunner, 2002). Calculated for each step of material transition, it evaluates systems regarding their potential to concentrate or dilute substances, so that a system process can either concentrate, dilute, or leave the substance distribution pattern unchanged (Rechberger, 1999; Rechberger and Brunner, 2002). Processes that concentrate a substance lead to a decrease in statistical entropy, while processes that dilute a substance lead to an increase in statistical entropy. Examples of processes that result in decreasing statistical entropy values are mining, refining, separate waste collection, mechanical sorting and recycling. Increases in statistical entropy values are related to dilution and mixing, e.g. when a substance is directed to a waste flow or to an environmental compartment. By quantifying the potential of each process to concentrate or dilute substances, SEA allows critical stages of dilution and concentration to be identified and the performance of different metabolic systems to be compared (Rechberger and Graedel, 2002).

Previous studies have shown that SEA is an insightful evaluation tool, applicable on various scales. The application cases include the European and Chinese copper cycles (Rechberger and Graedel, 2002; Yue et al., 2009), municipal solid waste incinerator technologies (Rechberger and Brunner, 2002), wastewater treatment plants (Sobańtka and Rechberger, 2013), a lead smelting process (Bai et al., 2015), battery recycling (Velázquez-Martinez et al., 2019a, 2019b), agricultural systems (Sobantka et al., 2012), the Austrian phosphorus and aluminium cycles (Laner et al., 2017; Rechberger and Laner, 2018), as well as a combined phosphorus-nitrogen cycle evaluation (Tanzer and Rechberger, 2020). Further, the continuous development of the SEA method led to the possibility to consider chemical compounds (Sobantka et al., 2012), and the inclusion of imports, exports and recycling loops (Laner et al., 2017). Using a modified statistical entropy function, the method was also applied for measuring the recyclability of e-waste (Zeng and Li, 2016), and mixtures of substances, resulting in the representation of statistical entropy evolution for each individual substance, while linking it to exergy analysis (Velázquez-Martinez et al., 2019). The latest application of the method has been performed to assess phosphorus use and related losses in a food-based bioethanol system (Wang et al., 2021). Despite these applications and methodological developments, the focus of SEA remains on the individual substance level, including the consideration of elements and compounds. However, the CE represents a system where a large diversity of CE strategies is applied and includes, besides material-based strategies (e.g. recycling), also component-based strategies (e.g. remanufacturing), and strategies that are applied on the product level (e.g. reuse). In this regard, evaluating a diverse set of CE strategies and their combinations remains a challenge (e.g. Lieder et al., 2017; Reike et al., 2018).

Given this background, Chapter 3 extends the SEA method to a Multilevel SEA method and demonstrates it on a simple case example of a vehicle life cycle. As the Multilevel SEA method allows expressing compositional changes for material flows, components and products, it also allows to define a reference state that delivers the highest functionality and avoids resource losses, thereby being directly related to the goal of the CE. This characteristic of the method allows measuring the system performance to a defined system state that preserves functionality on the highest level possible, so that single CE strategies, their combination, or the performance of an entire system, can be assessed by measuring the distance to the ideal (or otherwise defined) system state. By measuring the distance to a target state, independently of the means by which the state is achieved, the method represents an effectiveness assessment, that can be considered complementary to established and highly mature efficiency-based methods such as Life Cycle Assessment (LCA) (ISO, 2006), or Cost-Benefit-Analysis (CBA) (e.g. Hoogmartens et al., 2014).

Moreover, with changes of statistical entropy being present from stages of mining and resource extraction to stages of End-of-Life (EoL) treatment, the dilution and concentration activities performed in the system require some form of effort that can be delivered through manual labour, energy and other additional inputs. By measuring the effort in terms of changes in statistical entropy performed in a system, it is not distinguished by which means or how the effort is delivered. Instead, once a functional system state is reached (e.g. functional product), the absence of changes in statistical entropy not only indicates the preservation of functionality, but also the absence of effort required to produce or restore the functionality. The state that delivers the highest functionality, with minimal efforts is referred to as a state of ‘resource effectiveness’, and allows distinguishing a large range of systems, located between systems that, e.g. produce short cycles of production and destruction, from systems that preserve functionality.

By extending the method by the consideration of the time dimension, Chapter 5 demonstrates how additional CE strategies such as lifetime extension and changes in product and material stocks can be evaluated. Moreover, the consideration of time does not only allow assessing the overall dynamics of resource use (e.g. Müller et al., 2014) but also provides insights on the temporal effects of CE strategies and their combinations. Employing a set of scenarios that model the transition of a generic European vehicle stock from internal combustion engine vehicles (ICEVs) to higher shares of electric vehicles (EVs) until the year 2050, while employing additional CE strategies, it is demonstrated how the Multilevel SEA method can be applied in a time-dynamic context. Thereby, different effects, such as the influence of higher recycling rates, higher rates of component reuse, lifetime extension of vehicles and a higher intensity of vehicle use through shared use of vehicles are demonstrated.

Finally, Chapter 5 reflects on the results, providing a conclusion and outlook for further research.

2. Measuring the circular economy – A Multiple Correspondence Analysis of 63 metrics

2.1 The relevance of circular economy metrics

Large efforts are undertaken to make the transition from a linear economy towards a more circular economy. The continuous search for more suitable metrics for the CE indicates that present measurements of resource productivity and resource efficiency are not fully satisfactory in the CE context. In fact, the often proclaimed goal of resource efficiency, most frequently understood as producing more output from less input, misses the main goal of the CE, which is to maintain the value of products, parts, and materials over a maximum period of time (European Commisssion, 2015). Therefore, pure resource efficiency metrics do not necessarily track progress to a more circular economy, because their main aim is not the cyclic use of materials and products, but a reduced resource consumption (Bocken et al., 2016). Moreover, it is common practice to study only certain aspects of the socio-economic metabolism such as waste disposal and recycling efficiency, even though the CE concept requires inherently a systems perspective (Pauliuk, 2018). Given the complexity of the CE transition, the corresponding research landscape has been characterised as fragmented and granular (Lieder and Rashid, 2016; Ranta et al., 2017; Rizos et al., 2017). Therefore, more recent research attains to systematise CE thinking and knowledge compilation through the framing of CE thinking around the prolonging of resource productivity and thereby facilitate collective action (Blomsma and Brennan, 2017).

In this context, metrics are highly relevant for the development of a concept, as the measured features also shape the thinking and language within the concept and influence its development. Therefore, metrics can promote particular aspects of the concept. The examples from the longer established sustainability discourse can provide insights on the importance of metric developments (Azapagic and Perdan, 2000; Valenzuela-Venegas et al., 2016). In this regard, the following chapters identify the key features of CE metrics through a literature review and characterise the literature with respect to the identified features. The structure of the metrics, their relation to each other, and towards their assessed features, are evaluated by employing the method of Multiple Correspondence Analysis (MCA). Thereby, the focus of CE metrics, including the potential assessment gaps can be identified.

2.2 Literature review and identification of circular economy features and metrics

In the following, it is referred to a metric as a quantitative measure of a phenomenon. It allows considering the broad field of CE assessments, including indicators, scoreboards, assessment tools, and more. The identification of CE metrics started with the search of literature reviews on the circular economy via Web of Science and Google Scholar, using different combinations of search words such as ‘review’ and ‘circular economy’. Based on that search, the reviews of Lieder and Rashid, (2016), Ghisellini et al., (2016), Geissdoerfer et al., (2017), Elia et al., (2017) and Linder et al., (2017) were identified and used for a first literature identification. Further, the studies and reports on the CE by Milios, (2016) and Rizos et al., (2017), Saidani et al., (2017) and European Academies Science Advisory Council, (2016) were taken into account.

Additional literature was searched for through the same search platforms, using the keyword 'circular economy', with filtering options for 'metric', 'assessment', 'tool' and 'indicator'. The search categories included environment, economics, materials, engineering and other 27 categories. Also, less technical categories such as social science, geography, urban and interdisciplinary studies were included. Finally, an additional Scopus search was performed to include more recent publications for the time period between 2015 and May 2018[1]. Included subject areas were environment, economics, social science, engineering, business and management, material, decision, and multidisciplinary science. Based on titles and abstracts, the search results were manually filtered. Important selection criteria were terms such as 'analysis', 'assessment' and similar expressions that indicated a potential measurement of a single aspect or a set of aspects within the CE. On the other hand, studies that derive general guiding principles for the CE, cover educational topics, business models or focus on the development of technologies were excluded from further analysis. Given the framing of various resource-life extending strategies around the CE concept (Blomsma and Brennan, 2017), publications on metrics with different framing and scope, representing broad sustainability assessments, like environmental footprint studies, are excluded after additional analysis. Additional known articles identified as relevant for this analysis are Dahmus and Gutowski, (2007), Nelen et al., (2014), Stahel and Clift, (2016), Figge et al., (2018) and the Cradle to Cradle certified product standard MBDC, (2012). In total, the review results in 63 CE metrics, which are included in the assessment.

The identified literature is used to derive the key features of the CE (from here on 'CE elements') that can be quantified by using these metrics. The step of CE element identification is required as there is no detailed catalogue of CE elements which could be readily used to measure the different characteristics of the CE. Therefore, the CE elements are derived, being instrumental for the subsequent analysis. By using the derived set of CE elements, it is acknowledged that the precise meaning and distinction of some CE element terms are indeed context-dependent and have been defined differently by other authors. Examples for definitions under debate are cascading and downcycling, while assessments of these categories are already presented (Blomsma and Brennan, 2017).

For the identification of CE elements, an iterative process is followed, which consists of a metric description, identification of core characteristics assessed, and the noting down of the core element that is being measured. Each time a new element is identified, it is regarded as a category. Where possible, additional sources of element definitions are taken into account to make a cross-reference to more commonly established understandings. To be able to follow the derivation of each CE element's meaning, a subset of codes used to define the CE elements is provided (Table 1 and Table 2). This proceeding can be referred to as emergent coding or inductive content analysis (Saldana, 2012), which has been used in the CE context to derive core dimensions of CE definitions (Kirchherr et al., 2017b). Such an approach is also used in other disciplines and is recommended if knowledge about a research field is fragmented (Elo

[1] As this chapter represents the results of the first paper that has been published in the year 2019, additional and more recent literature is taken into account by reflecting on the findings in relation to reviews on CE metrics that have been published more recently, presented in Chapter 2.5.

and Kyngäs, 2008). A similar identification of main topics in a literature review has also been undertaken for resource efficiency by other authors such as Tecchio et al., (2017).

Another reason for choosing this approach is to avoid the risk of restricting or narrowing the perspective beforehand and potentially leaving some CE elements unrecognised. Employing this approach, each additional occurrence of a similar CE element tends to broaden the existing element's perspective, which might lead to more inclusive element categories, compared to the perspective within a specific metric. Nevertheless, the generalised description must still apply to all sources in which the element was identified. In the light of the large number and diversity of elements, this trade-off and the subsequent generalisation is regarded as a smaller deficiency. It must be stressed that the employed element definitions represent only one possible perspective, which is instrumental for the exploration of relations between the elements and metrics. CE metrics identified in the literature review, but lacking a clear empiric application or case study, could not be classified along the emergent element categories and were omitted from further analysis. A table with not considered metrics is provided in the supplementary information (SI 1).

Table 1: Exemplary display of a subset of codes for 1-12 CE elements, used to identify and categorise CE elements.

CE Element	Examples of codes used for identifying and categorising CE elements	Source
Waste disposal	Material flows directed to 'municipal solid waste [or] municipal solid waste incineration', 'amount of waste generated'	Haupt et al., (2016); Subramoniam et al., (2009)
Primary vs. secondary materials, parts and products	'DFi = substitution factor for different waste management systems based on their virgin material replacement efficiency'; 'direct material input (DMI)' vs. 'reutilised material (RU)'	(Li et al., 2013; Zaman and Lehmann, 2013)
Resource productivity or process efficiency	'resource productivity for EU28 has improved from 1.52 EUR/kg in 2002 to 1.95 EUR/kg in 2014', phosphorus (P) resource efficiency in US dollar per tonne, 'P utilisation efficiency was 81.1%'; 'amount of emissions (CO2, water, sewage) per one regenerated core (product)'	(European Commisssion, 2015; Golinska et al., 2014; Ma et al., 2015)
Recycling efficiency	'recycling rate of municipal waste', 'recycling as share of EoL waste'	(European Commisssion, 2015; Haas et al., 2015)
Energy consideration	'energy consumption per added industrial production value'; 'energy identification – presence of bill of energy'	(Cayzer et al., 2017; Geng et al., 2008)
Potential for recycling or remanufacturing	'quantity of material per product', quantification of waste flows: 'Waste etching solution (120 tonnes), waste copper foil (65.30 tonnes)'	(Asif et al., 2015; Wen and Meng, 2015)
Spatial dimension	'EU resource efficiency'; '[assessment of] efficiency of [the] regional circular economy in China [based on] decision making units (DMUs), 'each of which represents	(Dewulf et al., 2007; European Commisssion,

	an administrative region of China'; 'exergy values are weighed by the shares of the different countries in the European gas consumption'	2015; Wu et al., 2014)
Destination of flows	waste flows are quantified based on the following process destinations: 'Recycling, composting, landfilling'; 'matrix, representing the transient states' includes direction of transition; MFA shows destination of each flow in the system	(Haupt et al., 2016; Veenstra et al., 2010; Zaman and Lehmann, 2013)
Stock availability or concentration	'technology stocks [...] are further disaggregated into technology structures'; '18 million metric tons of waste' with specific composition, e.g. 'almost 6.3 million tons (as-received) is industrial waste such as shredder material from the car industry, metallurgical slags'	(Busch et al., 2014; Jones et al., 2013)
Additional process inputs	'fresh water consumption', water as direct material input 'DMI-water', 'liquid [ammonia, and sulfuric acid] as additional inputs into phosphorus products production'	(Ma et al., 2014; Wen and Meng, 2015)
Reuse, remanufacturing, recycling complexity	Swiss system is modelled through more than 28 processes and more than 100 flows (MFA system), '25 valorisation (utilisation) categories, including plastics, metals, glass, textiles, organics, sludge, slags, sand, etc.' , evaluation of calorific values of each fraction, and recycling options, while assessing challenges, e.g. 'main challenge is the control of tar and the production of a high quality slag.'	(Haupt et al., 2016; Jones et al., 2013)
Product, part and material retention	'fraction of mass of a product's feedstock from recycled sources'; 'fraction of a product that comes from used products'	(Ellen MacArthur Foundation, 2015; Linder et al., 2017)

Note: The exemplary codes provide an insight of how the categorisation as well as the derivation, based on a multitude of perspectives has been performed. The complete categorisation can be found in the supplementary information (Metrics categorisations with the provision of code example).

Table 2: Exemplary display of a subset of codes for 13-24 CE elements, used to identify and categorise CE elements.

CE Element	Examples of codes used for identifying and categorising CE elements	Source
Value change or productive use	'total economic benefit increases from US$235.3 million to US$638.2 million, to US$771.5 million from the status quo to scenario 2, and to scenario 4 [under different resource reutilisation options]'; 'utility of a product'; 'actual average number of functional units achieved during the use phase of a product'	(Ellen MacArthur Foundation, 2015; Ma et al., 2014; Park and Chertow, 2014)
Cascading use	Evaluation of a secondary resource over utilisation categories in other sector applications: fly ash to be used as 'road base', 'waste stabilisation', 'mining applications', etc.; 'waste reutilisation's profit based on the Emergy accounting', flows of materials are reutilised in the industrial park system at different processes	(Geng et al., 2010; Park and Chertow, 2014)

Modelling of material cycles	'Enterprise dynamics under influence of material scarcity', model includes multiple cycles such as 'material consumption rate, [...] material recovery ratio', etc.; MFA used to model 'closed-loop' and 'open-loop' recycling	(Asif et al., 2015; Haupt et al., 2016)
Downcycling and quality loss	'current market price of output fraction [vs] current market price of material [used as input]'; remanufactured, maintained, recycled products are categorised according to their change in value	(Nelen et al., 2014; Singh and Ordonez, 2016)
Longevity or residence time	'Overall longevity is therefore calculated as the sum of initial lifetime of the product, refurbished lifetime contribution and recycled lifetime contribution'; 'average lifetime of a product'	(Ellen MacArthur Foundation, 2015; Franklin-Johnson et al., 2016)
Sharing or utilisation of resource streams	'RU indicates the material reutilised in productive activities that consists of two flows: agricultural reutilisation (ARU) and industrial reutilisation (IRU), RU = ARU + IRU'; 'second indicator is the comprehensive utilisation level of materials such as coke oven gas, blast furnace gas, […, etc.]' in other sectors, e.g. 'blast furnace slag was being reused in the cement industry'	(Li et al., 2013; Ma et al., 2014)
Recycled material value	'current market price of output fraction'; 'waste reutilisation's profit, based on the emergy accounting'	(Geng et al., 2010; Nelen et al., 2014)
System stability	'the high estimate scenario results in […] 160% […] for lithium […] of world production [to serve UK demand in 2030]'; 'enterprise dynamics under the influence of material scarcity' are modelled, 'delay in material supply, […] gap in manufacturing, […]' are modelled	(Asif et al., 2015; Busch et al., 2014)
Materials mixing	'H as a measure of material mixing', […] n_i is the number of separation steps necessary to isolate material I', 'material mixing' (as separate axis in result plot); 'is the product separated out from other products at the end of its life?'	(Cayzer et al., 2017; Dahmus and Gutowski, 2007)
Supply risk and scarcity of resources	'recovery of scarce materials' and 'SR: supply risk of the material' as separate indicator; 'import dependence for selected raw materials', 'geographical concentration [of resources] and governance (as sub-chapter)'	(European Commission, 2016; Nelen et al., 2014)
Embedded stocks or distinct lifetimes	'technologies and their components are explicitly included with their own dynamic stocks and flows', 'embedded inflow [of materials]', use of 'stock and flow diagram[s]' together with 'time to exhaust material reserve'	(Asif et al., 2015; Busch et al., 2014)
Toxicity and clean material cycles	'toxic materials in product'	(Geng et al., 2008)

The assessed metrics are presented in (Table 3 and Table 4). For all considered metrics a short abbreviation and name is provided. The abbreviations are used in the subsequent figures. There are cases where the authors do not provide a name for their assessment method. In such cases a name is proposed and presented along with the corresponding abbreviation to allow for better referencing.

Table 3: Identified and assessed circular economy metrics and approaches (1-33).

	Name	Abbreviation	Authors	Title
1	Information theory based model for product recycling	ITPR	Dahmus and Gutowski, (2007)	What Gets Recycled: An Information Theory Based Model for Product Recycling
2	Cumulative exergy extraction from the natural environment	CEENE	Dewulf et al., (2007)	Cumulative exergy extraction from the natural environment (CEENE): A comprehensive life cycle impact assessment method for resource accounting
3	Indicator standards for sector-integrated eco-industrial parks	EIP-INDICATOR-SET	Geng et al., (2008)	Assessment of the national eco-industrial park standard for promoting industrial symbiosis in China
4	Remanufacturing for the automotive aftermarket-strategic factors framework	Reman-SF	Subramoniam et al., (2009)	Remanufacturing for the automotive aftermarket-strategic factors: literature review and future research needs
5	Emergy analysis of an industrial park	Emergy	Geng et al., (2010)	Emergy analysis of an industrial park: The case of Dalian, China
6	Multidimensional, multilevel business value framework	MD-business-value	Park et al., (2010)	Creating integrated business and environmental value within the context of China ' s circular economy and ecological modernisation
7	Markov-chain model for WEEE in China	Markov-chain	Veenstra et al., (2010)	An analysis of E-waste flows in China
8	Multi-scale integrated analysis of societal metabolism	MSIASM	Geng et al., (2011)	Regional societal and ecosystem metabolism analysis in China: A multi-scale integrated analysis of societal metabolism (MSIASM) approach
9	Sustainable supply chain networks	SSCN	Winkler, (2011)	Closed-loop production systems-A sustainable supply chain approach
10	Circular economy indicator system of China	CEIS	Geng et al., (2012)	Towards a national circular economy indicator system in China: An evaluation and critical analysis
11	Evaluation index system on the development level of circular economy in chemical enterprises	CE-enterprise-index	Wang et al., (2015)	Evaluation of the circular economy development level of Chinese chemical enterprises
12	Industrial symbiosis life-cycle-assessment	IS-LCA	Mattila et al., (2012)	Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbioses
13	Cradle to Cradle Certified Product Standard	C2C	MBDC, (2012)	Cradle to Cradle Certified Product Standard – Version 3.0

14	Circular economy toolkit	CET	Evans and Bocken, (2013)	Circular Economy Toolkit
15	Holistic evaluation of enhanced landfill mining	HE-ELFM	Jones et al., (2013)	Enhanced Landfill Mining in view of multiple resource recovery: A critical review
16	Reutilisation-extended economy wide MFA	RE-EW-MFA	Li et al., (2013)	Reutilisation-extended material flows and circular economy in China
17	Zero-waste-index	ZWI	Zaman and Lehmann, (2013)	The zero waste index: A performance measurement tool for waste management systems in a ‘zero waste city’
18	Technology-specific stocks and flows model	TSSFM	Busch et al., (2014)	Managing critical materials with a technology-specific stocks and flows model
19	Grey decision making tool for evaluation of remanufacturing companies	GDM-reman	Golinska et al., (2014)	Grey Decision Making as a tool for the classification of the sustainability level of remanufacturing companies
20	Circular economy efficiency composite index	CEECI	Ma et al., (2014)	Mode of circular economy in China’s iron and steel industry: A case study in Wu’an city
21	Multi-dimensional indicator set on the benefits of WEEE material recycling	Recycling-indicator-set	Nelen et al., (2014)	A multidimensional indicator set to assess the benefits of WEEE material recycling
22	Reuse potential indicator	RP-indicator	Park and Chertow, (2014)	Establishing and testing the ‘reuse potential’ indicator for managing wastes as resources
23	Circular economy policy data envelopment analysis	CE-DEA	Wu et al., (2014)	Effectiveness of the policy of circular economy in China: A DEA-based analysis for the period of 11th five-year-plan
24	System dynamics model of product multiple life cycles	Dynamic-PML	Asif et al., (2015)	System dynamics models for decision making in product multiple life cycles
25	Vector angle and Euclid. distance for evaluation of coordination and effectiveness of reg. development strategies	VA-ED	Chen et al., (2015)	Assessment of sustainable development: A case study of Wuhan as a pilot city in China
26	Resource efficiency scoreboard	RES	European Commisssion, (2015)	EU Resource Efficiency Scoreboard

27	Circularity indicator	EMF	Ellen MacArthur Foundation, (2015)	Circularity Indicator (Methodology)
28	Economy-wide-MFA	EW-MFA	Haas et al., (2015)	How circular is the global economy? An assessment of material flows, waste production, and recycling in the European union and the world in 2005
29	Resource and eco-efficiency of resource based firms	REERF	Ma et al., (2015)	A case study of a phosphorus chemical firm's application of resource efficiency and eco-efficiency in industrial metabolism under circular economy
30	Industrial symbiosis resource productivity indicator	IS-RP-indicator	Wen and Meng, (2015)	Quantitative assessment of industrial symbiosis for the promotion of circular economy: A case study of the printed circuit boards industry in China's Suzhou New District
31	Dynamic Substance flow analysis	DYNAMIC-SFA	Zhang et al., (2015)	The future of copper in China - A perspective based on analysis of copper flows and stocks
32	Product design and business model strategies model	CE-Strategy-Model	Bocken et al., (2016)	Product design and business model strategies for a circular economy
33	Circular economy indicator prototype	CEIP	Cayzer et al., (2016)	Design of indicators for measuring product performance in the circular economy

Table 4: Identified and assessed circular economy metrics and approaches (34-63).

	Name	Abbreviation	Authors	Title
34	Raw materials scoreboard	RMS	European Commission, (2016)	Raw Materials Scoreboard - European Innovation Partnership on Raw Materials
35	Longevity-Indicator	Longevity-I	Franklin-Johnson et al., (2016)	Resource duration as a managerial indicator for Circular Economy performance
36	Recycling and collection rates	RRs	Haupt et al., (2016)	Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System
37	Toxics concentration in plastic materials cycles	TOXICS-CYC	Leslie et al., (2016)	Propelling plastics into the circular economy - weeding out the toxics first
38	Agri-food input-output analysis	AGRI-FOOD-IO	Pagotto and Halog, (2016)	Towards a Circular Economy in Australian Agri-food Industry: An Application of Input-Output Oriented

				Approaches for Analysing Resource Efficiency and Competitiveness Potential
39	LCA-based eco-cost value ratio	LCA-EVR	Scheepens et al., (2016)	Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable
40	Product resource recovery routes	Product-RRR	Singh and Ordonez, (2016)	Resource recovery from post-consumer waste: important lessons for the upcoming circular economy
41	Performance economy metric	PERFORM-ECON-M	Stahel and Clift, (2016)	Stocks and Flows in the Performance Economy, from book: Taking Stock of Industrial Ecology
42	Material recycling index	MATERIAL-RI	Van Schaik and Reuter, (2016)	Recycling Indices Visualising the Performance of the Circular Economy
43	Sustainable Circular Index	SCI	Azevedo et al., (2017)	Proposal of a Sustainable Circular Index for Manufacturing Companies
44	Food waste life cycle inventory	FW-LCI	Edwards et al., (2017)	Life cycle inventory and mass-balance of municipal food waste management systems: Decision support methods beyond the waste hierarchy
45	End of use value recovery plan	EOU-VR	Cong et al., (2017)	Value recovery from end-of-use products facilitated by automated dismantling planning
46	Economic-Environmental Indicators to Support Investment Decisions	ECOENV-INVEST-I	Fregonara et al., (2017)	Economic-Environmental Indicators to Support Investment Decisions: A Focus on the Buildings' End-of-Life Stage
47	Regional environmental Input-Output Analysis	REG-ENV-IO	Genovese et al., (2017)	Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications
48	Adjusted raw material consumption	ARMC	Hu et al., (2017)	Assessing resource productivity for industrial parks using adjusted raw material consumption
49	Circular economy performance indicator	CE-PERFORM-I	Huysman et al., (2017)	Performance indicators for a circular economy: A case study on post-industrial plastic waste
50	Global socioeconomic material stocks model	GLOBAL-MAT-STOCKS-MODEL	Krausmann et al., (2017)	Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use
51	Statistical Entropy Analysis	SEA	Laner et al., (2017)	Statistical entropy analysis to evaluate resource efficiency: Phosphorus use in Austria

52	Mining-MFA-indicators	MINING-MFA-I	Lèbre et al., (2017)	The Role of the Mining Industry in a Circular Economy: A Framework for Resource Management at the Mine Site Level
53	Product-level-circularity-metric	PCM	Linder et al., (2017)	A Metric for Quantifying Product-Level Circularity
54	MaTrace model	MATRACE	Pauliuk et al., (2017)	Regional distribution and losses of end-of-life steel throughout multiple product life cycles -Insights from the global multiregional MaTrace model
55	End-of-life Eco-efficiency analysis	EOL-ECO-EFFICIENCY	Richa et al., (2017)	Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy
56	Continuous MFA for Building Materials	C-MFA	Schiller et al., (2017)	Continuous Material Flow Analysis Approach for Bulk Nonmetallic Mineral Building Materials Applied to the German Building Sector
57	Eco-environmental remanufacturing	ECOENV-REMAN-MODEL	Van Loon and Van Wassenhove, (2017)	Assessing the economic and environmental impact of remanufacturing: a decision support tool for OEM suppliers
58	Ease of Disassembly Metric	EDIM	Vanegas et al., (2018)	Ease of disassembly of products to support circular economy strategies
59	Building-information-modelling-based Whole-life Performance Estimator	BWPE	Akanbi et al., (2018)	Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator
60	Product Ecosystem Material Flow Analysis	PRODUCT-ECOSYS-MFA	Kasulaitis et al., (2018)	Dematerialisation and the Circular Economy Consumer: Comparing Strategies to Reduce Material Impacts of the Consumer Electronic Product Ecosystem
61	Potential value capture from resources embedded in waste	WASTE-VALUE	Overgaard et al., (2018)	Capturing uncaptured values — A Danish case study on municipal preparation for reuse and recycling of waste
62	Copper demand regression and stock dynamics	ESTM-STOCK-DYNAMICS	Schipper et al., (2018)	Estimating global copper demand until 2100 with regression and stock dynamics
63	Longevity and Circularity Indicators	LONGEVITY-CIRCULA-RITY-I	Figge et al., (2018)	Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy

Employing the identified CE metrics and elements, the next step is the creation of a categorisation matrix, in which each metric is classified along the total variable space through binary variables. Such an approach is particularly useful if many objects and attributes have to be measured (Hoffmann and Franke, 1986). The categorisation matrix is created based on the metric classifications presented in (SI 2). The multivariate method of Multiple Correspondence Analysis (MCA) was selected as the most suitable method both, for dealing adequately with the diversity of metrics and elements, and for providing a structuring framework that facilitates visual interpretation.

2.3 Multiple Correspondence Analysis of assessed CE elements and metrics

Correspondence Analysis is an established method within the family of multivariate data analysis methods, which first appeared in the 1960s (Blasius, 2001; Le Roux and Rouanet, 2010). It represents an exploratory method for graphical representation of associations between variables of large categorical data sets in order to explore their relationships (Clausen, 1998). In the present context of the assessment of CE metrics, it is used to structure the complex set of element categorisations which describe the CE metrics. The goal of Correspondence Analysis is to obtain a graphical representation of the original data matrix within as few dimensions as possible (Hoffmann and Franke, 1986). It is referred to as Multiple Correspondence Analysis (MCA) if the effect of each variable on every other variable is considered (Blasius, 2001). Based on each of the 24 identified CE elements, these are presented in more detail (Table 5), while the metrics are structured, allowing for a visualisation of their associations.

The questions that are explored with the help of the graphical representation of the MCA results are the following:

1. Which metrics correspond with each other, being similar in their overall CE element perspective?

2. Which CE elements are more closely related to each other?

3. What overall patterns can be identified?

4. Which CE elements oppose each other, as they are rarely integrated in the same CE metric?

5. Which CE elements contribute more to the differentiation between metrics?

6. Which CE metrics are located further away from the average metric?

7. Around which CE element combinations are the lowest metric densities and where are metric and element agglomerations located?

To answer these questions, a $I \times Q$ matrix, of I assessed CE metrics and Q identified CE elements is constructed before the MCA method can be applied. Each entry reflects the presence (Y=Yes) or absence (N=No) of a CE element in columns for each metric in rows. For the analysis of the resulting matrix, the MCA algorithm provided by Husson et al., (2010) is applied, employing the open-source statistical software R[2]. The calculation algorithm is also recommended by Le Roux and Rouanet, (2010). The calculation is performed for the first four principal components, which is regarded as sufficient since no changes were observed when considering a higher

[2] FactoMineR and mdatools (21.03.2018), online available under https://www.r-project.org/

number. Principal components can be understood as the latent or projected axes, which are constructed in such a way that the largest data variance is explained. In the background, the construction of principal component axes is based on the Single Value Decomposition technique, which is introduced in detail by Blasius, (2001) and Le Roux and Rouanet, (2010).

The advantages of the method are the non-specific data requirements, making the method applicable to essentially any matrix of categorical data, with the only requirement that data should not be negative (Clausen, 1998; Hoffmann and Franke, 1986). Each difference in categorisation results in the partition of data points (Le Roux and Rouanet, 2010). In this case, data points represent the projected CE metrics, while category points represent the projected CE elements. Therefore, the resulting scatter plot enables an intuitive and visual interpretation (Greenacre, 2017), based on the distances between both CE metrics and elements.

Applying the interpretation rules by Le Roux and Rouanet, (2010) and Blasius, (2001), the main properties for interpretation are explained and visualised through a simple example (Figure 1).

First of all, the distance between two metrics shows how different or similar the metrics are. The closer the metrics are located to each other, the more similar is their categorisation pattern. In the example plot, metrics *a* and *e* share the same coordinates, which means that they fully correspond in their assessment of CE elements, as they only assess the CE elements 1 and 3.

The centre of the plot represents the average metric. Therefore, the distance of a metric to the centre is another important property for interpretation. In the example plot, metric *b* combines the CE elements 1 and 4, which are most frequently assessed. The higher frequency of their assessment is also the reason for their more central location.

The frequency of a CE element influences also the weight a CE element has when determining the location of a metric. Unique categorisation patterns result in a metric's location being further away from the centre. In the example plot, the CE element 1 has a smaller influence on the location of metrics *a* and *e*, as it is also assessed by other metrics such as metrics *b* and *d*. The example shows that differentiating CE elements have a higher influence on the location of a metric.

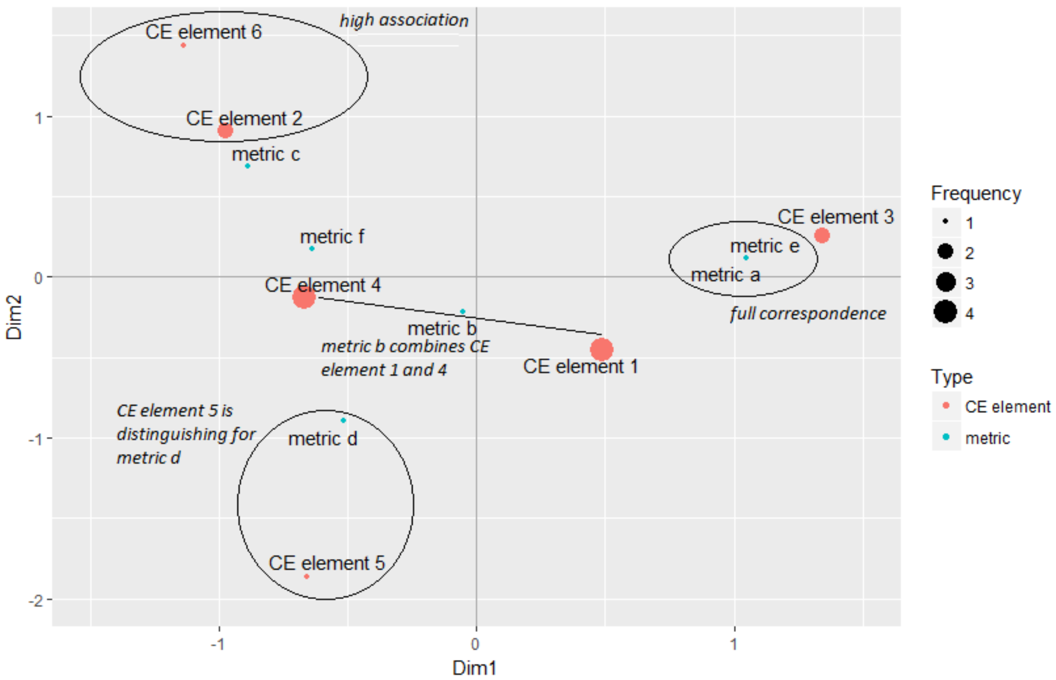

Figure 1: Simple MCA example for demonstrating the intuition behind the interpretation of MCA results.[3]

The relative positions of CE elements to each other reveal the degree of association. Stronger association is indicated by higher proximity, as it is the case of CE element 2 and 6, meaning that the CE elements appear more frequently together. A larger distance between CE elements means that they are usually not assessed by the same metric simultaneously, e.g. CE elements 3, 5 and 6. Further, it is shown that CE elements which appear less frequently within the overall set of metrics are located further away from the centre of the plot.

The principles introduced above are meant to facilitate the interpretation of the most important aspects of the resulting MCA plots in Section 2.4. For more detailed interpretation guidelines, it is referred to the supplementary information (SI 5) or Le Roux and Rouanet, (2010) and Blasius, (2001).

2.4 The relation between circular economy elements and metrics

Given the lack of a well-defined, broadly agreed definition of the scope of the CE and the diverse sub-fields within the CE, e.g. industrial symbiosis and remanufacturing, it requires a more flexible CE element and metric system. Therefore, the performed derivation of CE elements has to be viewed in the context of the diversity of CE perspectives and applications. In this context, the CE elements are considered instrumental for the analysis, pointing out that the results of the MCA are to be viewed only in relation to specific CE elements derived.

The identified CE elements and their descriptions are provided in a separate table, including the proposed name of the CE element, the abbreviation used in the MCA results and a short characterisation of each element (Table 5). The frequency of each element is also provided and

[3] Note: Circles, text in italics and line between CE element 1 and 4 are inserted afterwards The factor map has been produced with the MCA algorithm provided within the FactoMiner package for R by Husson et al., (2010) and re-projected using ggplot2- package.

might already indicate some assessment priorities of the 63 CE metrics. In order to deal with possible and probable overlaps in the CE elements' characterisations, the application of the MCA method is particularly useful for recognising and displaying the similarities of perspectives.

The results of the Multiple Correspondence Analysis reveal that the first two dimensions explain 27.15% of the total data variance, taking into account each of the CE element's influence on each metric's location simultaneously, which is a distinguishing quality of the MCA method that provides a high information density of the resulting plot. The influence of each CE element on the overall location of CE metrics in the plot is determined by the relative contribution of that particular CE element to the construction of the principal component axes, which is provided in the supplementary information (SI 3), while additionally the contributions of CE metrics on the principal component axes are provided in the supplementary information (SI 4). The identified and plotted CE elements show a good degree of scattering, which is an indication of the quality of element category choice, since the choice of element categories with a high similarity would result in a few aggregated groups of CE elements. In this case, the CE elements are well distributed, which allows an interpretation of the distances between CE elements and metrics[4]. Applying the interpretation rules, which have been introduced further above (Section 2.3) and are provided in more detail in the supplementary information (SI 5), the MCA results, the identified patterns and clusters are discussed in more detail.

Table 5: Identified circular economy elements.

	CE Element	Abbreviation	Freq.	Characterisation
1	Waste disposal	Waste disposal	44	This element is present if waste is specifically taken into account
2	Primary vs. secondary materials, parts and products	Primary vs. secondary use	43	This element is present if recycled, refurbished, and reused materials, parts and products are considered or evaluated in respect to primary materials, parts and products
3	Resource productivity or process efficiency	Resource efficiency productivity	43	Resource productivity is the relation between a monetary value produced and a unit of raw material used to produce the monetary value (Rizos et al., 2017). Process efficiency measures a similar relation, but instead of monetary units it employs the relation of resource inputs and intended outputs. The amount of undesired outputs, e.g. emissions, in relation to the amount of desired product output is also considered as a measure of resource efficiency
4	Recycling efficiency	Recycling efficiency	40	Recycling efficiency is defined broadly, taking into account the end-of-life material collection rate, the recycling process efficiency, and overall reutilised material flow
5	Energy consideration	Energy	36	This element is present if energy is specifically taken into account within the metric. Energy is considered

[4] The absence of any CE element data points at the bottom left part of the plot means that the selected metrics do not cover most of the CE elements included in the analysis.

				as an inclusive term for different forms and qualities of energy which are not further distinguished
6	Potential for recycling or remanufacturing	Recycling reman potential	32	This element is addressed, if stocks, flows or qualities of materials, parts or products are considered, with the aim of being reintroduced into the production and consumption system
7	Spatial dimension	Spatial	28	The spatial dimension is present, if differences in geographical location play a role in the consideration, or if the application involves the consideration of territorial units
8	Destination of flows	Flow destination	24	Destination of material, part or product flows is specified or assessed through the metric, because it is considered important where the flows are directed to (e.g. direction of a material flow is specified by a process description, flow diagram, MFA, or similar)
9	Stock availability or concentration	Stock availability concentration	23	This element is present if material stock is viewed within the perspective of future utilisation. Accounting for concentrations of products/parts/materials, or overall amount within a system is regarded as a determining factor to assess potential utilisation
10	Additional process inputs	Additional inputs	22	Additional process inputs are considered in the evaluation and enable processes to run. Examples are additional materials which are not present in the functional unit analysed, but can be also energy, labour, information and others
11	Reuse, remanufacturing, recycling complexity	Reuse reman complexity	21	This element is present if an integrated perspective is taken, which considers limitation factors, barriers, framework conditions, which can be stochastic product returns, which limit remanufacturing or the presence of a recycling system for a specific material, even though the material is introduced into the recycling system
12	Product, part, material retention	Retention	19	Retention is associated with products, parts or material being kept within the production and consumption system and can be expressed in time units or as product/part/material fraction from retained product/part/material (e.g. recycled content)
13	Value change or productive use	Value change	18	Value change can involve a reduction, maintenance or increase of material, part or product value, which usually involves a process. Productive use is referred to as distinctive from passive stocks of materials, parts or products
14	Cascading use	Cascading	16	Cascading use is the successive utilisation of materials, parts or products over different value chains and avoids discarding after final use
15	Modelling of material cycles	Modelling cycles	16	Quantitative consideration of reintroduced materials, parts, or products into production, use and other

				processes such as collection, disposal, etc., with consideration of both static and dynamic approaches
16	Downcycling and quality loss	Downcycling	15	Downcycling and quality loss is present, when functionality or quality of the material, part or product is reduced as compared to previous use
17	Longevity or residence time	Longevity	15	Temporal relationship between inflows and outflows to a stock, which results in a time duration of materials, parts and products, being present in a stock. The element is present if it is specifically accounted for or calculated
18	Sharing or utilisation of resource streams	Sharing	13	This element is regarded to be present if actors share and reutilise resource streams in an industrial symbiosis context
19	Recycled material value	Recyc material value	11	Recycled material value is understood in its broadest sense and can involve the change of the monetary material value after the recycling process, a reuse value in physical units, or include the valuation in alternative units, i.e. based on energy
20	System stability	System stability	10	System stability is assessed if inputs are considered as critical to ensure that subsequent steps within a system will be realised
21	Materials mixing	Materials mixing	10	Assessment of the degree of mixing of materials
22	Supply risk and scarcity of resources	Supply risk scarcity	9	Supply risk and scarcity of resources is taken as a motivation or is assessed in order to monitor or derive targets for resource systems
23	Embedded stocks or distinct lifetimes	Embedded stocks lifetimes	9	Stocks embedded in products represent an important source of materials and cores for the CE while products tend to have distinct lifetimes, which is accounted for
24	Toxicity and clean material cycled	Toxicity	5	Consideration of undesired substances, which could contaminate reutilised materials, parts and products and negatively influence the reutilisation potential

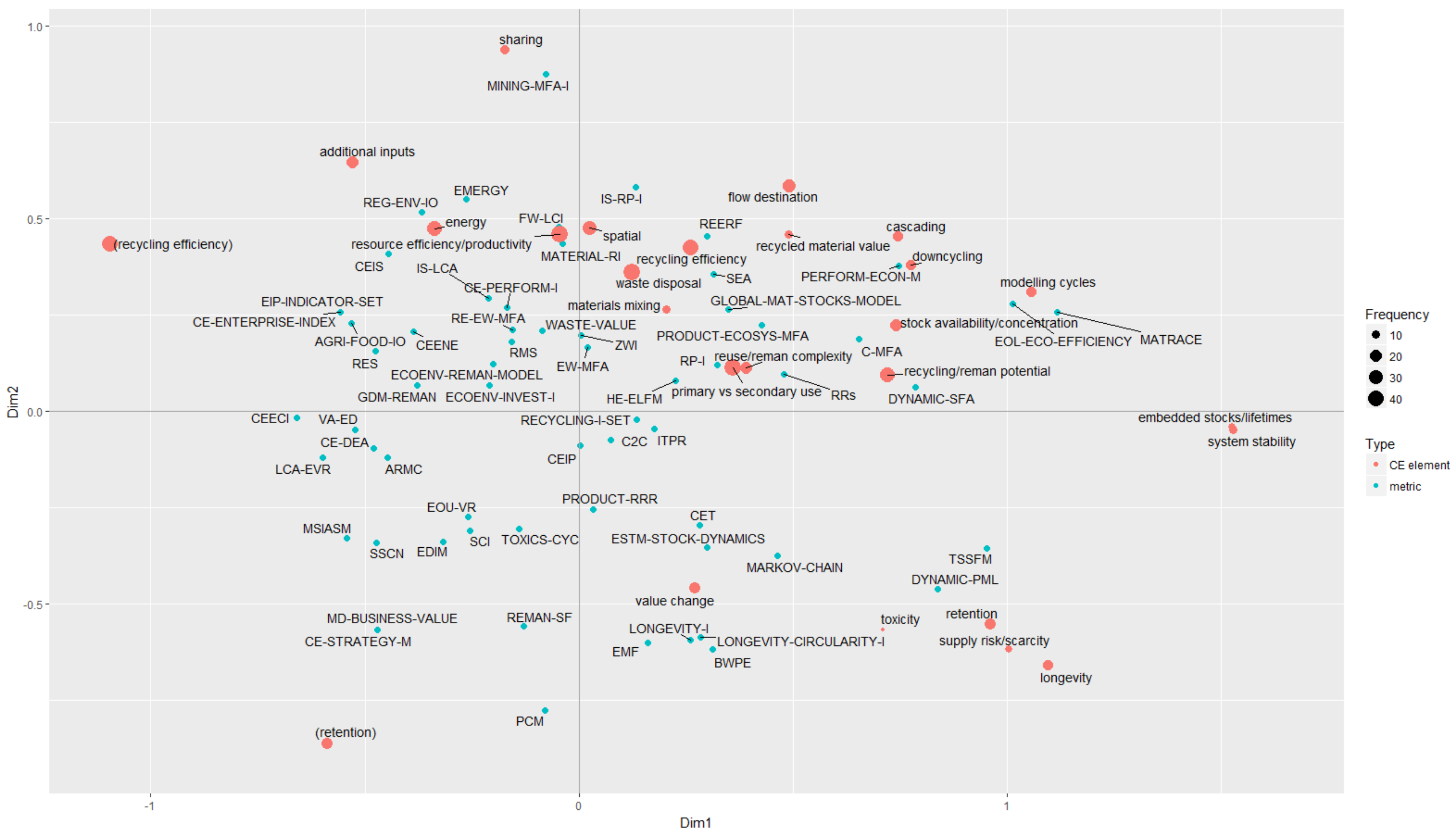

Figure 2: Multiple Correspondence Analysis factor map of categorical variables, representing assessed circular economy elements (red, lowercase) and associated circular economy metrics (turquoise, capital letters).

Note: The factor map has been produced with the MCA algorithm provided within the FactoMiner package for R by Husson et al., (2010).

2.4.1 Cluster 1: resource efficiency cluster

In general, the metrics located further away from the centre of the principal component space can be interpreted as being more focused on a fewer number, or less commonly assessed CE elements. In contrast, the four most frequent CE elements of waste disposal, primary vs. secondary use, resource efficiency/productivity and recycling efficiency are located closer to the centre of the principal component space, which is also highlighted visually by accounting for the frequency of each CE element (Figure 3). These CE elements confine a group of metrics to their left, and above the area of the first principal component axis, which is referred to as the resource efficiency cluster. The group holds metrics that largely correspond with each other, which is shown by the proximity of many of the metric data points. Compared to the overall scattering of the 63 metrics, the resource efficiency cluster (blue) has the lowest variance, thus representing the most homogeneous group of metrics. Its proximity to the most frequent CE elements, together with a lower variance within the cluster, reflects the most prevailing perspectives on the CE.

According to the interpretation rules of the MCA, the metrics of the resource efficiency cluster are less likely to assess the CE elements located at the opposite spectrum of the plot. This means that the metrics of this cluster and its defining elements of waste disposal, primary vs. secondary use, resource efficiency/productivity and recycling efficiency are not frequently combined in metrics with CE elements such as longevity, supply risk and scarcity, value change, retention, system stability, and embedded stocks/lifetimes (Figure 3). In the context of the CE definition that states that the value of products, parts, and materials should be maintained over a maximum period of time (European Commission, 2015a), the resource efficiency metrics appear rather disconnected to the elements which relate to the conservation of value, like value change, retention, longevity, and others.

This observation is of special relevance, as the cluster holds most of those metrics that are applied by governments and their agencies, showing the rather narrow focus on a few CE elements. Examples of these can be found in the circular economy indicator system of China (SEIS) and the European counterparts, represented by the Resource Efficiency Scoreboard (RES) and the Raw Materials Scoreboard (RMS). The Chinese circular economy indicator system is also applied to industrial park scale (EIP-indicator set) and the enterprise scale (CE-enterprise-index), which is the reason why the two metrics share the same coordinates, resulting in their full correspondence.

The cluster is also characterised by the presence of the CE element of energy, locating the two energy-based metrics, Emergy and Cumulated Exergy Extraction from the Natural Environment (CEENE), within the cluster. The element of energy is associated most with the elements of additional process inputs and resource efficiency/productivity, representing typical pairs of assessment perspectives, which are often applied in a spatial context. An important role also plays the CE element of recycling efficiency. Almost all of the metrics in the cluster assess this element (Figure 3).

Figure 3: Multiple Correspondence Analysis factor map with identified clusters of metrics. Colour codes indicate the Resource efficiency cluster (blue), Material stocks and flows cluster (green), Product-centric cluster (red).

Note: CE elements of recycling efficiency and retention are projected twice, as some metrics that do not assess the CE element split the group in two, requiring an additional projection to satisfy the constellation for the other half of metrics.

Despite the low number of CE elements within the first cluster, it combines different methodological approaches. Examples are Input-Output (IO) analysis metrics (REG-ENV-IO, AGRI-FOOD-IO), Economy-wide material flow analysis metrics (EW-MFA, RE-EW-MFA), LCA-based metrics (IS-LCA, FW-LCI), or metrics with a focus on remanufacturing (ECOENV-REMAN-MODEL, GDM-reman). Similarly, the indicator for the support of investment decisions (ECOENV-INVEST-I) evaluates projects mainly under the consideration of their resource efficiency performance. This variety of methodologies shows that different approaches can still assess a similar combination of CE elements.

In the upper part of the resource efficiency cluster, an area with a low density of metrics can be found. It is located between the elements of additional process inputs, sharing (reutilisation of resource streams) and recycled material value. Only two metrics, the Mining-MFA-indicator (MINING-MFA-I) and the Industrial-symbiosis resource productivity indicator (IS-RP-I) are located in this area of the plot. The low density of metrics reflects the absence of industrial symbiosis metrics, with a specific focus on these three CE elements. On the one hand, the gap might indicate that there is still potential for developing additional industrial symbiosis metrics. On the other hand, the low density of CE elements also shows some potential to refine further and diversify the industrial symbiosis elements.

The opposite situation is present at the periphery of the first cluster, which neighbours the second metrics cluster. Here, additional CE elements are combined with the resource efficiency cluster elements. Examples are the Zero-waste-index (ZWI), or the WASTE-VALUE metric. The ZWI assesses the virgin material replacement efficiency of cities (ZWI), considering the CE element of recycling/reman potential, while the WASTE-VALUE metric focuses on recycled material value. The assessment of these second cluster elements locates the corresponding metrics in a transitory zone between the two clusters. This example shows that it is important to view the MCA results as projections in a continuous space, and in relation to the CE elements, which makes the identified clusters less confining.

Regarding the LCA-based metrics, it shows how metric adaptations can lead to a wider spread and diversity of metrics. The reason for the wider distribution of LCA-based methods is their frequent combination with other metrics. Applications include the assessment of Industrial Symbioses (IS-LCA), the assessment of food waste management systems (FW-LCI), the evaluation of business models (LCA-EVR), or for the identification of more sustainable supply chain partners (SSCN). The range of applications reveals the flexibility of the LCA approach to be combined with a variety of metrics. At the same time, this characteristic makes it more challenging to identify opposing CE elements for LCA-based metrics. Still, some elements, like system stability and longevity, tend to appear less likely with LCA-based metrics. Therefore, metrics that incorporate these elements, such as the TSSFM- and MATRACE-metric can be identified as complementary metrics.

With the description of the first cluster, it has been shown how the MCA results can be used as systematic guidance for the selection of complementary groups of metrics. After identification of a set of metrics with complementary perspectives, the metrics can be further explored in more detail through a visualisation framework which is provided in the supplementary information (SI 6). The visualisation framework allows comparing the selected metrics in more detail, while providing a simple visual representation, based on colour coding, of each of the metric's CE elements assessed in a system context.

2.4.2 Cluster 2: materials stocks and flows cluster

The second cluster (green) is dominated by MFA-related metrics (Figure 3). Typical associations with CE elements are flow destination, waste disposal, stock availability/concentration, downcycling and quality loss, cascading use, and recycling/remanufacturing potential. Compared to the first cluster, the CE elements of the second cluster occur less frequently. Some of the CE elements are highly associated with each other. Examples of such CE element pairs are cascading use and downcycling, stock availability/concentration and recycling/reman potential. The most associated CE element pair consists of embedded stocks/lifetimes and system stability.

The material stocks and flows cluster has a strong interaction with the resource efficiency cluster. Especially in the transitory zone, metrics tend to combine elements from both clusters. The Reuse potential indicator (RP-indicator) and the REERF metric, which assesses the resource- and eco-efficiency of resource-based firms, are two examples of such metrics. Both metrics assess a high number of elements. In addition to the first cluster elements, they also account for the destination of flows, stock availability and concentration, and reuse/reman complexity, which locates them in the zone between the two clusters. Further, the REERF metric also assesses downcycling and quality loss, which explains its location closer to the centre of the second cluster.

That clusters are not fully confined, and that metrics can have a development direction towards a specific set of CE elements, can be shown on the example of MFA-based metrics. The example also illustrates how the variation of a metric leads to a change of the metric's relative location in the principal component space. The Economy-wide material flow analysis metrics, like the Economy-wide MFA (EW-MFA), or the Reutilisation-extended economy-wide MFA (RE-EW-MFA), represent metrics of the first cluster. These metrics have a spatial dimension and take mainly into account the CE elements of waste disposal, recycling efficiency, energy, resource efficiency/productivity and the destination of flows. The reason for the wide distribution of MFA-metrics along the first principal component axis into the second cluster is the assessment of additional CE elements such as material mixing (SEA), embedded stocks/lifetimes (PRODUCT-ECOSYS-MFA), longevity and downcycling (C-MFA), as well as system stability (Dynamic-SFA). The direction of the MFA metrics' distribution towards more rarely assessed CE elements, shows how the refinement of a metric influences its projected location. More importantly, this characteristic of the MCA method provides guidance on how the MCA results could be utilised to adapt existing metrics or design additional CE metrics. Further, as shown in the MFA example, organising metrics along CE elements reveals a novel perspective, which can be utilised for the development of metrics towards a specific set of CE elements.

2.4.3 Cluster 3: product-centric cluster

The third cluster (red) holds product-related metrics (Figure 3). These are represented by the Longevity indicator (LONGEVITY-I), which calculates the lifetime of resources in time units. A similar approach is inherent in the Product-level-circularity-metric (PCM). It employs monetary units as an alternative measure and has a stronger focus on the CE element of retention, which locates the metric closer to the additionally projected retention element. The Longevity-circularity indicator (LONGEVITY-CIRCULARITY-I), is analogous to the Longevity indicator (Longevity-I), extended by an additional circularity term. The circularity term calculates the amount of a material that passes through a cycle in relation to the preceding cycle. Other corresponding metrics are the Material circularity indicator of the Ellen MacArthur Foundation (EMF) and the Building-information-based whole-life performance indicator (BWPE). With the exception of the PCM metric, the metrics have in common that they focus on the CE elements of longevity and retention.

Other metrics in the product-cluster are located much closer to the centre of the plot, which indicates that they also hold first and second cluster CE elements. The Materials Circularity Indicator (MCI) is a good example of a product-centric metric which combines multiple elements of all three clusters. It considers the amount of virgin feedstock, recycling efficiency and unrecoverable waste while taking into account the time and intensity of product use. The multi-dimension indicator set (Recycling-indicator-set) assesses the benefits of material recycling from the perspectives of avoided impact, weight recovery, resource scarcity and value perspectives. The Information-theory-based-model for product recycling (ITPR) estimates the recycling potential for various product groups while assessing the elements of recycled material value, materials mixing and embedded stocks/lifetimes. Other product-centric metrics are the Circular Economy Indicator Prototype (CEIP) and the Circular Economy Toolkit (CET).

The categorisation approach does not take into consideration possible variations in the depth of analysis and the level of detail which vary considerably between methods. An example of limited depth of assessment is provided by the CET metric, which employs a questionnaire approach using a trinary scale (high/medium/low), that leads to a classification along with the CE elements. On the other hand, metrics such as the Cradle to Cradle Certified© Product Standard (C2C) are classified along with the same CE elements but consider the CE elements in more detail.

Overall, the product-centric metrics in the centre of the principal component space have in common that they consider a diverse set of CE elements that are often associated with different clusters. The C2C metric, for instance, evaluates the toxicity of materials, additional process inputs, e.g. water, takes into account the CE element of energy and waste disposal, but also the value change and retention, which are typical elements of the product-centric cluster.

2.4.4 Other metrics

Besides the three clusters of metrics, additional metrics termed as ‘other metrics’ are identified and are not included in any cluster. These metrics are either more isolated or distinguish themselves by not considering some of the more prevalent CE elements. The group includes product-, material-, and stock-dynamic metrics. The metrics are located at the periphery of the second and third clusters in proximity to the CE elements of embedded stocks/life-times and system stability (Figure 3).

The product-, material-, and stock-dynamic metrics derive the material flows from a dynamic consideration of stocks, based on lifetimes while considering a multitude of CE elements. Examples are the MATRACE metric, which assesses the global, multi-regional distribution and losses of steel, and the EOL-ECO-EFFICIENCY metric, which has been used to assess the metabolic system of lithium-ion batteries. The Performance-economy model (PERFORM-ECON-M) is similar to these metrics but does not take into account embedded stocks/lifetimes, which locates the metric closer to the centre of the cluster.

Other dynamic metrics are located close to the product-centric cluster. The group includes the TSSFM metric, that models technology-specific stocks and flows, and evaluates the transition to electric mobility with its consequences on resource extraction, and its potential for the CE. The product-multiple life cycle model (DYNAMIC-PML) evaluates the importance of multiple product life cycles under resource scarcity, while the Markov-chain model has been applied to WEEE flows in China for assessing the supply chain from collection to final disposal by transition probabilities at each stage. The dynamic perspective unifies the metrics, but due to their remote location at the periphery of the second and third clusters, they are not considered as a separate group.

The remaining group of metrics outside of any cluster distinguishes itself by excluding the more prevalent CE elements and is located below the resource efficiency cluster (Figure 3). Generally, the further a metric in this group is located from the centre of the plot, the fewer CE elements it considers. Most often, the corresponding metrics seem to have a rather narrow focus, i.e. assessing only a few CE elements. At the same time, they appear to combine very different perspectives. Examples are the assessments of regional performance and decision-making effectiveness of territorial units, represented by the Vector angle and Euclidian distance method (VA-ED) and the CE policy data envelopment analysis (CE-DEA). Other not clustered metrics are focusing on value creation (MD-BUSINESS-VALUE) or business models such as the CE-strategy-model, while others evaluate system aspects for recovery and reuse, classifying products according to their Product resource recovery routes (Product-RRR), or identify important factors which influence the remanufacturing rate (Reman-SF). Because the group distinguishes itself more by not considering the most common CE elements, it is not designated as a separate cluster. This observation can have two implications. First, if metrics measure only a few CE elements, it could indicate their limited scope of assessment. Second, it could mean that the identified CE elements can be further extended to more specialised categories related to policy, economic or business aspects, as these appear not to be well integrated with the other three clusters.

2.5 Implications for further metrics development

The current phase of CE concept development can be characterised as the validity challenge period, which means that the relationships of circular configurations are explored systematically, granting an important role to CE metrics for developing a deeper understanding of the CE concept (Blomsma and Brennan, 2017). In this context, the assessment that has been performed with the help of MCA provides important anchor points for the categorisation and structuring of CE metrics and their assessed CE elements, while contributing towards a concretisation of the CE concept.

The importance of monitoring the development of the CE through metrics has been stressed by the European Commission (2018a) as crucial to identify success factors, assess the actions taken and to set priorities in the long-term perspective. Moreover, while policies can influence the choice of metrics, it is also likely that the choice of metrics influences the thinking of regulators, business leaders and other stakeholders about the CE. Therefore, it is important to provide an overview of the field of CE metrics, the relations between CE metrics and the associations between CE elements. Even though various other approaches exist to reflect on the available perspectives of CE metrics and the elements that they measure, it shows that the MCA method is a suitable and practicable tool not only to assess metrics but also to guide their future development.

The analysis reveals that a rich set of CE metrics exists, that assess a wide range of CE elements. The differences in metrics density allow for a reflection on the dominant ideas about the circular economy revealing three main clusters of metrics, i) a resource efficiency cluster, ii) a materials stocks and flows cluster, iii) a product-centric cluster. The most prevailing CE perspectives identified to focus on waste disposal, primary vs. secondary use of resources, resource efficiency/productivity and recycling efficiency. It is important to highlight that today's regulative CE support already favours recycling if compared to overall reuse approaches (Ranta et al., 2017), a trend that is consistent with the MCA results that show a higher metrics density around material-centric clusters of resource efficiency and the material stocks and flows cluster. In this regard, a greater wealth of metrics exists on the level of materials, while the product- and system-dynamic perspectives are underrepresented.

Taking a more detailed view of the field of CE metrics, further patterns can be identified. One of them is that the more the metrics are located towards the right of the principal component space, the more specialised or narrow the CE elements become in their assessment perspective, and the less frequently they appear. Therefore, a potential trajectory for additional metrics development lies in areas of the MCA plot with a low metric density, more specifically in the direction towards more specialised CE elements between the second and third cluster. Based on that trajectory, future metric development should embrace CE elements such as value change and retention, recycling/remanufacturing potential, cascading, downcycling, and embedded stocks and life-times. These CE elements are especially of relevance in the context of the overall CE goal of preserving the value of products, parts and materials. Also, these elements provide a link between specific CE strategies and the overall system, thereby contributing to a more systemic analysis while considering quality elements, that are crucial for a more circular system.

When evaluating the results of the MCA, it has to be noted that CE metrics often assess the same CE element at different depths of analysis that is not accounted for by the MCA. Besides that, CE elements themselves have a different scope which means that there is an opportunity to refine some of the CE elements as it has been previously proposed, e.g. for recycling rates (Haupt et al., 2016). On the other hand, simultaneous projection of metrics and CE elements allows identifying complementary metrics for application, which has been most frequently demonstrated by the incorporation of the LCA methodology and other assessment methods.

With the lack of accepted CE element definitions that has been encountered during the analysis, the presented list of CE elements represents an attempt to provide a system for structuring the existing and future CE metrics. It also means that it is likely that some CE elements are not present in the assessment. One example is the level of standardisation within the CE that could be assessed by a metric for improving the degree of conformity, order and interoperability, leading to economies of scale and efficiency gains (Tecchio et al., 2017).

Reflecting on the results of the MCA, the following section provides an overview of CE metric reviews that mostly appear at the same time or after the MCA of CE metrics has been performed. Thereby, the MCA results are reflected upon taking into account additional reviews and their findings.

2.6 Other reviews on CE metrics and identified gaps and perspectives

This section discusses the main findings from existing reviews of CE metrics based on Corona et al., (2019); Harris et al., (2020); Helander et al., (2019); Iacovidou et al., (2017b); Kristensen and Mosgaard, (2020); Moraga et al., (2019) and Saidani et al., (2019). The results of the reviews are related to the MCA outcomes presented in Section 2.4.

The identified reviews assess CE metrics from different perspectives. While Iacovidou et al., (2017b) employ a broader resource and sustainability view, Kristensen and Mosgaard, (2020) assess micro-scale metrics that focus on single products or firms. Other reviews, such as those by Helander et al., (2019) look at environmental consequences in the context of the CE transition, while Harris et al., (2020) review CE metrics from a life cycle perspective, excluding metrics that target single stages of a life cycle such as the waste management phase, or single processes like remanufacturing. These different scopes of the reviews have to be taken into account when comparing their results.

Despite the differences in the assessment scope, there is a consensus to categorise CE metrics along the micro-, meso- and macro-scales (Corona et al., 2019; Harris et al., 2020; Helander et al., 2019; Kristensen and Mosgaard, 2020; Moraga et al., 2019; Saidani et al., 2019). Some authors further subdivide the three scales, e.g. Moraga et al., (2019) employ additional sub-categories at the macro-scale such as the city-, region- and nation-scale, while Corona et al., (2019) distinguish between the assessment of sectors, regions and global economy, products and organisations.

Further, the reviews structure the metrics according to different assessment perspectives, e.g. into environmental, economic, social and technical metrics (Iacovidou et al., 2017), with a similar categorisation also employed by Corona et al., (2019). Also, different conceptualisations of resource systems are employed, e.g. Iacovidou et al., (2017b) conceptualise their analysis around the preservation of value on the material, component and product levels to retain functionality. In their assessment of environmental metrics it is observed that these are dominated by LCA-based methods, with other commonly applied approaches like carbon accounting, (e.g. carbon footprints), pollutant emission metrics (e.g., acidification potential, human toxicity potential), energy-related (e.g. cumulated energy demand, exergy) and non-energy related resource depletion metrics (e.g. material intensity, recycled/reused content), efficiency metrics (e.g. weight recovery) and integrated metrics (e.g. ecological footprint). Economic metrics are largely discussed in the context of cost-benefit-analysis while pointing out additional elements such as feedstock availability, the capacity of the infrastructure, longevity of the assets, capital cost, and net profit. Social metrics consider aspects such as workers safety, income, participation or the number of jobs created. The authors stress that social impacts (positive and negative) need to be assessed together with their interrelationships and context. With social metrics representing the least assessed category, Kristensen and Mosgaard, (2020) stress that more attention should be directed towards their measurement. Another group of metrics represents technical metrics that focus on aspects like remanufacturability, recyclability or recoverability (e.g. technical recyclability assesses the value capture from recyclates). Here, a need for larger integration with a system-based approach is identified that could better represent the complexity and interdependencies that are present between the different system elements and CE strategies.

While Iacovidou et al., (2017b) employ a wider scope in their assessment, other authors limit their perspective by, e.g., identifying assessment gaps and therefore focusing on a sub-set of CE metrics, e.g. at the micro-scale. Employing a narrow scope includes some risks as any measures employed might not be reflected in relation to the overall system, thereby potentially leading to outcomes associated with rebound effects or problem shifting. This critique is supported by Pauliuk, (2018) who shortly reflects on existing metrics in the appraisal of the British CE standard, proposing a generic system that serves as an accounting framework that should avoid burden-shifting or 'cherry-picking' when choosing a CE strategy. Thereby, Pauliuk (2018) also acknowledges that trade-offs between different CE strategies exist and argues in favour of a dashboard approach that provides a systemic overview while allowing for a diversity of perspectives to be included through specialised indicators.

A different approach is taken by Saidani et al., (2019), who first analyse three product metrics in more detail (CET, MCI, CEIP) (Saidani et al., 2017), and extend their review to 55 metrics (Saidani et al., 2019), with the goal to guide practitioners in their CE metrics choice. Therefore, their review is structured along ten categories that include elements that also reflect on the usability of the metrics: 1) levels (micro-, meso-, macro-), 2) loops (maintain, reuse, remanufacture, recycle), 3) performance (intrinsic, impacts), 4) perspective (actual, potential), 5) usages (benchmarking, communication, improvement), 6) transversality (generic, sector-specific), 7) dimension (quantitative, qualitative), 9) format (formulas, excel, web-based tool) and 10) sources (academics, agencies, companies). The authors identify that many CE assessments focus on single CE strategies (e.g. recycling) not covering the interaction with other CE strategies and are therefore more likely to underrepresent the full complexity that is present in the CE transition. One of the main conclusions derived is the need to assess circularity at different complementary levels, a result that directly relates to the outcomes of the MCA presented further above. Moreover, the authors point out how assessment perspectives change depending on the scale of the assessment. With a larger assessment scale (e.g. macro-scale), the focus on recycling becomes more pronounced, at the expense of other CE strategies such as reuse, remanufacturing and maintenance, with the latter being least frequently assessed. Also, there is a shift towards scoreboard approaches, which is supported by the MCA results as well. Further, Harris et al., (2020) point out that macro-scale assessment frameworks consider multiple criteria such as waste management, secondary resources, production and consumption, but at the same time largely neglect stocks, remanufacturing, refurbishment and reuse.

The relationship between the assessment perspective and the scale of assessment is also observed in other reviews. Moraga et al., (2019) identify little integration between micro- and macro-scale metrics, which is also supported by Saidani et al., (2019). Harris et al., (2020) elaborate on that issue by stating that various adequate metrics exist on different scales, while the challenge remains in connecting the micro- and macro-scales. A possible solution is seen by employing the meso-scale, that is often employed when assessing potentially symbiotic systems, such as industrial parks, thereby providing a possible link between the micro- and macro-scales. Another proposal is the use of complementary metrics (e.g. Saidani et al., 2019, that cover a wider range of perspectives while linking it to a systemic approach (Corona et al., 2019; Pauliuk, 2018). Here, the MCA results indicate that there are no fully confined metrics and that combined, or hybrid approaches already exist that allow connecting the different assessment perspectives. An alternative proposal in that regard that has not yet been covered in the analysis represents the societal functions framework that is discussed in the review by Harris et al., (2020). In the framework, societal needs are employed as an absolute reference state (Alaerts et al., 2018), so that products and other means of providing a required function can be linked, thereby allowing for a diversity of CE strategies and their combinations to be employed (Alaerts et al., 2019).

Other elements identified that require more attention are the inner loops that include CE strategies like reuse and lifetime extension, and the linkage of CE indicators to environmental impacts, as correlations between them are not yet fully mapped and understood (Harris et al., 2020; Kristensen and Mosgaard, 2020). As a result, it is proposed to better link CE metrics and LCA-based assessments (e.g. Harris et al., 2020; Saidani et al., 2019). In this regard, some efforts have already been directed to narrow some of these gaps, with examples provided in Section 2.4. Other newly developed metrics further expand on the relation of environmental impacts and the CE transition, with one example represented the Retained Environmental Value (REV) metric (Haupt and Hellweg, 2019). The REV metric accounts for the environmental impacts displaced by value retention processes (e.g. recycling) that are set in relation to the original environmental impact of a product while taking into account the difference of environmental impacts during the use phase of the retained and the alternative product. Thereby, the environmental impacts of different routes or CE strategies can be incorporated and employed for a relative comparison.

The review by Corona et al., (2019) largely supports the main findings presented above. The authors state that the identified gaps relate to the quality of recycled material flows, the assessment of social impacts and consumer effects (e.g. sufficiency strategies) that could lead to an overall reduction in consumption rates. Nevertheless, the authors stress additional perspectives that would need to be integrated into CE metrics to a higher degree, including the measurement of material use over multiple cycles, the provided utility, evaluation of scarcity of the materials used, and the overall challenge of integrating the different perspectives into a combined systemic analysis.

For the further development of metrics, the reviews recommend using established and mature methods such as LCA, MFA, or Multi-regional Input-Output (MRIO) analysis. Among others, Iacovidou et al., (2017) propose employing MFA in combination with metrics that focus on the assessment of value, while Pauliuk, (2018) recommend using MFA, its organisational offspring of Material Flow Cost Accounting (MFCA) and LCA, together with stock and residence time accounting as these would ensure for a better reflection on system linkages. Helander et al., (2019) promote the use of footprint approaches to ensure an environmentally sound transition towards a more circular system, while Harris et al., (2020) direct attention for improving the link of environmental impacts via LCA and MRIO analysis, representing an established research direction (Cabernard et al., 2019; Christis et al., 2019; Donati et al., 2020; Geerken et al., 2019; Hertwich and Wood, 2018; Piñero et al., 2018).

Concerning the MCA results, it can be reflected that some of the proposed linkages, especially when it comes to LCA- or MFA-based approaches have been already established. Examples, where LCA-based approaches are linked to meso-level assessments are provided in the context of industrial symbiosis or concerning the selection of value chains. Further examples are shown for MFA- and IO-based methods. Reflecting on the MCA results, the CE perspectives assessed represent generic categories that cover a wide range of elements that other reviews have also reflected upon, e.g. recycling efficiency, value change, retention. On the other hand, it is to note that other CE elements have not been explicitly covered by the MCA, e.g. the social perspective, or have been aggregated to a larger degree, e.g. the economic perspective is covered on a general level, while the review of, e.g. Iacovidou et al., (2017b) distinguishes various value-/cost-categories. Therefore, it could be argued, that the metrics assessed by the MCA, underrepresent social aspects and provide only a coarse assessment of economic aspects while focusing to a larger degree on what has been previously referred to as 'technical' metrics. In this regard, the identified metrics of the MCA show larger similarity to metrics assessed by, e.g. Saidani et al., (2019), than to the metrics assessed by, e.g. Iacovidou et al., (2017b), who also include metrics that in many aspects could be referred to as overall sustainability metrics, not being necessarily limited to circularity assessments. Even though the reviews reflect on the CE metrics from their specific perspective, many of the conclusions are aligned with the MCA results presented further above.

Moreover, the reviews provide a perspective on the potential for further metric development and based on the observations that, e.g., a greater wealth of metrics exists on the level of materials than on the level of products, and that only a few metrics combine system and product perspectives under the consideration of the preservation of value, led to the consideration of these aspects in the further development of Statistical Entropy Analysis presented in Section 3 while acknowledging that further CE element combinations could be potentially integrated as well. Therefore, the case study application that follows in Section 4, additionally demonstrates how the incorporation of stocks, recycling and remanufacturing potential, embedded stocks and lifetimes can be combined with a time-dynamic perspective that assesses product-system interactions with a combination of different CE strategies applied.

3. Multilevel Statistical Entropy Analysis

3.1 Material Flow Analysis and Statistical Entropy Analysis

As shown in the assessment of different CE metrics (Section 2), different strategies exist to increase the circularity of a material flow system. Assessing their effectiveness at keeping resources in closed loops can be challenging and a multitude of perspectives exists that could be taken into account, including the trade-offs between different CE strategies that can occur and that can be difficult to judge. Therefore, deciding on the optimal combination of CE strategies is a complex task for companies and governments seeking to make investments in a circular transformation (Lieder et al., 2017; Reike et al., 2018), which requires the ability to make robust assessments of CE strategies and their combinations to facilitate optimal adaptations of material flow systems.

In this context, an established method to evaluate metabolic systems is material flow analysis, which is chosen as a primary method that provides a sound basis for further evaluations. Based on the principle of the conservation of matter, MFA systematically quantifies and maps the stocks and flows of materials between processes for a defined system, designated by a system boundary in space and time (Brunner and Rechberger, 2016). Thereby, MFA results provide a transparent and consistent overview of a material system that allows identifying key processes and flows for optimisation to decrease environmental pollution or improve the use of resources, e.g. by changing the dynamics of accumulation and depletion of stocks (ibid.).

One key aspect of material processes is the transformation of input flows into output flows. In the transformation of material flows, processes can concentrate, dilute or leave the substance concentration unchanged. Typical processes related to concentration activities are the extraction and processing of raw materials, the production of semi-finished goods (e.g. metal ingots) and the sorting, separation and recycling of materials. Dilution occurs in the manufacturing of products, or when materials are mixed, directed to a waste flow or emitted to the environment. Concerning single substances, flows of higher substance concentration are typically considered to have a higher potential for utilisation so that the power of a system to influence concentration or dilution represents an important feature of a material flow system (Brunner and Rechberger, 2016).

To better evaluate the results of an MFA and quantify the power of a system to concentrate or dilute substances, the method of SEA has been developed (Rechberger, 1999). Originating from information theory, SEA is based on Shannon's Statistical Entropy function (Shannon, 1948). In information theory, it measures the variance of a probability distribution, thereby quantifying the amount of information about a system state. Translated and applied to material flow systems, the method quantifies the potential of processes and systems to concentrate or dilute substances. In this context, an important transformation step has been the translation of the variance of a probability distribution to the variance of substance concentration in a set of material flows.

Applied to MFA results, statistical entropy values are expressed in terms of relative statistical entropy (RSE), calculated by relating them to a state of maximal dilution so that RSE values are always located in the interval [0, 1]. The RSE value of one represents the highest possible state of dilution of a substance, and the value of zero indicates the opposite state of its full concentration. Therefore, the more uniformly a substance is distributed among a set of material flows in a system, or the more it is diluted to the environment, the closer the RSE value is located to the maximum.

SEA studies that evaluate the metabolism of single substances have proven to be of high value to assess improvement potentials in the substance utilisation. Nevertheless, metabolic production-consumption systems are typically characterised by transforming several substances and material flows that interact with each other. To better link several substances in material flow systems, a coupled MFA has been developed and demonstrated on the phosphorus and nitrogen flows in Austria (Tanzer et al., 2018). Other studies that explicitly consider multiple substances in an MFA context are often undertaken to quantify their separate substance flows, e.g. the flows of alloying elements steel recycling (Ohno et al., 2014) or aluminium recycling (Løvik et al., 2014; Modaresi et al., 2014a). While the consideration of several substances allows to better represent their interaction and consider qualitative changes within the system it also allows determining the possible applications of the output flows recovered which adds complexity to the system and its evaluation (Andersson et al., 2017a; Kampmann Eriksen et al., 2018; Nakamura et al., 2012; Ohno et al., 2014; Ziemann et al., 2018). In this regard it is to note that specialised methods exist, e.g. flowsheet simulations, representing a method that is rooted in process engineering and process optimisation that reflects on the detailed interactions and reactions in, e.g. metallurgical processes, but also considers parameters such as particle size distribution and is also proposed to be used for product design (Reuter, 1998; van Schaik et al., 2002; Van Schaik and Reuter, 2010, 2006, 2004). These models require detailed process knowledge and therefore, most frequently focus on material processing routes, e.g. in metals recycling.

However, besides material-based strategies, important CE strategies exist on the component and product level, representing the inner loops in a CE that are less frequently assessed. Therefore, in the context of MFA, the simultaneous consideration of different substances and materials provides a possibility to express additional hierarchical levels, including those of the component and product, that are rarely assessed jointly within a system perspective (see Section 2). For this reason, the SEA method is extended to the multilevel SEA method that considers the additional component and product levels.

Further, the method is developed to provide an alternative perspective for the analysis and evaluation of metabolic production-consumption systems, particularly from the perspective of resource effectiveness. Resource effectiveness is defined here as a state in which the functionality of resources is maximally preserved over time, with minimal effort. It is to note that the concept of effectiveness is related to the degree of reaching an objective. In the CE context, it can be linked to achieving a specific quality, e.g. effectively separating toxic pollutants from recycled plastics (Leslie et al., 2016), or reaching a specific system state, e.g. CE policy effectiveness (Wu et al., 2014). By measuring system performance as a distance to an ideal state (Section 3.3), it is possible to measure the relative performance of a material flow system. Thereby, the multilevel SEA method introduced in the following is expected to contribute to the system evaluation tool family, providing a complementary perspective to the impact-, energy-, and cost-based evaluations.

3.2 Multilevel Statistical Entropy Analysis

3.2.1 Conceptual introduction to Multilevel Statistical Entropy Analysis

For the conceptual introduction of the multilevel Statistical Entropy Analysis, it is proposed to distinguish between substances, materials, components and products (Table 6). Structuring a product into its sub-units is not a trivial task (Gershenson et al., 2003; Lorenzi and Di Lello, 2001). In this context, the 'bill of materials' (BOM) can serve as a guideline to designate products and components. The BOM structures the product elements in relation to each other and distinguishes in addition to products (e.g. car) and components that are used in the final assembly (e.g. engine), also sub-components and subassemblies (Cinelli et al., 2017).

Only the two top levels of the BOM, the product and component level, are employed in the following, not further disaggregating components into sub-components and subassemblies. Instead, components are described in terms of their material composition and can consist of mono-, or multi-substance materials. The substance composition of a material allows for a first level (material level) of differentiation of entropies, distinguishing simple materials composed of a single substance, such as copper from more complex materials that contain a series of different substances in specific concentrations, such as carbon-manganese steel or polypropylene with additives. At least theoretically, a component could be made from a single, mono-substance material, but most components will require the combination of several, more complexly built, multi-substance materials. The materials represent the building blocks of components, allowing for another hierarchical level (Figure 4).

The term good is employed in the original SEA method but is not used in the multilevel SEA approach, as it represents a wider category holding both, components and products. Goods are defined as economic entities of matter with a positive or negative economic value that consist of one or several substances (Brunner and Rechberger, 2016). Thereby, goods can entail products, components and other entities, e.g. TV sets, hard disk drives, but also waste wood or sewage sludge. The term is used for the formal introduction to the original SEA method (Section 3.2.2).

It is already indicated that the number of possible levels can vary according to the particular system and the building blocks that are to be assessed. Examples of alternative or additional levels are possible and could be chemical elements, sub-components and subassemblies, particular brands of products or components, each representing a building block for the next level. Therefore, one guideline would be to document the levels and the building blocks employed. Thereby, a transparent description should be provided, which is of special importance if a comparison between different systems is intended. In the case of comparing different scenarios that are modelled within the same system, e.g. only recycling rates change, while the system structure with the number of processes and flows remains the same so that a direct comparison can be undertaken. In that case, the levels employed, the product, its components, and materials, including the system structure, do not change (see Section 3.2.3).

Table 6: Terms, definitions and examples used to describe different hierarchical levels.

Term	Definition	Example
Substance	single type of matter, which consists of chemical elements or compounds	Al, Polypropylene (PP)
Material	a substance or a mixture of substances	Al, Al alloy, PP containing additives
Component	part of a product that is used as a direct input in the final assembly of the product that is built with the intention to provide a functionality	engine, wheel, car body
Product	object that is assembled from components and is produced as a final output of a production process with the intention to provide functionality to its user	Car
Good	economic entity of matter with a positive or negative economic value that consist of one or several substances	Car, engine, copper pipe, waste wood

Substances, materials and components that are not investigated and of interest are treated as a single separate fraction: 'others'. By considering such a fraction 'others', the mass balance of the system investigated is always ensured[5].

Further, the detail of the system description and the choice of which and how many levels are considered is defined by the question to be answered. For example, when analysing or comparing a used car part system performance, it is not relevant nor required to consider a detailed chemical element composition of the dismantled parts. Therefore, the notion of 'investigated' substance, material, component or product part refers to the fact that it is not possible, or unnecessary, to know all chemical elements, compounds, materials and components that are present in a complex metabolic system in detail. If an end-of-life device is entirely shredded in all systems selected for comparative analysis, there is no need to know the device's building blocks at a component level. In fact, the question of the resolution and detail of system description is also present in other assessment methodologies, e.g. a car-related life cycle inventory should provide as much detail as possible, but the corresponding model of a car is likely to be less detailed than the one used by a car manufacturer (Hawkins et al., 2012).

[5] Note that materials, components or products always represent flows since these are assessed in a material flow system that quantifies mass flows over a time period.

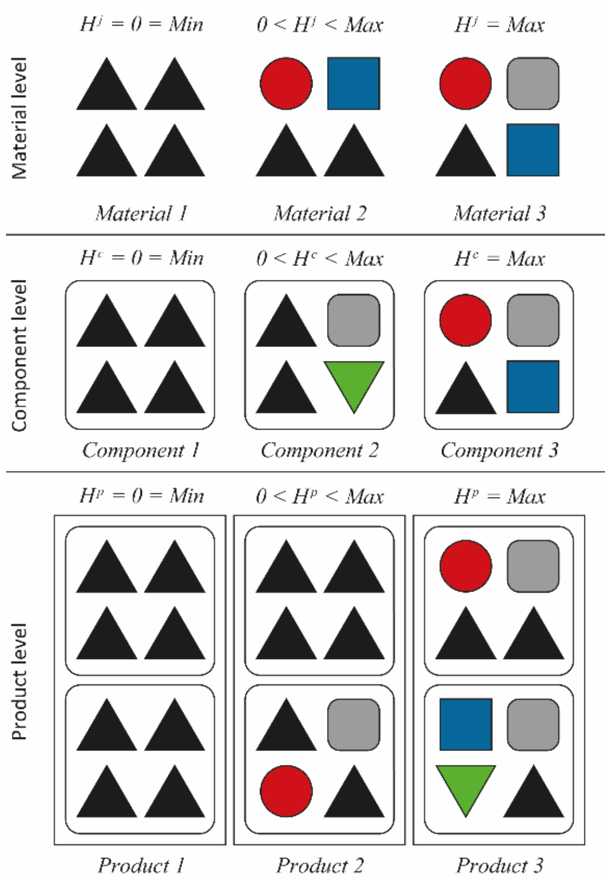

Figure 4: Conceptual representation of the material, component and product levels and the influence of substance and component distribution on statistical entropy values[6].

The conceptual representation of three levels in Figure 4 shows how the distribution of substances, but also the diversity and complexity of components, affects the statistical entropy values. For a single material, the lowest statistical entropy value (H^j) is reached if the material consists of a single substance. The more different substances are present on the material level, the higher the H^j-value. The largest H^j-value is reached if all substances investigated are equally distributed. Analogously, at the component level, the lowest statistical entropy value for a component (H^c) is reached if the component consists of a single substance. By increasing the number of substances in the component, the H^c-value gradually increases until the maximum value is reached, representing the most complex component's substance composition (Figure 4). At the product level, the statistical entropy value (H^p) increases if the product uses more types of components and/or if the components have a more complex substance composition. The H^p-value is at its minimum if the product consists of components (or a single component) only, which consist of a single substance. With this conceptual introduction, a first intuition behind the concept is provided so that the formal introduction of the Statistical Entropy Analysis (Section 3.2.2) can be extended to the multilevel Statistical Entropy Analysis (Section 3.2.3).

[6] In all cases statistical entropy values increase from left to right for the material (H^j), component (H^c) and product levels (H^p).

3.2.2 SEA – a formal introduction

The original SEA methodology utilises the information on both the goods, which represent entities of matter that are made up of a single or several substances, e.g. wood (Brunner and Rechberger, 2016), represented in the flow rate M_i of good i, and substances, represented by the concentration c_{ij} of substance j in good flow i. From both values the substance flow rate (X_{ij}) is calculated.

$$X_{ij} = M_i c_{ij} \tag{1}$$

Statistical Entropy values are calculated for each stage in a system that consists of a set of material flows between processes, imports to and exports from the system. An illustration of the transformation of a material flow diagram into a stage flow diagram is provided in Figure 5. More detailed descriptions on the transformation procedure are provided by Rechberger and Graedel, (2002) and Laner et al., (2017).

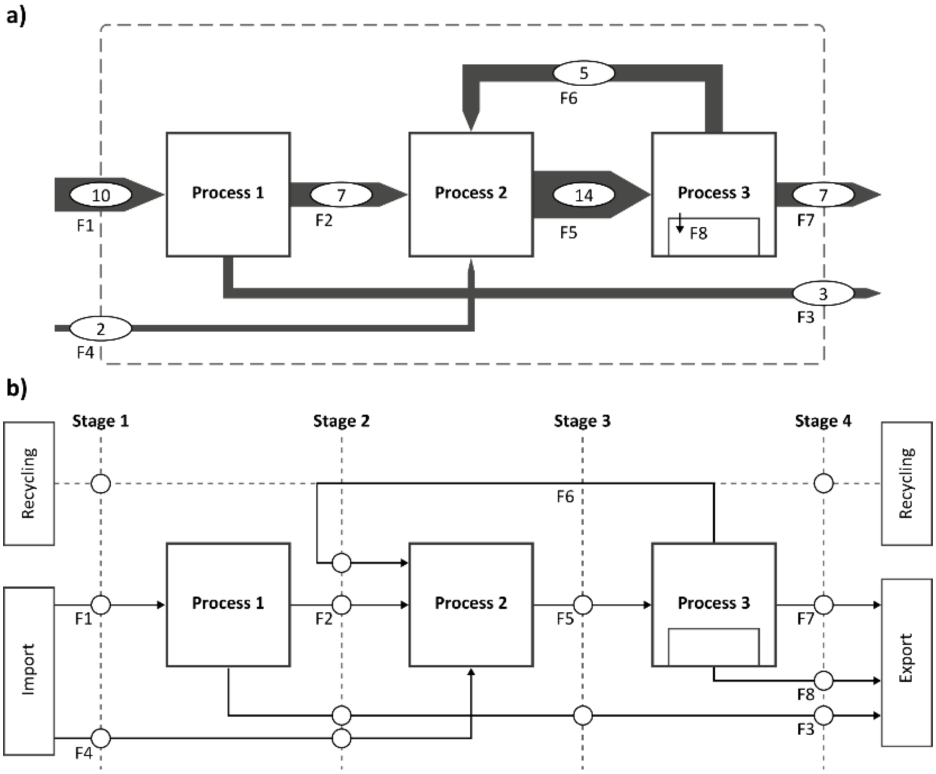

Figure 5: Illustration of the transformation of all types of flows in a material flow system (a) to a stage flow diagram (b) (from Laner et al., 2017).

Based on the set of I material flows, normalised mass fractions are calculated according to Equation (2). $\sum_{i=1}^{I} X_{ij}$ in Equation 2 is the total throughput of substance j through the system and can be regarded as the functional unit, making different systems comparable. Together with the concentrations (c_{ij}) that are expressed as relative values in identical mass per mass units (e.g. kg of substance j per kg of good i), the standardised mass fractions (m_i) enter Equation (3)[7].

[7] *ld()* stands for 'logarithm dualis', which is the logarithm to the base 2.

$$m_i = \frac{M_i}{\sum_{i=1}^{I} X_{ij}} \tag{2}$$

$$H^j(c_{ij}, m_i) = -\sum_{i=1}^{I} m_i \cdot c_{ij} \cdot ld(c_{ij}) \tag{3}$$

Statistical Entropy is expressed as a dimensionless relative statistical entropy value (H^j_{rel}), ranging between [0,1]. H^j_{rel} is the ratio of H^j/H^j_{max}, H^j_{max} calculated according to Equation (4.1). For open systems, the largest H^j-value is reached if a substance is directed to a compartment, where it is maximally diluted (e.g. emission of a heavy metal into the atmosphere), i.e. the compartment with the lowest background concentration of the substance ($c_{j,geo,min}$).

$$H^j_{max} = ld\left(\frac{1}{c_{j,geo,min}}\right) \tag{4.1}$$

In closed systems, the largest H^j-value is reached if a substance is equally distributed and the concentrations in all good flows are the same (4.2).

$$H^j_{max} = ld\left(\sum_{i=1}^{I} m_i\right) \tag{4.2}$$

If a flow consists of a single pure substance, the *H*-value of zero is reached, representing the other extreme. For a more detailed methodological introduction, please see (Rechberger and Brunner, 2002; Rechberger and Graedel, 2002).

3.2.1 Multilevel SEA - Combined analysis of substances and components

In order to extend the single substance SEA to the level of a product, the method is first extended to the level of the component. In a second step, the component entropy values are used to calculate the product entropy.

The formal description of the component starts with the quantification of the component's mass. The mass of component *n* is expressed through M^c_n (in mass per time[8]), which is equal to the sum of investigated substances *j* in the component, $M^c_n = \sum X_{nj}$ (in mass per time). Usually, not all substances of a component can be assessed and the fraction 'others' is employed to describe the rest of the component, which can be treated as a separate 'unknown' substance in the calculations. To express the relative mass of component *n* in relation to all investigated substances at a system stage and over all components *N*, the mass of the component M^c_n is divided by the sum of all substances at a system stage $\sum\sum X_{nj}$ (in mass per time). This leads to a normalisation of the component mass M^c_n (mass per time divided by mass per time, [-]), as it is shown in Equation (5).

$$m^c_n = \frac{M^c_n}{\sum_{n=1}^{N} \sum_{j=1}^{J} x_{nj}} \tag{5}$$

[8] Any material flow system expresses the flows of materials over a defined time period. Therefore, formally each component and product represents a component flow and product flow over time, which for better readability is simply referred to a/the component or product.

Further, each component is described by its substance composition, expressed in substance concentrations (mass of a substance divided by the total mass of the component [-]). For this reason, the sum of concentrations $\sum c_{nj}$ of all investigated substances j=1,…J, with J number of substances in the component n (including the substance 'others') always equals to one. Together with the substance concentration c_{nj}, the normalised component mass m_n^c ([-]) enters the statistical entropy function through Equation (6). Here, the conceptual similarity to the original approach presented in Equation (3) becomes apparent. The differences are represented in the simultaneous consideration of several different substances and the normalisation on the level of the component.

$$H_n^c(c_{nj}, m_n^c) = -\sum_{j=1}^{J} m_n^c \cdot c_{nj} \cdot ld(c_{nj}) \quad (6)$$

Once the component entropy values have been calculated, they can be translated to relative statistical entropy values ($H_{n,rel}^c$) for each component n ([-]). Similar to the material level, maximum statistical entropy H_{max} at the component level can be expressed in two ways. If substances are diluted within the system boundary, H_{max} is calculated for a system state in which all substances are present in one material flow and are therefore maximally diluted, or equally distributed (e.g. all components of a product are shredded and mixed in a waste flow). The mixed waste flow with full dilution of all substances is calculated according to Equation (7), which is equivalent to Equation (6), with the difference that all substances are diluted in one material flow (n=1 and $m_n^c = 1$), representing maximum entropy for a specific system. If substances are diluted to compartments outside of the system boundary (e.g. emission of carbon to the atmosphere), the maximum statistical entropy function is also calculated according to Equation (7) but adapted for the substance that is diluted to a compartment outside the system boundary by calculating its dilution according to Equation (4.1).

$$H_{max}(c_{nj}) = -\sum_{j=1}^{J} c_{nj} \cdot ld(c_{nj}) \quad (7)$$

Dividing each component entropy value by the maximum entropy value leads to the relative component entropy $H_{n,rel}^c$, Equation (8).

$$H_{n,rel}^c = \frac{H_n^c}{H_{max}} \quad (8)$$

3.2.2 Multilevel SEA - Relative Statistical Entropy of products

The next hierarchical level is the level of the product. The product statistical entropy H^p consists of two parts: the contribution to statistical entropy resulting from the substance composition of its components (complexity of components based on their substance composition), which is expressed by the relative component entropy values $H_{n,rel}^c$, Equation (8), and the number and the diversity of different components in a product (complexity based on the diversity and number of components a product is made of). Component diversity is lower if a higher number of identical components is present in the product. By distinct components, it is referred to structurally different components, e.g. engine and wheel, with structurally identical components being the wheels of a car. While the material level is included on the level of the component through $H_{n,rel}^c$, it is assumed that the number of different components in a product provides an additional approximation of the product complexity (Figure 4). Therefore, an increase in H^p can occur in two ways: through an overall larger number of distinct components in a product and through a more complex substance composition of each of its components. In this context, the structuring of materials and components as commonly applied in BOM can be used as a guideline for the selection of components and substances analysed. Conceptually, the dilution of substances within a component and the dilution of a component within a product is equivalent. This ability to express composition changes on the level of the component and the product allows CE strategies involving both destructive (e.g. shredding) and non-destructive techniques (e.g. disassembly and reuse), and combinations thereof, to be assessed.

For the calculation of H^p, which represents an additional conceptual extension to the next hierarchical level, two additional properties are required: the number q_n of every distinct component n, each having their own substance composition (expressed through $H^c_{n,rel}$) and the overall number of components N[9]. Dividing the number of each distinct component by the overall number of components, the component concentration c_n ([-]) is calculated, Equation (9).

$$c_n = \frac{q_n}{N} \tag{9}$$

Together with the $H^c_{n,rel}$values, the component concentrations c_n enter the product statistical entropy function H^p, which is calculated for each component from n = 1 to N, Equation (10).

$$H^p\left(c_n, H^c_{n,rel}\right) = -\sum_{n=1}^{N} ld(c_n) \cdot H^c_{n,rel} \tag{10}$$

Through the component entropy term $H^c_{n,rel}$, each component's composition and relative mass is included in the product entropy function, while through the component concentration c_n the number and diversity of each component is considered. Regarding the effect of the component concentration, both an overall lower number of components in a product (e.g. a historic car from the 1950s vs. a modern car) and a larger number of identical components in a product (e.g. Li-ion battery cells in an electric vehicle) increase the component concentration c_n, which contributes to lower product entropy values, reflecting lower product complexity. This effect can be observed with constant $H^c_{n,rel}$ (SI 7: example 1, SI 8: example 2), which shows how processes like sorting, selective dismantling or collection of specific components could be assessed. Overall, the product entropy function behaves in such a way that a larger number of distinct components (low c_n) and a more equal substance distribution between the components (high $H^c_{n,rel}$) lead to larger product statistical entropy values.

The maximum product statistical entropy value is reached if each substance that is present in a product is uniformly distributed between the components. It means that no further change in substance distribution can increase the dilution of substances in the product. In this state, components can only distinguish themselves by their mass fraction in the product, and not by their substance composition, so that $\frac{H^c_{1,rel}}{m^c_1} = \frac{H^c_{2,rel}}{m^c_2} = \frac{H^c_{n,rel}}{m^c_n}$. In such a state, the maximum degree

[9] If all components in a product represent distinct components that appear only once, a simplified calculation can be employed: $H^p_{rel} = \sum_{n=1}^{N} q_n \cdot H^c_{n,rel}$, not requiring Equation (11) and (12).

of substance dilution in each component is determined by the total number of N components in a product, so that H^p_{max} is calculated according to Equation (11). After acquiring H^p_{max}, the value provides a reference for the calculation of H^p_{rel}, Equation (12). It is important to note that the product entropy function expresses the combined state of dilution of all present substances, including their mass, their dilution within each other (both expressed through each $H^c_{n,rel}$ for each component n) and their dilution among N given components. It has to be stressed that the product entropy values are not disconnected from the maximum entropy values on the substance and component level since the mass and substance distribution of each component is represented by each $H^c_{n,rel}$ value and is set in relation to maximum substance dilution (H_{max}) within the system (e.g. to an entropy value of a waste flow) (see Section 2.3). Therefore, each of the levels (material, component and product) are always integrated. Further integration of products and separate material flows is elaborated in the supplementary information (SI 9: example 3, SI 10: example 4, SI 11: example 5, SI 12: example 6, SI 13: example 7).

$$H^p_{max} = ld(N) \tag{11}$$

$$H^p_{rel} = \frac{H^p}{H^p_{max}} \tag{12}$$

The lowest H^p_{rel}value of zero is reached if the product consists of only one component, which itself consists of a single substance only, $H^c_{n,rel}$=0. As the number of substances and components of a product in a system is given, the number of substances and components cannot be changed. In such a case, products with n >1 number of components can reach the H^p_{rel}value of zero only if the number of substances is lower or equal to the number of components. Only then can each distinct substance be fully concentrated in each distinct component, leading to an entropy value of zero (lowest component complexity) for each component. It is important to note that outside of the component and product structure, substances can always be concentrated to full purity (at least theoretically, e.g. after an ideal recycling process, which separates each substance into a pure fraction), and entropy value reduces to zero. Therefore, the extreme cases of zero entropy and H_{max} can always be modelled for any system.

3.2.3 Case study of a simple automotive reuse and recycling system

To illustrate the multilevel SEA method and some of the lessons that can be learned from its application, first a simple case study on the recycling and reuse of components of a simplified car is presented (Figure 6). The case study aims to demonstrate the multilevel SEA method on a simple system, allowing for an evaluation of system changes in the context of the CE strategies employed. At first, a configuration is modelled, which simulates one life cycle for specific end-of-life scenarios. In a second step, the system is extended to simulate four consecutive life cycles. The systems are modelled employing the software STAN (Cencic and Rechberger, 2008). Through the modelling of consecutive system cycles, it is aimed to assess how different CE strategies perform over several recycling/reuse cycles. In addition to the demonstration of system behaviour that considers several life cycles of a consumer product, aspects such as increasing levels of impurities in subsequent recycling cycles are taken into account.

The case study system consists of four processes: production, disassembly of the product and reuse of components, shredding of components that are not reused, and recycling of materials from the shredder fraction (Figure 6). The use phase is not considered because it is assumed that the car itself does not undergo any material changes during use. These four processes have been chosen as they allow the recirculation of materials through the recycling process as well as the recirculation of components through the non-destructive process of disassembly and reuse to be modelled. Further, the system set up reflects the two main end-of-life vehicle processing routes, which are based on dismantling or shredding (Ferrão and Amaral, 2006).

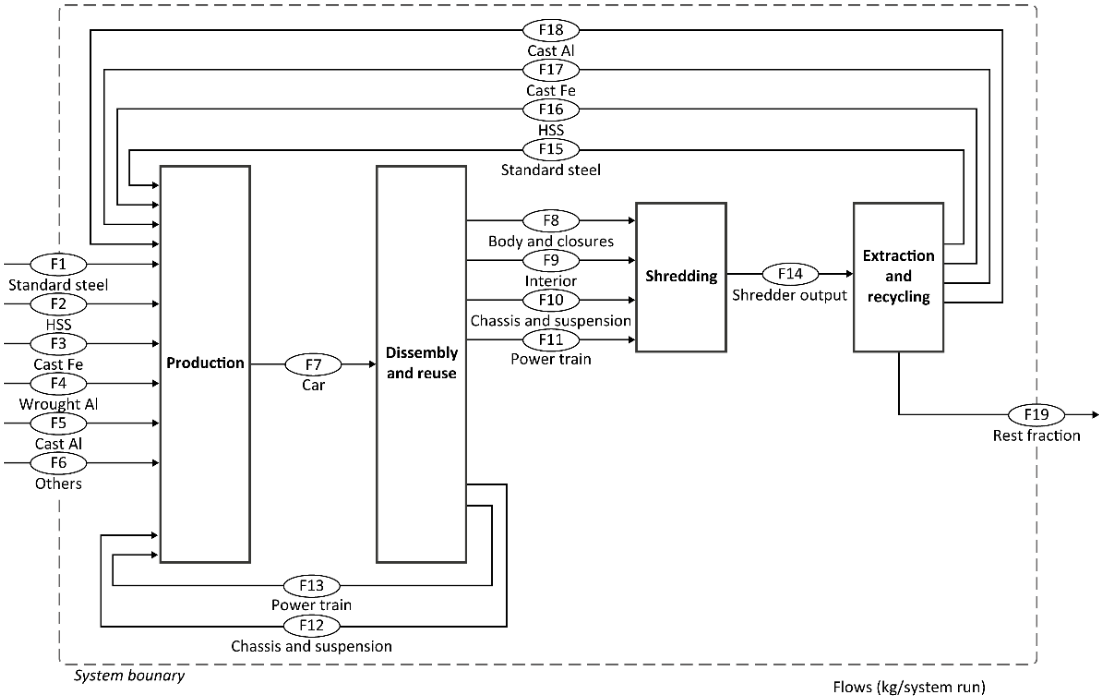

Figure 6: Illustration of the reuse and recycling system structure employed for modelling different scenarios.

In the production stage of the case study system, different combinations of inputs are used to produce the final product (car). These inputs represent reused components, recycled or virgin materials. Virgin material inputs are modelled as imports into the system, leaving out up-stream processes such as mining and refining to keep the system simple (Figure 6). After the production stage, and an average product life, at some point in time the product reaches its end-of-life status. It now enters a disassembly process, where the components can be either reused to produce a new product or be directed to the shredding process. After the shredding process, the shredder output fraction is either recycled or exported as a mixed rest fraction, representing a waste flow.

The simplification of the system is apparent, and its primary purpose is to serve as a straightforward demonstrator of the multilevel SEA method. If applied to specific plants, e.g. recycling plants, each process could be easily subdivided into a sequence of more detailed processes, such as air classification, magnetic separation, eddy current separation and others. The same applies if the method is applied to larger metabolic consumption-production systems, such as regional or larger economies and sectors. Further simplification also applies to the detail of product composition and structure. The product employed in the case study is modelled through four component groups (further components). Each component consists of different material combinations, which have been previously used and scaled to represent an average global car for other modelling purposes by Modaresi *et al.*, (2014) (see Table 7).

Table 7: Average car composition, divided into four main components and six material groups (based on Modaresi et al., 2014c).

Group name	Standard steel (kg)	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	61	0	0	12	2	173	248
Total (kg)	585	223	111	34	66.3	363	1382.3

Systems with different reuse and recycling scenarios are analysed. The first two systems represent extreme cases, where either all components enter the shredder process and none of the materials are recycled or where all components are reused (Figure 7).

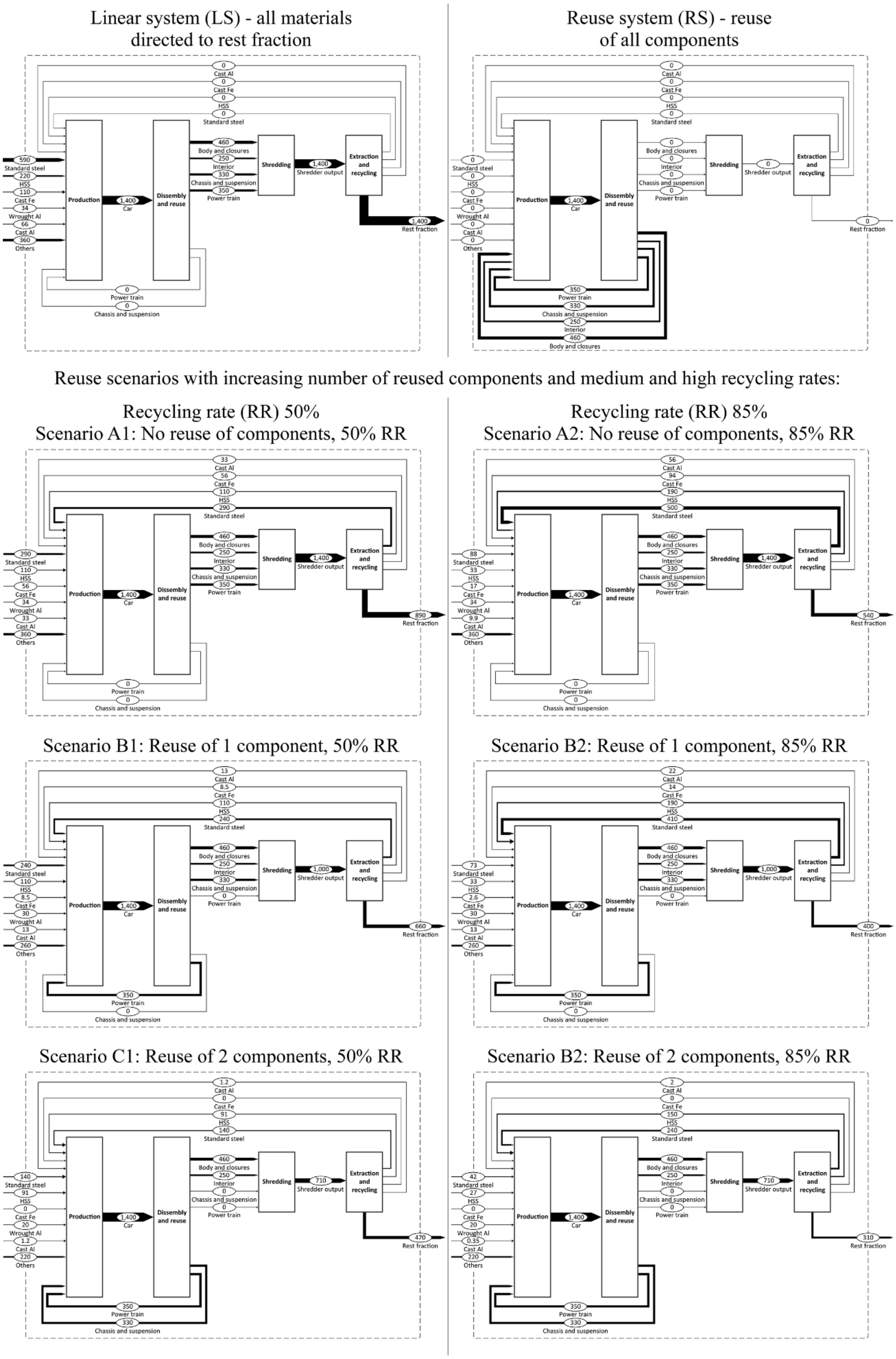

Figure 7: Extreme linear and full reuse scenario, followed by three reuse scenarios for a simple automotive system, each with a medium (50%) and a high (85%) recycling rate, values in kg per car.

In the first case, all materials are directed towards a rest fraction and leave the system as a waste flow, leading to the highest possible dilution. This case represents the so-called linear scenario (LS). In the second case, all car components are disassembled and reused, whereas no destructive processes are applied to the components and no waste flows and recycling flows are generated, representing the circular, or reuse scenario (RS). All alternative system configurations are intermediate cases between the entirely linear and circular scenarios (Figure 7). The extreme cases are used to evaluate the system performance as they indicate the distance of each of the intermediate system scenarios and system configurations to the ideal state of circularity, or the most linear system.

In scenarios A1 and A2, no reuse of components takes place and all components enter the shredder process. In scenarios B1 and B2 one component is reused, while in scenarios C1 and C2 two components are reused. For each scenario, a recycling rate of 50% (for scenarios A1, B1, C1) and 85% (for scenarios A2, B2, C2) are applied to the shredder output.

For each of the scenarios, the system is extended with additional product life cycles (Figure 8). The aim is to assess the differences in system performance over consecutive life cycles. As the systems differ only in the number of cycles, all other parameters are kept constant (as introduced in Figure 7), only one system is plotted explicitly (Figure 8). All systems receive the same initial system input (5 500 kg, which is the amount required to sustain four cycles of the linear system, see Figure 8). This ensures that different system performance, measured in RSE, is not a consequence of a different absolute resource quantity imported into each system.

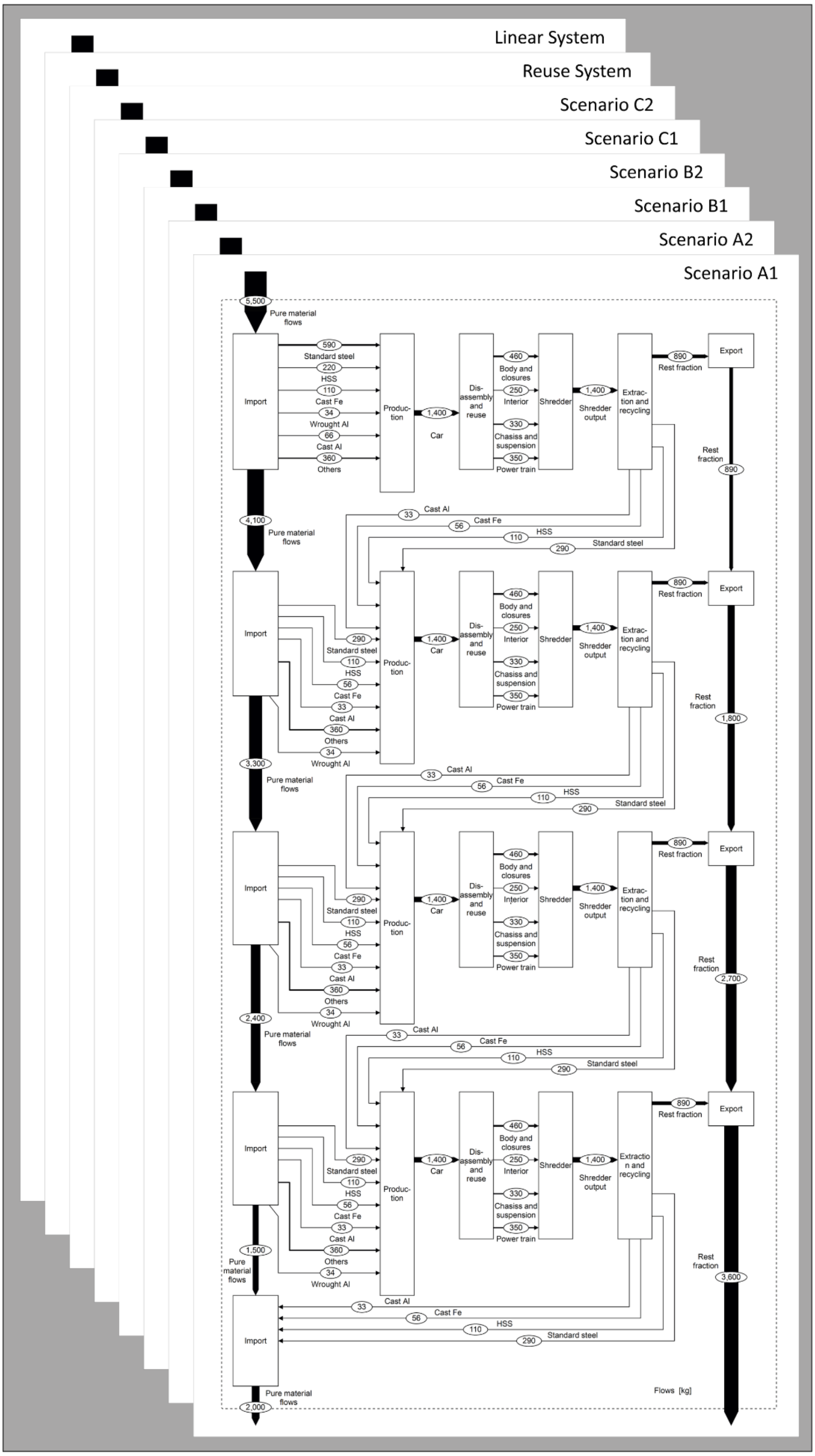

Figure 8: MFA systems for four product life cycles, based on the previously introduced single product cycle MFA systems

Note: Caption of the no reuse – 50% recycling system, all values rounded.

For each cycle, increasing levels of impurities are assumed for the recycled material flows. The recycling flows are modelled to be contaminated by the fraction 'others', which consists of materials that are not of our interest in the material flow system. Cross-contamination for the first cycle is modelled with one per cent and with two per cent with each additional cycle. These values are used to start with low impurity levels, but also to show the effect of higher impurity levels on the results, which is discussed in the sensitivity analysis in Section 3.3.4.

3.3 Evolution of Relative Statistical Entropy

3.3.1 Development of Relative Statistical Entropy over one product life cycle

The results of the multilevel SEA application to the case example are first discussed in more detail with regard to the first product life cycle, as shown in Figure 9. In the second step, the performance of systems for consecutive cycles is elaborated (see Section 3.3.2).

All systems start with a relative statistical entropy (H_{rel} = RSE) value of zero. It indicates that only separate pure materials are used as inputs in the production phase of the first system run. In the product stage, all scenarios are identical and the RSE value increases to 0.19. The increase in RSE shows the effect of dilution of the initially pure materials into the components and the product. After this initial dilution, the RSE values start to follow different trajectories depending on the applied combination of component reuse and recycling rates. For the RS scenario with the reuse of all components, the RSE value remains constant over all stages as no components enter the shredder and the recycling process, thereby avoiding dilution or concentration of materials (purple line). It is assumed that no components are worn out and lost for the next cycle.

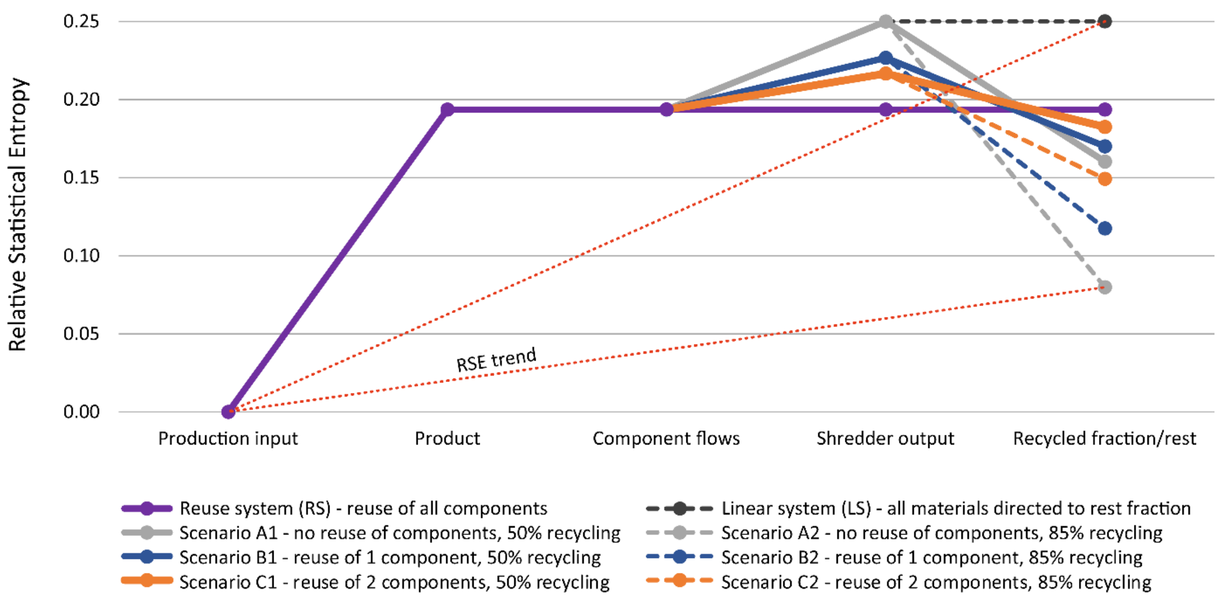

Figure 9: Development of RSE for the first five stages of the initial product life cycle.

All other scenarios deviate from the constant RSE value of the reuse system. The first change in RSE appears after the components enter the shredder process. Here, the four different reuse scenarios can be distinguished: no reuse (grey, scenarios A1 and A2), the reuse of one component (blue, scenarios B1 and B2), the reuse of two components (orange, scenarios C1 and C2), and the reuse of all components (purple, scenario RS). The LS scenario with no reuse of components has the highest RSE value because all components are transferred to the shredder fraction, leading to the largest dilution (RSE = 0.25). The other scenarios partially avoid dilution at the shredder stage through reuse, which is shown by the RSE value of 0.23 for the reuse of one component and the RSE value 0.22 for the reuse of two components. The degree to which the reuse of a component reduces the RSE value depends on the component's composition and its relative fraction in the product, so that the reuse of a more complex component has a higher potential to prevent dilution.

Therefore, the composition of a component affects all three levels: the dilution of materials in the component, the product, as well as in the subsequent flows, if the materials are liberated and mixed. In general, the destruction of components with a lower complexity in their composition has a lower potential to increase RSE values compared to more complex components. The same reasoning also applies to products.

The results also show that a dilution at one stage influences the RSE values of downstream stages. In the present case, the shredder output influences the subsequent recycling stage. The recycling configuration is set to either 50% or 85% for each reuse scenario. If no recycling is applied on the shredder output, no RSE reduction takes place. The changes in RSE show that dilution at the shredder output stage comes at the cost of RSE changes, e.g. through a recycling process that must be applied to the shredded fraction to reduce the RSE values afterwards. The largest overall dilution is present in the linear system due to the complete absence of reuse and recycling. Any other system has lower RSE values, which is either a result of lower dilution at the shredder output stage, higher recovery of functionality on the material level through recycling, or due to component functionality preservation through reuse. Therefore, the degree of RSE changes that can be observed when restoring the functionality of materials and components indicate some of the costs of initial dilution.

The most considerable RSE reduction is observed for the scenario in which no components are reused, but a high recycling rate of 85% is applied (A2). It shows that recycling is most effective for reducing RSE if a large fraction of diluted input material enters the recycling process and if the process is capable of separating most of the materials into almost pure fractions (1% impurities). The result is a set of near-pure material flows (RSE = 0.08). The application of a lower recycling rate of 50% leads to a RSE value of 0.16, which shows that the positive effect of higher recycling rates is more significant when fewer components are reused.

For scenarios with the reuse of one component, the effect of recycling is reduced to RSE values of 0.12 for the 85% recycling configuration (B2) and 0.17 for the 50% recycling configuration (B1). For scenarios with the reuse of two components, a further decrease in recycling effectiveness is observed, leading to RSE values of 0.15 (C2) and 0.18 (C1), respectively. Comparing the achieved changes in RSE, it can be observed that RSE reductions between the shredder output and the recycled fraction decrease at constant recycling rates, e.g. for 50% recycling from 0.08 (no reuse) to 0.05 (reuse of one component) and 0.03 (reuse of two components), with an increasing number of reused components. Two reasons are responsible for the decreasing reductions of RSE (making the reductions of RSE smaller). First, a lower rate of component reuse provides a larger potential to extract and recycle an overall larger mixed material flow. Second, the more components are reused, the lower the RSE value of the shredder output fraction is (less dilution), which in turn reduces the potential for further RSE reductions from higher recycling rates. These observations show that not only a higher overall material and component functionality is preserved at higher rates of reuse, but also that higher reuse rates require lower RSE reductions to be obtained from other circular economy strategies, such as recycling.

Comparing the initial starting RSE value of the product to the final value after the first life cycle allows an RSE trend to be drawn indicating the yield and purity (functionality) of recycled materials (Figure 9). In the following, highly purified materials are considered to have a higher level of functionality, as they can be utilised in a larger number of applications. This perspective, abstracts from other forms of material functionality which is achieved through other chemical and physical properties. With this in mind, the RSE trend shows to which degree the cycle is closed from a material perspective (measured from the RSE point of the production input). The flatter the RSE trend, the higher is the purity of the recovered materials.

The RSE trend can be also used for the measurement of product functionality preservation. In that case, the RSE trend would start at the point of the functional product (RSE value of the product) and be also represented by a flat line. In the case example, the maintenance of product functionality is represented by a flat line shown by the system of full reuse of components (purple), which is further referred to as the circularity reference level. The circularity reference level represents a system state which at all times preserves functionality and avoids resource losses. Measuring the distance of other systems to the circularity reference level allows the assessment of their performance, as compared to an absolute circular system state.

From the discussion of the results of the first product's life cycle, it is demonstrated that the multilevel SEA enables simultaneous assessment of the combined effect of two or more different CE strategies. It is shown how reuse and recycling strategies can be represented in terms of RSE simultaneously while showing that trade-offs between different CE strategies exist. High recycling rates are most effective for systems with a low level of reuse (e.g. A2), as they can decrease RSE to a larger extent and reach overall lower RSE values. This perspective represents the goal to recover functionality on the material level. From the perspective of functionality preservation on the level of the product, the goal would be to maintain RSE values as close as possible to the level of the product. By including additional system cycles, the next section shows how the systems behave over consecutive cycles.

3.3.2 Development of Relative Statistical Entropy over consecutive product life cycles

To assess the system behaviour over consecutive life cycles, the RSE values are calculated for four cycles. The development of RSE over the four cycles shows the performance of scenarios with different reuse and recycling configurations (Figure 10).

Similar to the first life cycle, the LS scenario reaches the highest RSE value also after four consecutive life cycles. It shows the largest degree of dilution among all present systems (Figure 10), while the RS scenario maintains a constant RSE value. All components re-enter the production process and do not produce any waste flows, resulting in zero additional pure material inputs required for the next life cycle. Another distinct characteristic of this system is the absence of any RSE changes. For this reason, it provides an interesting reference case with constant RSE values over time (cycles), independent of the number of consecutive product life cycles. Because all other systems represent combinations of different reuse and recycling configurations, their RSE values are located between the RS scenario and the LS scenario.

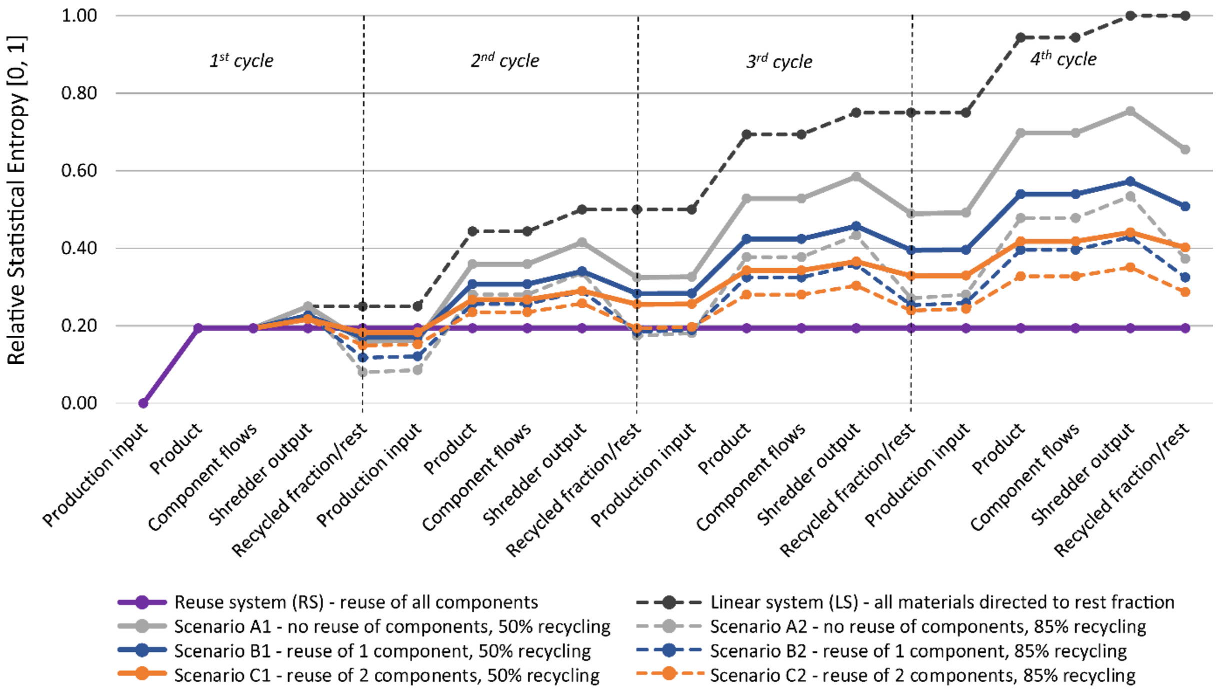

Figure 10: Development of Relative Statistical Entropy (RSE) for eight different reuse and recycling configurations, over four consecutive product life cycles.

The development of RSE for all intermediate scenarios shows how the combination of reuse and recycling options influences the RSE changes over the next life cycles. By modelling consecutive cycles, it is also shown that system performance is rather to be measured as the distance to the circularity reference level as it represents a system that avoids resource consumption, dilution and functionality losses at the material and component levels.

The goal of product functionality preservation translates in RSE terms as the minimisation of RSE increases, or the minimisation of the distance of any system to the circularity reference level (purple line, Figure 10). In this context, the system A1 with no reuse of components and a low recycling rate has the poorest performance among all scenarios, while the system C2 with the highest reuse and recycling rate can keep the RSE values closest to the circularity reference level. The system B2 with the reuse of one component and a high recycling rate performs better than both the system with a combination of high reuse and low recycling rate (C1) and the system with a combination of no reuse and high recycling rate (A2). These results also show that the system A2 with no reuse of components and a high level of recycling performs only slightly better than the system B1 with the reuse of one component and a recycling rate of 50%. The different system performance in terms of RSE demonstrates how the multilevel SEA can quantify and help to identify effective systems that preserve functionality over consecutive life cycles during which a combination of different CE strategies is being applied. Overall, the results reflect that additional improvements in the car metabolic system can be achieved by more dismantling, implying greater additional efforts to improve both the design for disassembly as well as sorting systems (Pauliuk et al., 2017).

Further, the results show that depending on the number of life cycles, the performance of systems can change in relative terms. Systems can change their relative position and distance to the system that is best in maintaining functionality, depending on the number of consecutive life cycles. The reason is that some systems follow a steeper trajectory, with initially lower RSE values, e.g. low reuse and high recycling systems (A1, B1), while others have a flatter trajectory, which maintains lower RSE values the more cycles are performed (B2, C2). For this reason, systems can change their relative position. This example shows that if a system is designed to operate for three or more product cycles, the reuse of one component can already sufficiently improve the system performance, compared to a high recycling system. After four product cycles, the reuse of two components with a low recycling configuration performs approximately the same as the high recycling scenario. This shows that the effectiveness of reuse increases relative to that of recycling with an increasing number of product/component use cycles.

The different impacts of an additional increase in recycling or reuse under a given set of possible scenarios can be a relevant question for decision-makers that aim to improve system circularity but must choose from a limited number of available options. In Table 8, the analysed scenarios that combine different levels of reuse and recycling, are ranked according to the final RSE value after four cycles. The lower the RSE value, the closer it comes to the RSE of the circular scenario that preserves component and product functionality over consecutive cycles (time), without generating waste.

Table 8: Relative Statistical Entropy ranking of scenarios with different reuse and recycling combinations, after four product life cycles (with RSE values in a separate column).

1.	High level of reuse and high level of recycling (C2)	0.29
2.	Low level of reuse and high level of recycling (B2)	0.32
3.	High level of recycling and no reuse (A2)	0.37
4.	High level of reuse and low level of recycling (C1)	0.40
5.	Low level of recycling and low level of reuse (B1)	0.51
6.	Low level of recycling (A1)	0.65
7.	No reuse – no recycling (LS)	1.00

3.3.3 Changes in Relative Statistical Entropy and resource effectiveness

The previous analysis shows that RSE values in multilevel SEA convey information about the capability of different combinations of reuse and recycling to minimise resource losses from a material system. While the overall development of RSE indicates the system performance, another type of information that can be derived from the multilevel SEA is the effort associated with the increase and decrease of RSE. This is reflected by the degree of RSE changes a system undergoes throughout the course of different cycles. The cumulated RSE changes that each of the systems requires to arrive at its final RSE value are calculated by adding each absolute change between two consecutive system stages in the system, with the results provided in Figure 11.

The cumulated RSE changes are determined to a higher degree by the level of component reuse than by the level of recycling (Figure 11). The reason is that each component that loses functionality is shredded, which leads to higher material dilution measured in RSE increases.

To restore the functionality on the material level, the RSE increases must be reversed through recycling. Changes in RSE in both directions, increases and decreases, lead to larger cumulated RSE changes. As any change in RSE requires activities to process products, components or materials, the changes in RSE can be linked to some form of effort to drive these activities. Therefore, both elements, the absolute RSE values (Figure 10) and the cumulated changes in RSE that are undertaken by a system to arrive at the final RSE values (Figure 11) can be integrated into the two dimensions of resource effectiveness: (1) the maintenance of functionality (proximity to the circularity reference level) and (2) with minimal effort (minimal RSE changes). Both elements are included as axes in the resource effectiveness framework (Figure 12).

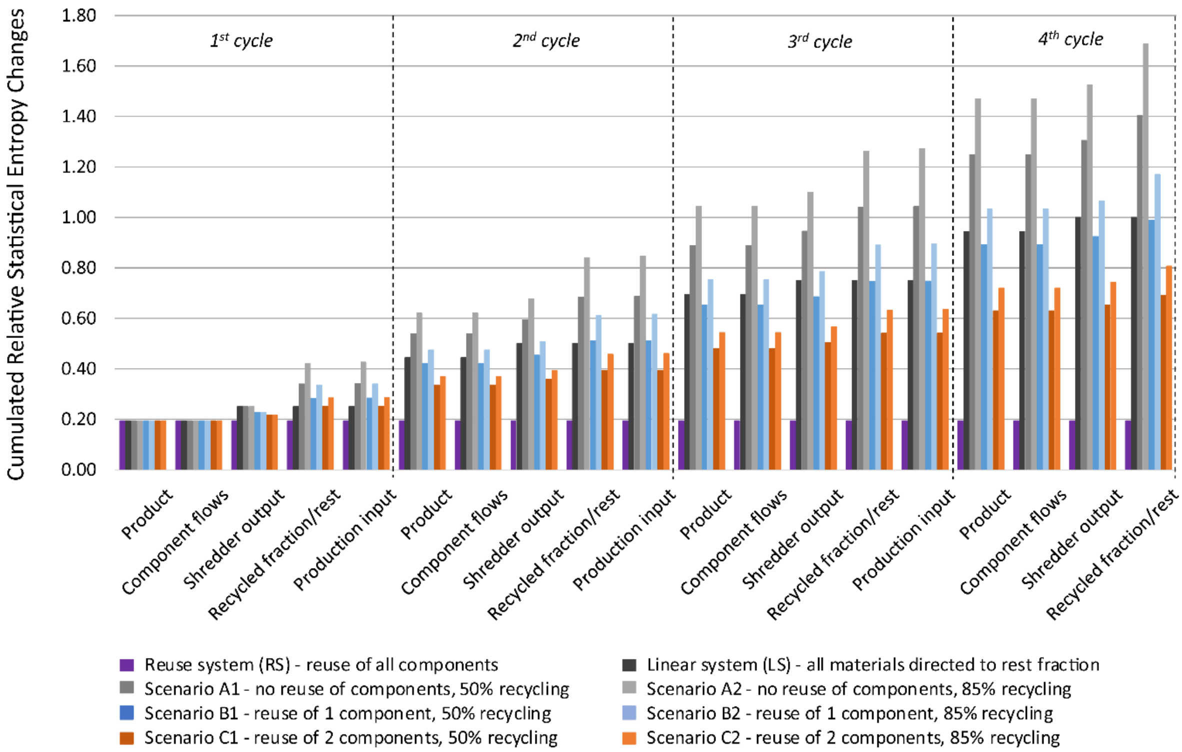

Figure 11: Cumulated Relative Statistical Entropy changes (ΔRSE_{cum}) over four system runs.

The framework can display any material flow system and allows its distance to be measured to the point of perfect resource effectiveness as well as the distance between different MFA systems. By projecting the systems under study, it is possible to distinguish three directions along which a material flow system can be situated (Figure 12). First, in a fully linear scenario the end-of-life product is entirely converted into waste after each life cycle. The position of such a linear system is represented by the LS system in Figure12. Second, any higher level of reuse locates the system closer to resource effectiveness. Third, once a system has deviated from perfect resource effectiveness, efforts, expressed as RSE changes, are required to regain the initial functionality, which moves systems towards lower absolute RSE values (on the x-axis), but also towards larger cumulative RSE change values (on the y-axis). Therefore, recycling systems can achieve a decrease in RSE, but only at the cost of larger cumulative RSE changes, making a system potentially circular, but not always more resource effective.

Furthermore, a higher recycling rate is likely to increase the cumulative RSE changes disproportionately, the closer the recycling rate approaches 100%, compared to RSE changes at the lower ranges of recycling rates, as is indicated in Figure 12. Increasing efforts of recycling at higher recycling rates are reported by, e.g. Baum and Pehnelt, (2018). Also, higher recycling rates have an effect on the quality of the recovered materials, which for some materials decreases with increasing rates of recycling (e.g. Kampmann Eriksen et al., 2018). Both aspects, the quantity and the quality that is achieved by the recovery system, are represented as the *distance to circularity* for a specific system (Figure 12).

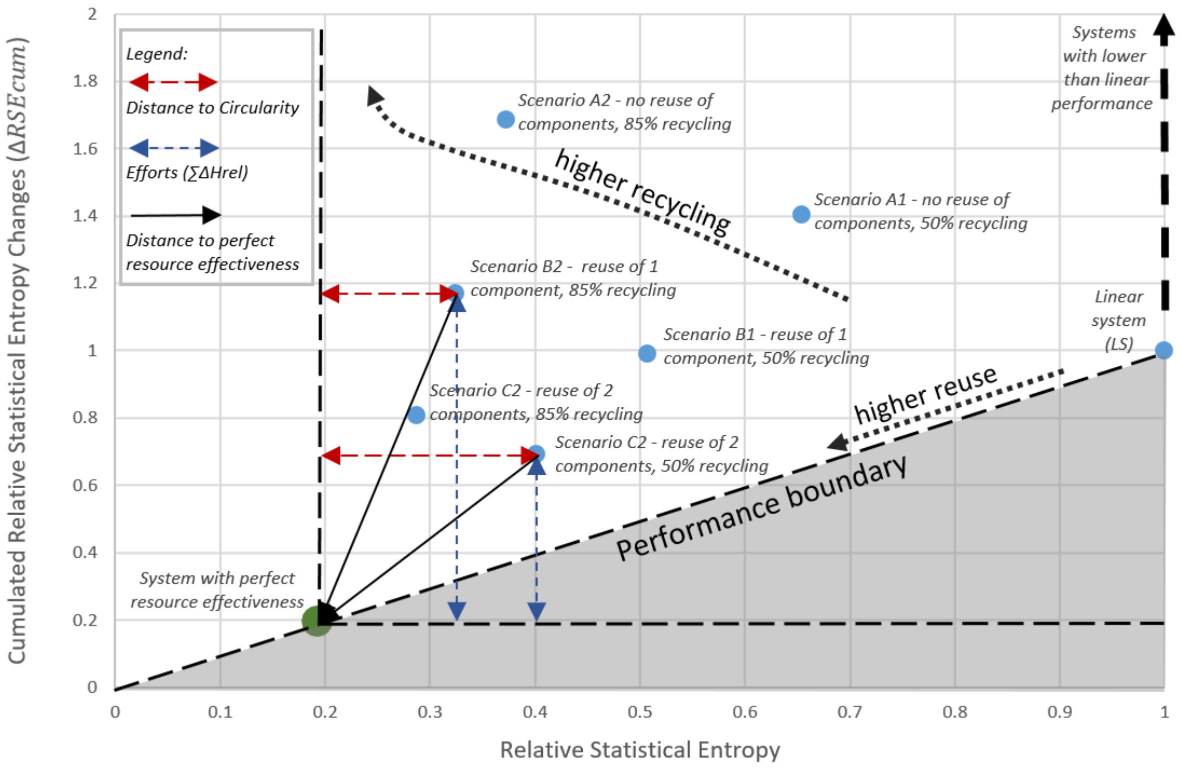

Figure 12: Resource effectiveness framework: It represents the distance to circularity and the required efforts, expressed as cumulated RSE changes (ΔRSE_{cum}) for each scenario that are required to regain functionality on the material, component or product levels. The combined vector of both indicates the distance to perfect resource effectiveness of a scenario.

Within the set of systems presented here, and because of the laws of thermodynamics, no system will be able to maintain itself forever or always restore full functionality. The, partly unavoidable, distance to full restoration of functionality, without the additional expense of efforts, is indicated by the *distance to perfect resource effectiveness*. Within the present set of systems, only the system which fully reuses all components represents a perfect resource effective system. Therefore, for the present set of systems, the distance to resource effectiveness can be decreased by two types of system improvements. First, it can be decreased by a higher level of reuse or through higher recycling rates. Both options decrease the distance to circularity, but at different cumulated RSE changes, represented as *efforts* (ΔRSE_{cum}) in Figure 12. It is important to note that apart from the entire product lifetime extension and component maintenance, the complete elimination of the distance to resource effectiveness of a system is impossible to achieve once functionality has been lost. Moreover, from a certain point on, the decrease in the distance to circularity is likely to result in the increase in the distance to resource effectiveness, being a result of increased marginal efforts to reach higher recycling rates. This is an important reason why a fully resource effective and circular system is not achievable with recycling alone. That the marginal efforts increase with higher rates of recycling is reported in different contexts, e.g. indicated by research on the identification of optimal recycling rates (Tonjes and Mallikarjun, 2013), for modelling disassembly and recycling systems taking account of CO_2 savings and costs (Igarashi et al., 2016) and by assessments of dismantling boundaries for car plastics recovery, which shows an exponential increase in the time required to disassemble an additional unit of plastic (Tian and Chen, 2016). The representation of the material flow systems in the resource effectiveness framework shows the limits of a set of systems to achieving circularity through the *distance to circularity*. The presence of any distance to circularity also indicates the reliance of a system on additional external inputs required for setting up a new product life cycle as any distance indicates functionality loss that has not been restored by the system itself and has therefore to be compensated by external inputs in the form of imported components or materials.

3.3.4 Sensitivity analysis

After the discussion of the main results, it is important to assess the main drivers and their influence on RSE changes. In general, a sensitivity analysis assesses how the input values influence the output values of a model, in this case how variables such as the recycling rate, purity of the recycled material flows, the composition of each component and the reuse rate influence the RSE values at each stage. Thereby, it is possible to identify the most influential variables. The sensitivity analysis is performed on a reuse scenario of one component and four product cycles. Monte Carlo simulations are undertaken for 10,000 system runs using MS Excel® and @Risk 7.6 software (Palisade Corporation, 2018). The sensitivity analysis is performed via multivariate stepwise regression analysis, resulting in normalised regression coefficients. Normalisation of the regression coefficients allows the relative importance of each coefficient to be evaluated. A positive normalised regression coefficient means that the output value increases if the input value increases, and vice versa. If the value is zero, it means that there is no significant relationship between the input variable and the output value. Thereby, the method allows the most influential factors and stages on RSE values to be identified, as presented in Table 9 (with the full table provided in SI 14).

Table 9: Normalised regression coefficients for the four most relevant factors and stages on RSE values at each stage, with the full table provided in SI 14.

	Initial run			1st Cycle			2nd Cycle			3rd Cycle		
Name	Product	Shredder output	Recycled fraction and rest	Prod. input	Shredder output	Recycled fraction and rest	Prod. input	Shredder output	Recycled fraction and rest	Prod. input	Shredder output	Recycled fraction and rest
Reuse	-	*-0.905*	*0.413*	*-0.55*	*-0.877*	*-0.453*	*-0.71*	*-0.851*	*-0.635*	*-0.77*	*-0.847*	*-0.7*
Recycling rate	-	-	*-0.864*	*-0.38*	*-0.441*	*-0.86*	*-0.45*	*-0.484*	*-0.735*	*-0.53*	*-0.518*	*-0.699*
Purity after recycling	-	-	*-0.112*	*-0.01*	*-0.008*	*-0.071*	*-0.01*	*-0.01*	*-0.044*	*-0.01*	*-0.01*	*-0.036*
Standard steel/Chassis*	*-0.537*	*-0.3*	*-0.09*	*-0.04*	*-0.078*	*-0.067*	*-0.07*	*-0.099*	*-0.094*	*-0.04*	*-0.048*	*-0.044*

Note: R^2 values are located between 0.95 and 0.99, indicating that the relationship between input and output variables is linear, which allows the application of regression-based sensitivity analysis.* Other influential factors on initial product RSE are the fractions of others in car interior (-0.55), standard steel in car body (-0.37), others in car body (0.23) and chassis (0.17), HSS in car body (-0.15) and chassis (-0.17).

The results of the sensitivity analysis show that the level of reuse and the recycling rate are by far the most influential factors on the final RSE value, followed by the purity of materials after recycling and only then by the composition of each component. The component composition has a particularly important influence on the initial product RSE values but decreases rapidly in influence for all materials with each additional cycle, here exemplarily shown for standard steel content in the chassis[10] (Table 9). The more substantial influence of the component compositions on the RSE values at the first life cycle can be explained by the absence of other factors at the initial product manufacturing stage, such as the effect of possibly previously applied CE strategies. Therefore, once the reuse of components and recycling start to affect RSE values, the original product and component composition become less relevant in determining the RSE result. Further, the observed influence of contamination with non-targeted materials has a similar influence on the RSE results as a single material composition change within a component (SI 14).

Overall, the level of reuse and the recycling rate are by far the most influential factors on the final RSE value, being at least four times more influential than the next most important factor (not considering the initial product stage due to the absence of the influence of recycling and reuse). The sensitivity analysis supports the previously discussed results, namely that a larger level of reuse and recycling leads to lower RSE values. The level of reuse has the largest influence at the shredder output stage. It determines the number of components that are directed to the shredder, thereby affecting the degree of material mixing at the end of the first life cycle. The largest influence of the recycling rate can be observed at the stage of the recycled fraction and rest. The sensitivity results show that the most significant impact on the degree of circularity of a product metabolic system is achieved by combining different CE strategies.

[10] As the component composition and the influence of material variations show a similar pattern, these are left out of the results table, but are provided in the sensitivity results (SI 14).

4. Resource effectiveness – an application case to the European automotive system

4.1 Vehicle production and End-of-life treatment

After the introduction of the resource effectiveness framework and the extension of Statistical Entropy Analysis to the multilevel Statistical Entropy Analysis, the method is applied to a generic European automotive system that represents a more complex system that allows demonstrating the method in a time-dynamic context, including the consideration of additional CE strategies such as lifetime extension and sufficiency strategies.

In the European Union (EU), as in other parts of the world, the need for mobility is largely satisfied through the use of personal passenger vehicles, accounting for more than 70% of all journeys (European Automobile Manufacturers Association, 2019). In 2017, a stock of 264 million vehicles was employed for this purpose (EC, 2019). With a global share of 24% of all passenger vehicles produced (16.5 million units), the EU-28 also represents one of the major production regions (European Automobile Manufacturers Association, 2019), making the automotive sector not only one of the most important economic sectors (European Economic and Social Committee, 2016), but a major resource consumer as well.

In the year 2015, 19 million tons of metals were required to maintain and renew the stock of vehicles, while the output of metals from the treatment of end-of-life vehicles (ELVs) was around 8 million tons (Huisman et al., 2017). The difference between the two flows is explained by unregistered exports of vehicles and ELVs, including the 3 to 4 million vehicles of unknown whereabouts (EC, 2018), which indicates the challenge of closing material loops before considering other limitations such as the fundamental limits of recycling (Ignatenko et al., 2008; Reuter et al., 2006). With the aim to establish a more circular economy (EC, 2020, 2018b, 2015), there is a need to better understand the patterns and dynamics of resource use.

In this context, the previously introduced methods of MFA and multilevel SEA (see Section 3) are applied, enabling a combination of diverse CE strategies, both destructive (e.g. recycling) and non-destructive (e.g. reuse of components) to be evaluated while measuring the system performance in reference to a functional product state (see Section 3.3.1). Deviations from the functional product state, e.g. through the failure of a component, demand subsequent processes like recycling, remanufacturing or the production of a new component and are therefore linked to some form of effort (e.g. inputs of energy, human labour). As statistical entropy directly measures the dilution and concentration activities performed in the system, effort is expressed in terms of changes in statistical entropy (as introduced in Section 3.3). In this context, by analogy with the second law of thermodynamics and the corresponding unidirectional nature of processes, the rationale is that the increases in statistical entropy (e.g. shredding of a vehicle), as well as decreases in statistical entropy (e.g. sorting, heavy media processing), are both related to effort that is required to perform the processes.

In the following, multilevel SEA is applied to a case study of a generic European automotive system to assess the resource utilisation and related losses of product, component and material functionality over time, while identifying the most effective CE strategy combinations that preserve functionality at the highest level with minimal effort. The method is applied to a set of future scenarios of the automotive system in order to provide insights into how system changes as a consequence of a series of commonly applied CE strategies, e.g. a higher share of EVs, improved recycling, higher reuse of components, higher utilisation of the existing vehicle stock, or an increase in the vehicle lifetime, all influence the trajectory of the system's evolution.

4.2 Linking stocks to material flows and Statistical Entropy Analysis

For the evaluation of the resource effectiveness of possible future transition paths of the EU automotive system, a sequence of steps is followed (see Figure 13). Depending on the parameters that characterise each of the scenarios employed (see Section 4.2.4), a stock-driven model is used to calculate the flows of vehicles between the production, the use, and the ELV treatment phases. The outputs from the stock-driven model are used as inputs for the generic MFA, thereby translating the overall vehicle flows into a more detailed set of material flows for each system phase within a certain period of time. By employing additional parameters such as reuse and recycling rates, a further scenario differentiation is achieved. Finally, SEA is applied to the MFA results.

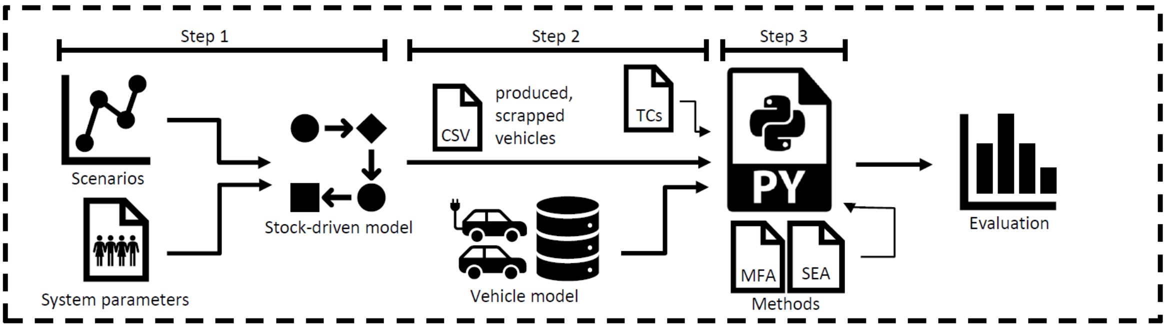

Figure 13: Sequence of methodological steps followed to calculate the Relative Statistical Entropy, (abbreviations: CSV = 'comma separated values' data set, TC = 'transfer-coefficients' file, PY = 'Python' program, MFA = Material flow analysis, SEA = Statistical Entropy Analysis).

4.2.1 <u>Stock-driven vehicle model</u>

Stock-driven models have been employed in different contexts, e.g. to estimate the evolution of housing stock and related material flows in the Netherlands (Müller, 2006), Norway (Bergsdal et al., 2007), and China (Hu et al., 2010), as well as for evaluating more specific material flows, e.g. steel (Pauliuk et al., 2012; Yan et al., 2013). Besides the stock-driven model approach that calculates the material flows based on historical or extrapolated stock data, with the in-use stock being the main driver for the material cycle, another model type is the input-driven model, which uses input and output flow data to calculate the stock (Müller et al., 2014). In the following, the stock-driven model is employed, which is based on the model provided by Pauliuk (2020). The model serves two purposes: (1) to quantify the inflows of vehicles to the use-phase and (2) to quantify the outflows of vehicles from the use-phase to the ELV-phase for each year. The model distinguishes between inflows and outflows of electric vehicles (EV) and internal combustion engine vehicles (ICEV). The structure of the model and the parameters employed are summarised in Figure 14.

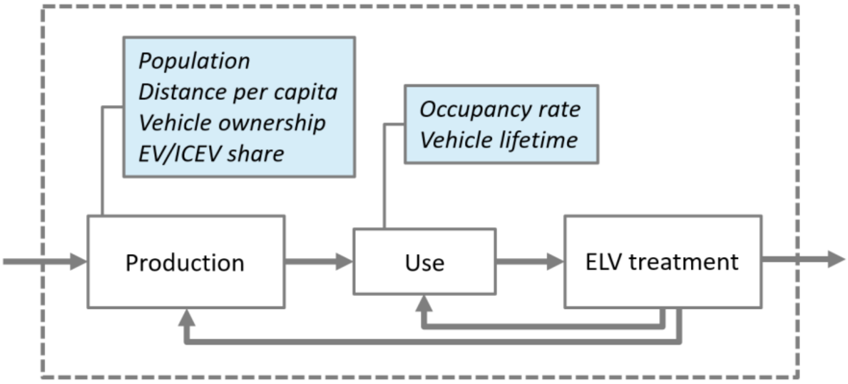

Figure 14: Overview of the stock-driven model and parameters with an influence on overall flows of vehicles.

For the time period 2010 – 2017, the inflows of vehicles are based on reported data for the EU-28 (European Commission, 2019c), with the 2018-2019 values being extrapolated based on the German vehicle stock evolution (Statista, 2020). For the projection of the future vehicle stock for the time period 2020 – 2050, the data is extrapolated based on the projected population by EEA, (2020) and a constant vehicle ownership rate (in the base scenario) in the EU, employing the base year 2019.

The vehicle stock is used to derive the outflows and inflows of vehicles per year. Based on an average vehicle lifetime of 16 years (scrapping age of vehicles) with a standard deviation of 5 years (Modaresi et al., 2014b), the renewal rate expresses that in each year an average of $\frac{1}{16}$ of the vehicle stock is replaced with newly produced vehicles. The number of new vehicles that enter the vehicle stock can be multiplied by the EV/ICEV ratio of each scenario (see Section 2.4).

The outflows of vehicles are derived based on the inflows of vehicles to the use system per year. The parameters that influence the outflows of vehicles include the size of the vehicle stock, the share of EVs/ICEVs in each age cohort (holding vehicles of the same age), and the lifetime function employed. Even though different lifetime distribution functions exist, the example of Müller (2006) is followed, using a normal distribution applied to each vehicle age cohort. In this case, the use of the normal distribution is applicable as vehicles are (1) considered a mature product with low initial failure rates, while (2) the average vehicle lifetime of 16 years with a standard deviation of 5 years locates the distribution far away from negative lifetime values. Otherwise, both aspects, the higher initial failure rates, e.g. such as in the case of electric and electronic equipment, as well as a lifetime distribution that is located closer to negative lifetime values, make the employment of a Weibull distribution advisable (e.g. Bakker et al., 2014; Geyer, 2020; Zeng et al., 2018). Further, the example of Modaresi et al. (2014b) is followed, employing the identical lifetime function for EVs and ICEVs, with more information, including the overall model provided in the supplementary information (SI 15).

Based on the scenarios employed that, among others, model a demand reduction and an extension of the vehicle lifetime, additional system parameters are required (see Figure 14). In order to keep the functional unit constant, the average distance driven per capita is set to 12,000 km/capita/year, representing a rounded average value for the EU-28 (Enerdata, 2016). The intensified use of the vehicle stock is modelled through a higher occupancy rate per vehicle so that the average distance driven per vehicle (15,000 km/vehicle/year), and the average vehicle lifetime remain constant. Based on the known vehicle stock, the population size and the distance driven per capita, the occupancy rate of 1.52 (capita/vehicle) is derived for the year 2019, using the MS Excel® solver method. The derived occupancy rate is in the range of the reported value of 1.4 and 2.7 capita/vehicle for the EU-28 countries (Fiorello et al., 2016). For scenarios that model a reduction in the vehicle stock, the occupancy rate increases over time, reaching the value of 2.14 (capita/vehicle) in the year 2050. Another set of scenarios increases the vehicle lifetime, which reduces the renewal rate and leads to a demand reduction for new vehicles as well as to a time delay in the vehicle outflows from stock to EoL treatment.

In addition to the changes in the flows of vehicles, two components, here identified as the *EV battery* (for EVs) and *other powertrain components* (for ICEVs), are employed to quantify the component flows that are replaced during the use phase of a vehicle. The lifetime of the EV battery is modelled with 9 years and a standard deviation of 3 years (Bobba et al., 2020), with the same lifetime distribution being applied to *other powertrain components*. Together with the component flows, the derived flows of vehicles are employed as inputs to the MFA. Thereby, the flows of EVs and ICEVs and related components are translated to more detailed material flows, which are introduced in the next section.

4.2.2 Material flow analysis of the automotive sector

In the automotive sector, MFA has been applied to analyse the use pattern of materials like aluminium, steel, polybrominated diphenyl ethers (Cheah et al., 2009; Choi et al., 2017; Hatayama et al., 2014; Niero and Kalbar, 2019), scarce and critical metals (Andersson et al., 2017a; Restrepo et al., 2017), as well as the flows and stocks of components (e.g. Bobba et al., 2019, Diener and Tillman, 2015). The MFA model employed consists of three main sub-systems (1) production, (2) use, and (3) ELV treatment (Figure 15), with each of them comprising more detailed processes and flows. For better readability, the production sub-system, the use sub-system and the ELV sub-system are referred to as 'production system', 'use system' and 'ELV (treatment) system' in the following.

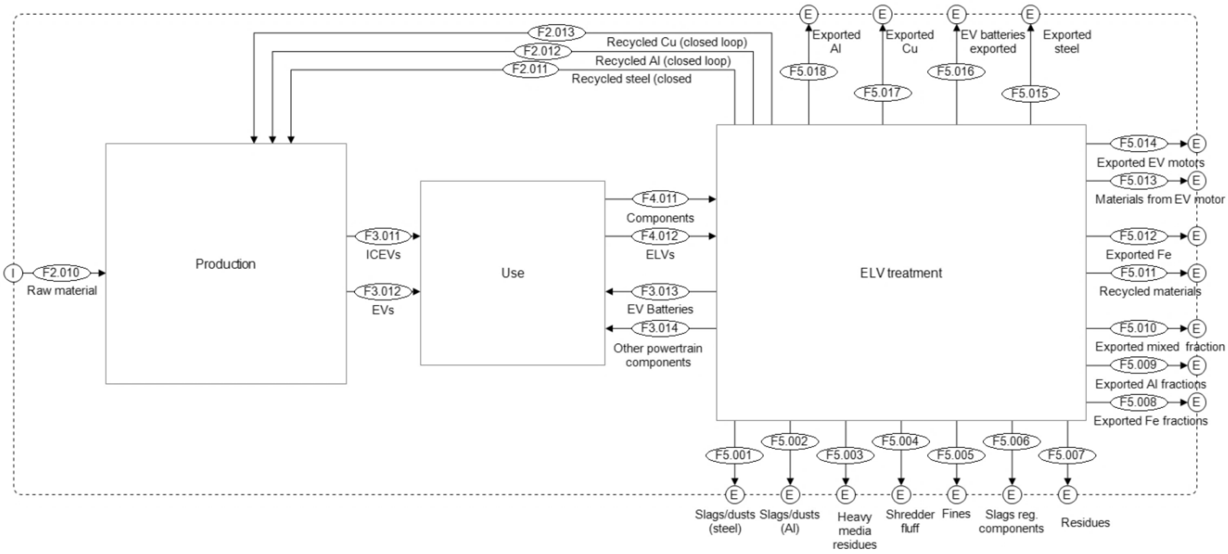

Figure 15: Car metabolic system, with its three sub-systems referred to as the (1) production system, (2) use system, and (3) ELV (treatment) system.

For the conversion of the vehicle flows from the stock-driven model described further above, the component composition for each vehicle type is based on the characterisation by Hawkins et al. (2013). Overall, 16 material categories (iron, steel, plastic, copper, glass, aluminium, cast aluminium, paint, rubber, carbon black, lead, ethylene carbonate, graphite, neodymium, lithium manganese oxide ($LiMnO_4$), Lithium hexafluorophosphate ($LiPF_6$) (further referred to as materials) and 11 groups of car parts, assemblies and sub-assemblies (further referred to as components) are employed. The components and materials considered represent a mass fraction of 95% for EVs and 96% for ICEVs of the original vehicle compositions (Table 10) (SI 16).

Table 10: Composition of Electric vehicle (EV) and Internal combustion engine vehicle (ICEV) (values in kg), distinguishing between common EV and ICEV components and distinct EV and ICEV components, including the representation of the overall mass for the materials employed.

	Components	Iron	Steel	Plastic	Copper	Glass	Aluminum	Cast aluminum	Paint	Rubber	Carbon black	Lead	Ethylene carbonate	Graphite	Nd	LiMn04	LiPF6	Total mass
Common EV and ICEV components	Interior and exterior	-	70.6	118.8	11.5	-	18.5	-	11.8	5.3	-	-	-	-	-	-	-	236.4
	Tires and wheels	-	46.9	-	-	-	-	-	-	18.1	8.3	-	-	-	-	-	-	73.4
	Brakes	18.2	10.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	28.8
	Chassis	-	172.5	5.9	4.1	-	-	-	-	-	-	-	-	-	-	-	-	182.4
	Body and doors	-	389.0	25.0	-	28.8	-	-	-	-	-	-	-	-	-	-	-	442.8
	Lead battery	-	-	0.7	-	-	-	-	-	-	-	11.2	-	-	-	-	-	11.9
EV components	EV battery	-	-	21.3	57.9	-	35.8	-	-	-	-	-	46.4	54.6	-	56.7	5.5	278.2
	EV motor and transmission	4.5	35.9	8.1	109.5	-	184.4	-	-	3.7	-	-	-	-	1.7	-	-	347.9
ICEV components	Engine	89.3	29.0	-	-	-	-	29.8	-	-	-	-	-	-	-	-	-	148.1
	Transmission	-	26.6	4.0	-	-	12.1	-	-	-	-	-	-	-	-	-	-	42.7
	Other powertrain	-	53.1	29.7	6.5	-	-	-	-	-	-	-	-	-	-	-	-	89.3
EV		22.7	725.4	179.7	183.1	28.8	238.7	-	11.8	27.1	8.3	11.2	46.4	54.6	1.7	56.7	5.5	1,601.8
ICEV		107.4	798.3	184.0	22.1	28.8	30.6	29.8	11.8	23.4	8.3	11.2	-	-	-	-	-	1,255.9

The production system and the ELV treatment system are linked by the use system, which is represented by the stock-driven model introduced further above (Section 4.2.1). The number of vehicles produced as well as the relative fraction of EVs and ICEVs determine the flows in the production system. Similarly, the outflows of vehicles from the use system result in the ELVs to be treated in the ELV system.

4.2.2.1 Vehicle production and use systems

The vehicle production system reflects the production of the individual components and the vehicle assembly. Three component categories are distinguished: components produced for (1) EVs, (2) ICEVs and (3) the so-called glider that represents a vehicle without the power train and that is employed in the EV as well as in the ICEV (see Table 10). The material flows are determined by the composition of each component and by the demand for vehicles in a specific year, including the distribution of EVs/ICEVs (Figure 16). Raw material inputs into the production system are modelled as pure material flows, with additional flows of recycled materials returning from the ELV system (steel, cast aluminium, copper). Other materials are recycled in an open-loop recycling process and are therefore directed to other sectors. The degree to which the recycled materials can be reused in the car production process is limited by the corresponding absorption capacity of the vehicle numbers produced. An example is the utilisation of recycled cast aluminium (cast-Al) that is primarily utilised in the ICEV engine block and transmission components, representing the main sinks for recycled cast-Al (Modaresi et al., 2014a). In the following, the recycled cast-Al uptake potential is limited by the cast-Al fraction of the *engine*, the steel uptake potential is limited by the vehicle's *body and doors*, and the copper uptake is limited by the *EV motor and transmission*. In the case that, in one or more years, the production system cannot take up the recycled materials, a surplus of recycled material can occur that is not utilised in the vehicle system and instead is exported to other sectors (Buchner et al., 2017).

Besides the recycling of materials, a reuse of two components, the *EV battery* (for EVs) and *other powertrain components* (for ICEVs), is implemented. Even though in practice, a larger number of components could be reused and remanufactured, consideration of the two selected components allows the effect of functionality maintenance to be assessed at the level of the component. Component reuse avoids the need for production of new components for repair activities during the vehicle lifetime. Even though the simplification of the model is apparent, the proposed component selection allows scenarios in which a large proportion of car components are exchanged, scrapped, or reused to be modelled, thereby establishing a more comprehensive flow diversion as compared to one in which minor components (e.g. brake callipers) are reused.

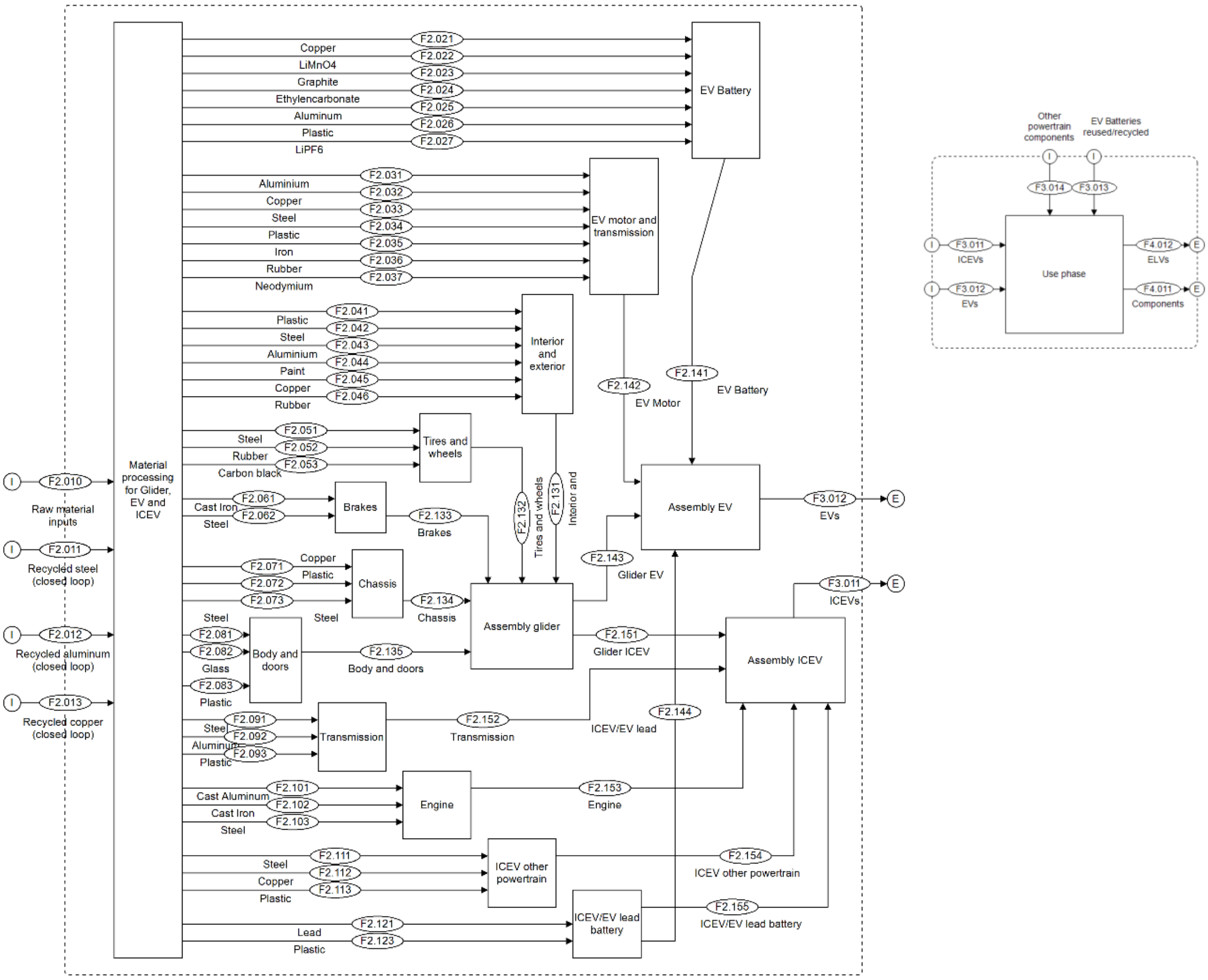

Figure 16: Vehicle production and use systems.

4.2.2.2 ELV treatment system

The implementation of the ELV directive (Directive 2000/53/EC) resulted in an intensified study of ELV system assessments in terms of specific material fractions, e.g. automotive shredder residue (ASR) (Cossu and Lai, 2015a), treatment processes (e.g. Ciacci et al., 2010), and ELV systems of EU member states (e.g. Andersson et al., 2017, Restrepo et al., 2017). Despite compliance among a large majority of EU-member states with the ELV directive's (2000/53/EC) targets to recycle and reuse 85% and recover 95% of the vehicle mass (Eurostat, 2020), few studies take an overarching EU perspective (e.g. Mathieux and Brissaud, 2010). The reasons for this could be the diversity of ELV treatment systems and/or the uncertainty and variability regarding the input and output material flows and their composition, especially when translating the available information to the European level (SI 17). In this context, it must be stressed that the MFA derived here can only represent a generic model.

The structure of the ELV treatment system is based on the study by Andersson et al. (2017a), who provide one of the most detailed MFA studies concerning the processes and mass flows for the EU member state Sweden. As the system structure varies between individual ELV treatment plants and between countries, the complexity of the system structure is reduced to represent the main processes, thereby allowing for a larger number of literature sources to be considered, especially when deriving the compositions of the material flows (SI 19).

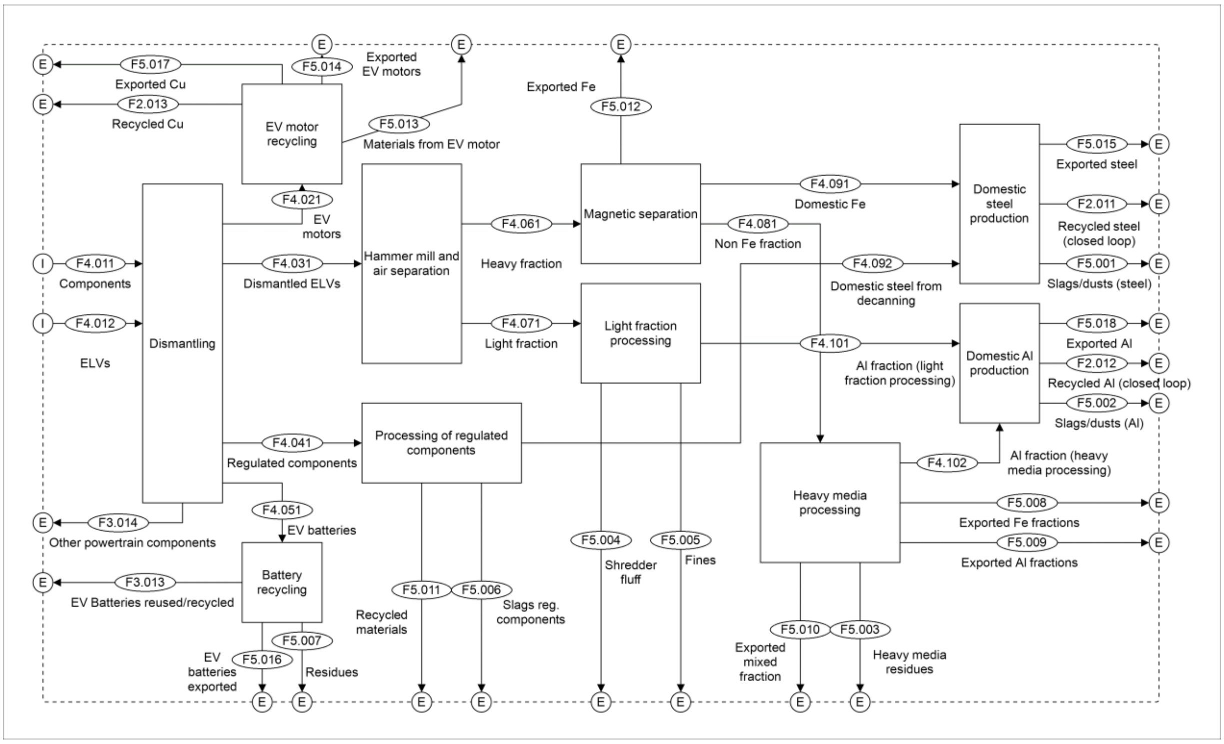

Figure 17: ELV treatment system.

The ELV treatment process starts with the dismantling of vehicle components. Some components, like batteries, represent regulated components and require separate recycling processes. Depending on the vehicle age and condition, most valuable components are dismantled to serve as spare parts for reuse, ultimately resulting in around 90% of the vehicle being directed to the shredder (Cossu and Lai, 2015a; Despeisse et al., 2015). In the ELV model employed, the reuse of components is modelled through the partial reuse of *Other powertrain components*, *EV batteries,* and *EV motor and transmission*. In addition to components that enter the system as part of the vehicle (integrated in the ELV), component flows generated during the vehicle lifetime (*Other powertrain components* and *EV batteries and transmission*) are also included.

After dismantling and the diversion of some components to specialised processes, like battery recycling, the remaining ELV hulks enter the shredder, where the vehicle is compacted and cut by a hammer mill (Vermeulen et al., 2011). Air separation partitions the shredded fraction into a light and a heavy fraction, which enter two different treatment processes. The heavy fraction largely consists of metals, which are further segregated by magnetic separation into ferrous and non-ferrous scrap that eventually enter a specialised metal recycling process. The light fraction is divided into different fractions of automotive shredder residue (ASR), further referred to as shredder fluff. Shredder fluff consists of light combustible materials in varying proportions, e.g. rubber, plastic, and textiles (Gradin et al., 2013; Mancini et al., 2012; Ruffino et al., 2014; Santini et al., 2011). The non-ferrous fraction typically undergoes an eddy-current separation, where metals such as aluminium and copper are separated (Despeisse et al., 2015), with the rest of the material sent further for heavy media processing. Based on the density of the materials, additional material fractions of different density groups are produced, which are exported to be treated in more specialised processes, are landfilled, or enter the energy recovery process (Cossu and Lai, 2015a; Mancini et al., 2014).

Based on the processes and material flows shown in Figure 17, additional literature sources are employed to derive transfer-coefficients (TCs) that describe the partitioning of the material input flow to the output flows of each process, thereby allowing the material flows in the ELV system to be modelled. Based on the vehicle flows and the shares of EVs/ICEVs, the material flows can be calculated for each year, while allowing the introduction of system improvements based on the scenarios employed. Each of the scenarios can then be evaluated for its ability to produce functional components and materials, while quantifying the effort that is expressed in terms of statistical entropy changes over time.

4.2.3 Relative Statistical Entropy changes over time

In the following, the previously introduced multilevel SEA method (Section 3.2) is applied. It allows considering additional hierarchical levels of components and products and evaluate different combinations of CE strategies. Further, it has been demonstrated that SEA results can be related to an ideal CE state that preserves functionality at the highest possible level (see Section 3.3). In a production – use – end-of-life system, the preferred state that is employed in the following represent the functional product state. Therefore, once this functional product state is reached, the functionality should be preserved for a maximum period of time. From that point on, any increase in RSE indicates a functionality loss that can only be restored by employing additional processes that reverse the RSE increase (e.g. a worn-out component is discarded, processed or replaced). Therefore, the rationale is that any changes in RSE should be avoided as long as possible once a functional product state is reached to avoid the effort required for returning it to the initial functional state. The changes in RSE (ΔRSE) between system stages (e.g. stage a-e) are calculated according to:

$$\Delta RSE_{a-e} = |RSE_e - RSE_d| + |RSE_d - RSE_c| + \cdots + |RSE_b - RSE_a|$$

The calculation of the material flows and the RSE values is performed in a combined MFA-SEA model (SI 20).

4.2.4 Future transition scenarios for the automotive system

The scenarios employed in the following serve the evaluation of possible future states of the EU automotive system through SEA. They are explicitly stated as hypothetical, being subject to typical limitations encountered when projecting possible future developments discussed in detail by Vergragt and Brown (2007). Nevertheless, the base scenarios that determine the uptake of EVs over time are based on (Hill and Bates, 2018), with the overall employed scenarios being summarised in Table 11, followed by a more detailed description.

Table 11: Scenarios employed in the analysis with their corresponding key parameters, indicated by the colour codes (S = 'scenario', D = demand reduction, REU = reuse, REC = recycling, LFT = lifetime, EV= electric vehicles, ICEV = internal combustion engine vehicles).

	S70	S100	S70-REU	S70-REU-REC	S70D	S70D-REU	S70D-REU-REC	S70D-LFT	S70D-REU-REC-LFT	S100-REU-REC-LFT
Share of EVs in 2050 (sales) 70%	■		■	■	■	■	■	■	■	
Share of EVs in 2050 (sales) 100%		■								■
Demand reduction (from the year 2025)					■	■	■	■	■	■
Higher reuse of components			■	■		■	■		■	■
Improved ELV recycling (from the year 2030)				■			■		■	■
Lifetime increase								■	■	■

Scenario I – II: (S70 and S100)

In the first two scenarios, the only transition driver is the increased market share of EVs. In the year 2050, the share of EVs sold is 70% (*S70*) and 100% (*S100*). Other parameters, like lifetime and ELV recycling system performance, are left unchanged. The first two scenarios thus focus only on the different speed and magnitude of EV uptake.

Scenario III – increased component reuse (S70-REU)

The third scenario builds upon the *S70* scenario with the addition that higher reuse of vehicle components is implemented. The reuse of components is modelled through the flows of *EV batteries*, and *EV motors* for EVs and *Other powertrain components* for the ICEVs. The components are sourced via two routes: (1) from ELVs that enter the dismantling process and (2) from components that brake down and are removed during the lifetime of a vehicle (see Figure 17). EV motors enter the recycling system only as part of an ELV.

The increase in reuse is modelled as an increase in the diversion rate away from the process of hammer mill and air separation, directing the components to specialised processes like *EV motor* recycling, battery recycling, or to the reuse flow of *other powertrain components* (see Figure 17). For component flows that enter the recycling system as part of an ELV, the diversion rate of the components to specialised processes (EV battery recycling and EV motor recycling) increases for *EV batteries* from 0.45 to 0.95 and from 0.3 to 0.5 for *other powertrain components*. For components that do not enter the recycling system as part of an ELV, the diversion rates are set to 0.95 for *EV motors* and *batteries* and 0.5 for *other powertrain components*. The uptake of components is limited by the number of components produced for spare parts for one year, reflecting the situation that used components are only employed as spare parts for repair and not employed in the production of new vehicles.

Scenario IV – increased component reuse and recycling (S70-REU-REC)

In addition to the increased reuse of components, the *S70-REU-REC* scenario includes an improvement in the ELV recycling system. As the ELV recycling system is modelled via TCs, system improvements are also translated to TCs that are employed from the year 2030 onwards. Even though it is unlikely that system improvements occur during a time period of one year, the rapid transition allows the effects of recycling and reuse to be clearly distinguished. The changes implemented in the ELV system from the year 2030 onwards are summarised in Table 12.

Table 12: Improvements in the ELV recycling system from the year 2030 onwards, based on reported sources and assumptions to be found in the supplementary information (SI 21).

Process	Improvement
EV motor recycling	10% improvement in the reuse of the metal fraction that is present in EV motors (iron, steel, copper, aluminium)
Battery recycling	Recycling of battery materials doubled, (compensated by reductions of batteries exported)
Hammermill and air separation	Diversion of iron and steel increased from 96.7% to 97.0%, and of plastic from 86.7% to 90.0%
Magnetic separation	Domestic recycling of ferrous metals increased by 10%, as well as diversion of copper from ferrous fraction
Heavy media processing	Diversion of copper from 14.5% to 60.0%, and glass from 50.0% to 80.0%
Domestic steel production	Closed-loop recycling of ferrous metals increased by 20% (potential uptake limited by the demand created by the component body and doors in a specific year)
Domestic Al production	Closed-loop recycling of cast aluminium increased by 70% (potential uptake limited by engine cast aluminium demand in a specific year)

Scenario V - VII – demand change (S70D, S70D-REU, S70D-REU-REC)

Scenarios *V-VII* build upon the scenarios *I*, *II* and *IV,* with the only difference that a demand reduction for new vehicles is implemented. The demand reduction is modelled through a higher occupancy rate per vehicle, which increases steadily from 1.52 capita/vehicle in the year 2020 to 2.14 capita/vehicle in the year 2050. The modelled increase in the occupancy rate per year results in a vehicle stock reduction of 74 million vehicles in 2050 compared to the 272 million vehicles in the year 2020. The increase in the occupancy rate is based on the assumption that an increasing use of various car-sharing strategies will be employed, representing one element of the updated Circular Economy Action Plan of the EU (European Commission, 2020).

Scenario VIII to X – lifetime increase (S70D-LFT, S70D-REU-REC-LFT, S100D-REU-REC-LFT)

The scenarios *VIII* to *X* model the effect of a lifetime increase in the vehicle stock from the year 2020 onwards. The lifetime increases from 16 to 18 years for the scenarios *S70D-LFT*, *S70D-REU-REC-LFT and S100D-REU-REC-LFT*. The last two scenarios are included as they combine all CE strategies employed in previous scenarios with EVs, representing 70% and 100% of all vehicles entering the stock in 2050.

4.3 Future flows and Relative Statistical Entropy changes

4.3.1 Flows of produced vehicles and ELVs

The flows of newly produced vehicles that enter the use system (Figure 18A) and the outflows of ELVs from the use system entering the ELV system (Figure 18B) are projected over time (in millions of vehicles per year). A distinction is made between the total flow of vehicles, EVs and ICEVs. The projections are shown only for the *S70*, *S100*, *S70D*, the *S70-D-LFT and the S100D-LFT* scenarios, as all other scenarios build on one of these projections (e.g. *S70D-REU* employs the flows of vehicles from the scenario *S70D*, with additional improvements in the reuse *'REU'*). The increase or decrease in the uptake of EVs and ICEVs is shown by the slopes for each scenario graph, e.g. the inflows of ICEVs being directly related to the number of EVs entering the vehicle stock in a specific year. Aggregation of the inflows of ICEVs and EVs results in the total inflows of vehicles for each scenario. The total inflows and outflows of vehicles decrease for the scenarios with a demand reduction (*S70D*), while the increase in the vehicle lifetime leads to a further reduction of total vehicle flows (*S70D-LFT*). Besides the overall number of vehicles that enter the use system per year, Figure 18A also shows the intersection of EV and ICEV graphs, indicating when EV and ICEV inflows become equal.

The outflows of vehicles from the use system to the ELV system are shown in Figure 18B. The outflows of vehicles react with a delay that results from the vehicle lifetime. For this reason, the outflows of vehicles start changing only towards the year 2030. The changes of outflows between the different scenarios accelerate towards the year 2035, from then on following a similar pattern as the inflows in the year 2020, with the difference that the curves are smoothed due to the lifetime function applied.

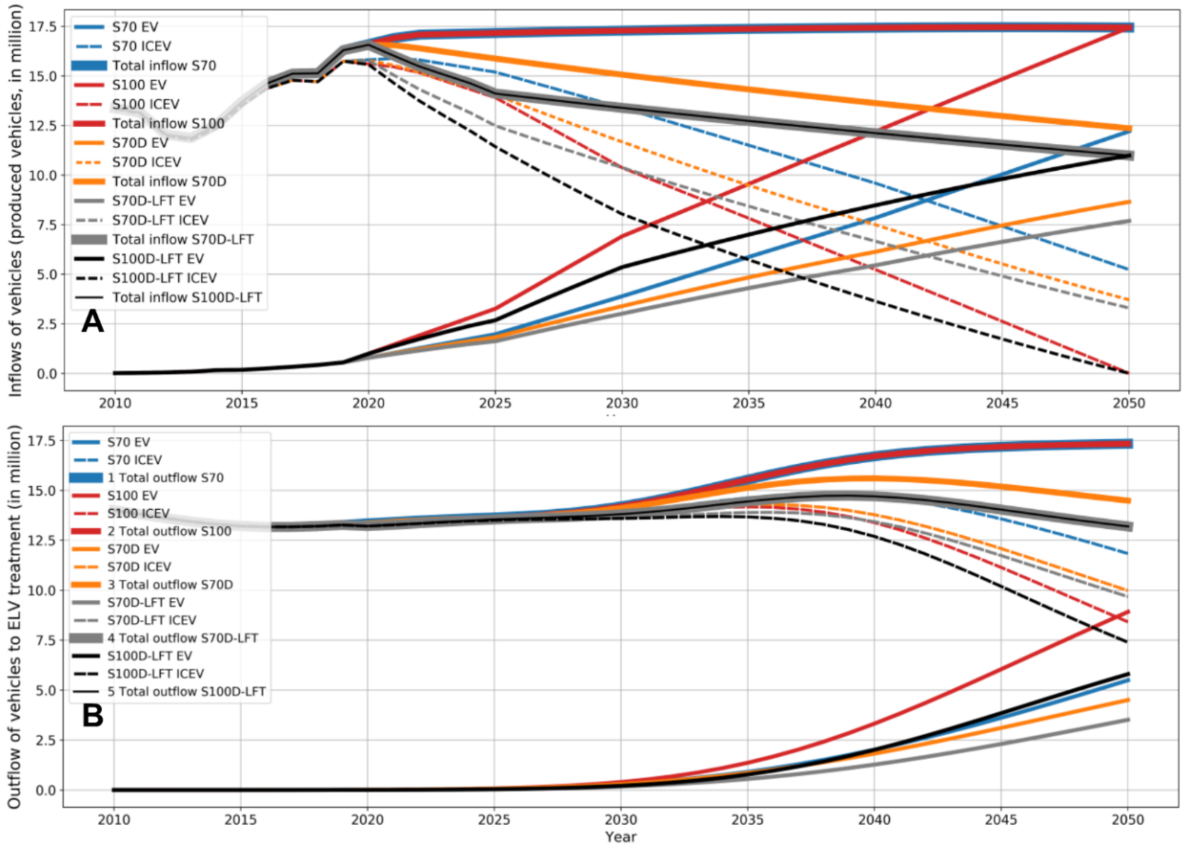

Figure 18: (A) Inflows of vehicles from the production system to the use system, and (B) outflows of vehicles from the use system to the end-of-life treatment system as end-of-life vehicles (ELVs).

The inflows and outflows of vehicles are used as inputs to the MFA-SEA model. Before presenting the results of the MFA-SEA model over time, a single-vehicle's RSE values, distinguished by its materials and components, are presented, followed by a discussion of a vehicle's life cycle.

4.3.2 Relative Statistical Entropy changes over a single-vehicle's life cycle

The direct comparison between the material composition of each component in terms of its mass (Figure 19A), the resulting RSE values (Figure 19B) and the RSE per kg of material employed (Figure 19Figure 19C) allow to illustrate how each component and its materials contribute to the overall RSE of the vehicle. According to the vehicle's composition presented further above (Table 10), the same three main component groups are distinguished.

The glider components are common to both vehicle types (EV and ICEV) and represent a large fraction in terms of their mass as well as in terms of RSE. The comparison between the material composition and the resulting RSE values shows that components with a less complex material mix like the *body and doors* or the *chassis* (see Figure 19A) have lower RSE values if compared to their mass fraction in the vehicle (see Figure 19B). The reason is that both components are composed of only a few materials, with one material, in this case steel, being the dominant constituent. The contribution of steel to the components' RSE values is small, and if expressed in terms of RSE/kg (Figure 19C), steel becomes even less important, while other materials such as copper, glass and plastic have a larger influence on the components' RSE (Figure 19Figure 19B).

Employing another component example of the *interior and exterior* shows that the presence of a larger diversity of materials and their higher dilution is reflected in higher RSE values. In this case, rubber, paint, aluminium and copper represent 20% of the component's mass (Figure 19Figure 19A) but contribute 45% to the component's RSE (Figure 19Figure 19B). Expressed in RSE/kg, Figure 19Figure 19C shows that rubber, paint, aluminium and copper are present in a highly diluted form. Given that larger component complexity and higher material dilution (here expressed in higher RSE values) has an implication for subsequent end-of-life treatment processes, e.g. having a negative influence on their recyclability (Gutowski et al., 2011; Iacovidou et al., 2017; Tam et al., 2019), RSE values can be employed to identify material and component hot-spots that make recycling more challenging, while triggering further considerations, e.g. regarding product design.

The comparison between EV and ICEV specific components shows how component composition and component mass contributes to their different RSE values. Both EV components, the *EV battery* as well as the *EV motor and transmission,* have a large mass (Figure 19Figure 19A) that together with their more complex material composition and higher material dilution (Figure 19Figure 19B) results in their high RSE values. In contrast, the ICEV related *engine*, *transmission* and *other powertrain* components exert relatively low influence on the overall RSE of the vehicle. Besides copper and plastic, which are diluted to a higher degree, the base metals steel, iron, aluminium and cast-Al add little to the RSE of ICEV specific components (Figure 19Figure 19B). The higher RSE values of the EV components and their materials (Figure 19Figure 19B, 7C) draw attention to the challenges that are related to their recycling and the related effort involved (e.g. Oliveira et al., 2015; Yun et al., 2018; Zeng et al., 2014). As an example, Nd that is present in a highly diluted form (Figure 19Figure 19C) requires more targeted recycling processes and therefore remains a challenge for the recycling sector due to related effort and costs, despite the potentially high-value recovery (e.g. Bandara et al., 2014).

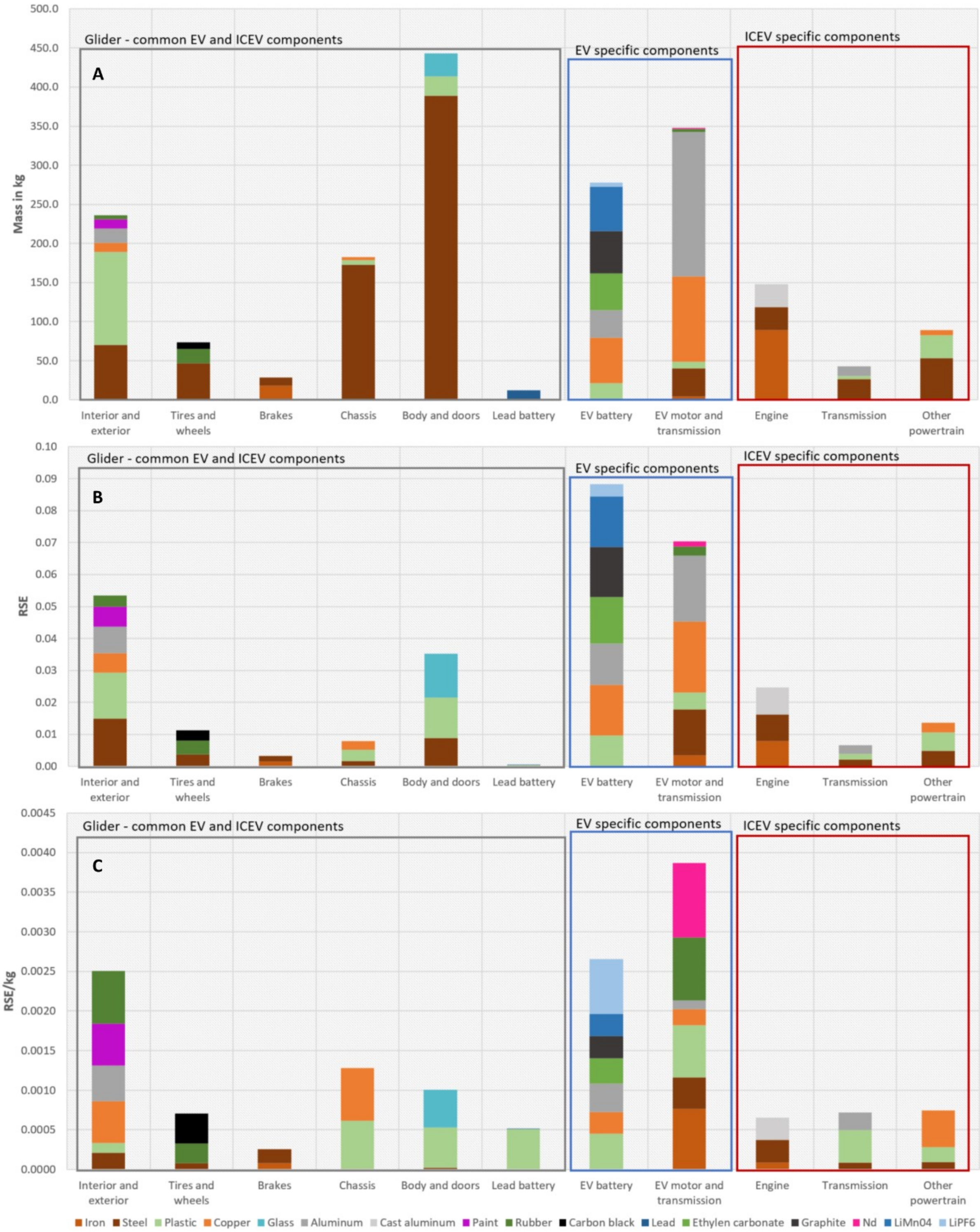

Figure 19: Component material composition (in kg) (A), Relative Statistical Entropy (RSE) for components and materials (B), and RSE per kg of material (EV = electric vehicle, ICEV = internal combustion engine vehicle).

Development of Relative Statistical Entropy over a single-vehicle's life cycle

The life cycle of a vehicle starts with the production phase, representing a dilution and/or mixing process of the very pure and refined raw materials, which is shown by an increase in RSE for both the ICEV and EV and is expressed as ΔRSE (see Figure 20Figure 20). The RSE increase is larger for the EV, resulting from the higher material dilution within the *EV battery* and the *EV motor and transmission* components. Both components have a high mass while representing a higher complexity in their material composition, resulting in overall higher ΔRSE values. For the ICEV, the *engine*, *transmission* and *other powertrain components* represent the ICEV specific components, which lead to a smaller RSE increase as they have a less complex composition, consist of less diverse raw materials and have an overall lower mass.

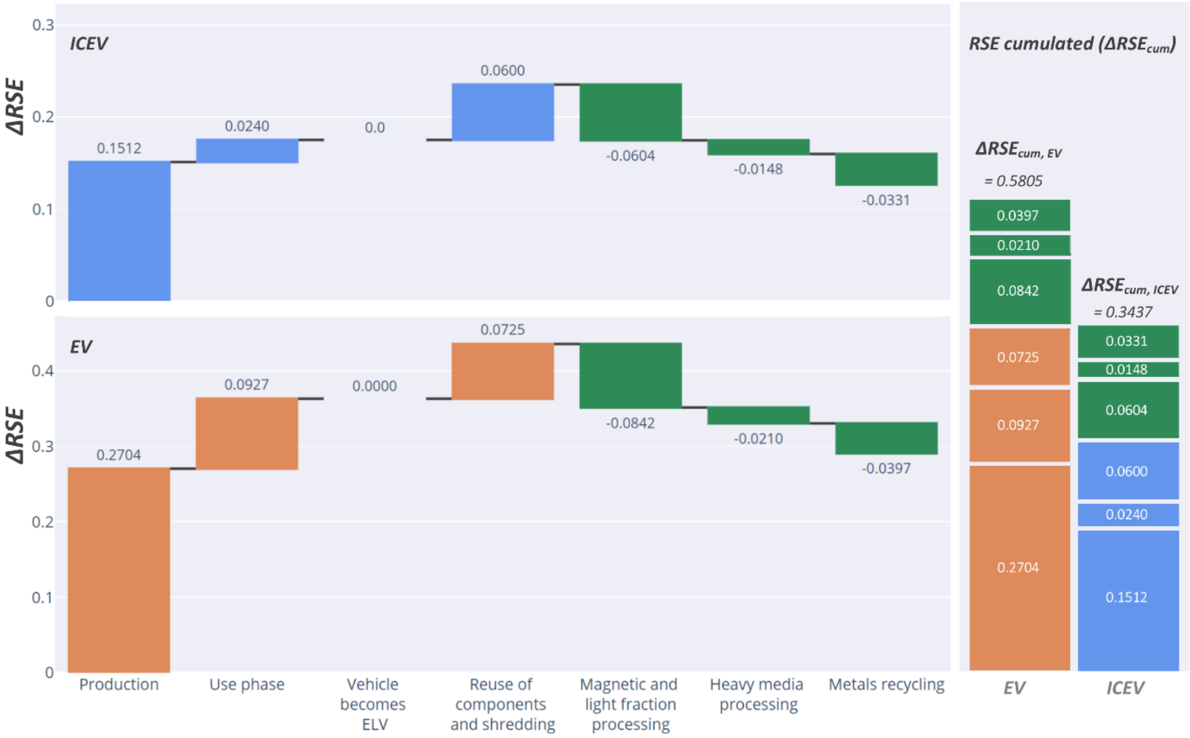

Figure 20: Changes in Relative Statistical Entropy (ΔRSE) for a single-vehicle (ICEV and EV) during its life cycle, additionally shown as cumulated values (ΔRSE_{cum}).

The higher dilution of materials that is related to the EV specific components also has a strong influence on the ΔRSE in the use-phase of the vehicle. With an average battery lifetime of 9 years, the replacement of the battery during the use-phase of the EV by a newly produced battery means that additional ΔRSE are produced to prolong the lifetime of the vehicle. The here assumed high degree of EV battery reuse in other, non-automotive applications leads to a small fraction of 7% of the ΔRSE being attributed to the end-of-life handling of the battery. Nevertheless, the overall increase in RSE that is related to the replacement of the EV battery is substantial, representing 34% of ΔRSE of the initial EV production. Therefore, the high fraction of the ΔRSE that is attributed to the battery, also in light of the overall life cycle, as is shown by the cumulated ΔRSE-values over all system stages ($\Delta RSE_{cum,\ EV}$) (Figure 20Figure 20), highlights the importance of preserving the battery and extending its lifetime.

For the ICEV, the components replaced during the vehicle lifetime are modelled through *other powertrain components* as it is assumed that the *engine* and *transmission* have the same lifetime as the vehicle. If compared to the EV, the ΔRSE are smaller for the ICEV use-phase, with a higher share of 43% of ΔRSE being related to RSE reductions performed during ELV recycling. Comparing the two cases of vehicle maintenance and component replacement that are performed during the use-phase, and in light of their relative weight regarding the overall ΔRSE_{cum}-values of the entire vehicle life cycle, the magnitude of the ΔRSE related to replacing the EV battery must be highlighted.

After the use-phase, the vehicle reaches its end-of-life and enters the ELV system. The disassembly and diversion of components for further reuse and specialised recycling processes play not only an important role in preserving components but also influences the downstream material recycling processes. The level of disassembly of the components and their diversion from shredding affect the ΔRSE at the *reuse and shredding stage*. The degree to which RSE increases can be avoided depends on the type of components that are diverted and on their respective component mass.

Following the vehicle through the ELV system, the reuse and shredding stage is succeeded by material recycling processes. The here modelled ELV recycling processes are described in more detail further above (Figure 20Figure 17) and are represented by three stages of (1) *magnetic and light fraction processing*, (2) *heavy media processing,* and (3) *metals recycling*. The three stages have in common that each of them reduces RSE values and recovers functionality by sorting, separating and concentrating target materials in specialised flows. The reduction of material dilution in the flows leads to reduced RSE values. Here it should be noted that ELV system performance can be improved by optimising the recycling processes in terms of material yields and purities or by installing additional processes that extend the number of recovered materials.

Besides the adaptation of the ELV system, it should be stressed that improvement in the ELV system is not limited to the ELV treatment processes alone but can also be achieved by adapting any preceding stage. Starting with the product design that determines the choice of materials and their initial level of mixing, the lifetime, the degree of disassembly and reusability of the components as well as the relative fraction of EVs and ICEVs that enter the ELV system will all influence the ΔRSE in the automotive system under consideration. Therefore, the ΔRSE for a single-vehicle life cycle indicates how processes such as production, replacement of components, component reuse, and the ELV recycling processes are interconnected and can only be effectively evaluated from a systems perspective.

Further, the case example demonstrates which processes increase, maintain, or reduce RSE values. It is shown that the preservation of functionality at the component and product level is reflected by the absence of ΔRSE, with production and ELV treatment processes being able to either increase or decrease RSE values. While aiming to preserve the initially achieved state of the functional product, any subsequent increase in the RSE value represents a loss of functionality. The lost functionality must be restored through recycling and similar processes (e.g. remanufacturing) as well as production processes that are also quantified in terms of ΔRSE. Therefore, besides employing a single-vehicle life cycle perspective, as demonstrated in Figure 20Figure 20, in the following ΔRSE are cumulated (ΔRSE_{cum}) for the entire system for every single year for the time period 2010 - 2050, thereby enabling evaluation of the scenarios introduced in Section 2.4.

4.3.3 Changes of Relative Statistical Entropy over time

Following the introduction of the results of the single-vehicle life cycle (Section 4.3.2), the transition scenarios are evaluated until the year 2050. With the functional unit remaining constant for all scenarios over time, the resulting ΔRSE_{cum}-values are directly comparable. The results are presented for the production system (Figure 21Figure 21A), the ELV treatment system (Figure 21Figure 21B) and for both systems combined (Figure 21Figure 21C). The substitution of components replaced, reused and recycled are included in the overall ΔRSE_{cum}-values for each year.

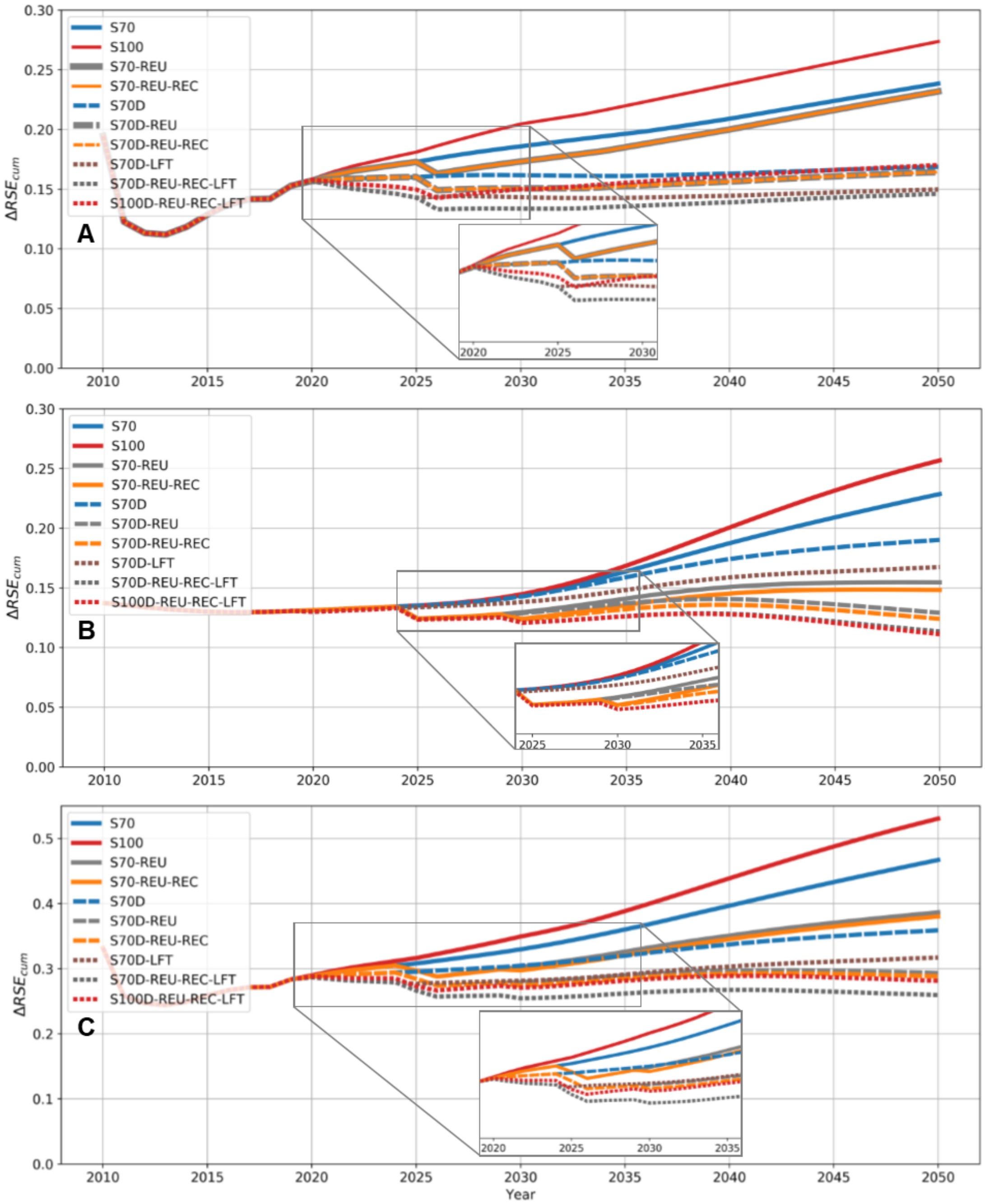

Figure 21: Changes of Relative Statistical Entropy per year for (A) production of new vehicles, (B) ELV treatment, (C) production and ELV treatment combined.

4.3.3.1 Production system

For the vehicle production system, the ΔRSE_{cum}-values show four distinguishable trajectories (Figure 21Figure 21A). The largest RSE changes result for the *S100*-scenario, followed by the second group of scenarios (*S70*, *S70-REU*, *S70-REU-REC*) with lower ΔRSE_{cum}-values. The next two sets of scenarios are related to a demand reduction (*S70D*, *S70D-REU*, *S70D-REU-REC)* and an additional lifetime increase (*S70D-LFT, S70D-REU-REC-LFT, S100D-REU-REC-LFT*). The *S100D-REU-REC-LFT* scenario bridges the gap between the two latter sets of scenarios due to its continuous increase in ΔRSE_{cum}-values, a result of the more rapid increase in the share of EVs produced.

The accelerated uptake of EVs in the *S100* scenario shows the largest ΔRSE_{cum}-values in the production system. One reason is the higher mass of EVs (~350 kg) when compared to ICEVs, which outweighs the effect of the less complex EV product structure assumed here, leading to a net effect of higher ΔRSE_{cum}-values (see Figure 20Figure 20). The second group of scenarios (*S70*, *S70-REU*, *S70-REU-REC)* shows a slower increase in ΔRSE_{cum}-values, with a delay in the increase of ΔRSE_{cum}-values due to the slower uptake of EVs. It must be noted that besides the reuse of components, which can partly substitute for the production of components required during the lifetime of a vehicle, the recycling strategies employed have only a limited effect on the ΔRSE_{cum} reduction in the production system. The reasons are related to the limited closed-loop recycling in the automotive system. Another reason is related to the system boundary conditions since upstream processes such as mining and raw material processing were not included in the production system proposed. The intensified reuse of components from the year 2025 that is implemented in the reuse scenarios shows the effectiveness of component preservation in reducing ΔRSE_{cum}-values.

The next set of scenarios includes the effect of a vehicle demand reduction, which could be achieved through an increasing occupancy rate per vehicle. The increase in the occupancy rate and, in addition to that, the increase in the vehicle lifetime both lead to an absolute reduction of vehicle flows, which is shown by the two different downward shifts in the curves between the years 2020 and 2025. The last two scenarios show that a similar effect could also be achieved through an increase in the vehicle lifetime. The lifetime effect leads to a parallel shift in the curves towards lower ΔRSE_{cum}-values since it also translates to an additional demand reduction for new vehicles. From the year 2025, the additional implementation of the reuse strategy demonstrates how a combination of CE strategies can lead to an additional decrease in ΔRSE_{cum}-values, while showing the overall effectiveness of a demand reduction strategy.

4.3.3.2 ELV system

Compared to the production system, the overall increase in the ΔRSE_{cum}-values is delayed for all scenarios due to the lifetime of vehicles. Further, based on the CE strategies applied, a high differentiation between the scenarios is present.

First, it can be observed that the proposed increase in the component reuse rate in the year 2025 reduces the changes in RSE in the ELV system (see Figure 2121B). The reason is the prolonged preservation of functionality at the component level, diverting the components from the destructive material recycling processes, and thereby avoiding the correspondingly high RSE increases.

Second, in addition to a higher component reuse rate, further improvements related to material recycling are proposed to be implemented in the year 2030. These improvements are reflected by a downward shift in the ΔRSE_{cum}-curves (see Figure 21Figure 21B). It should be noted that improvements can lead to both increases and decreases in ΔRSE_{cum}-values. Increases in ΔRSE_{cum}-values will occur if proposed system changes do not reduce initial material mixing upstream and are instead implemented only in the later stages in the system (e.g. heavy media processing). Such end-of-pipe improvement would imply undertaking greater effort to separate the more diluted material flows into fractions of the required purity. On the other hand, optimisations of upstream processes (e.g. higher dismantling) will prevent mixing and dilution later on so that processes further downstream will receive a less diluted material flow. Such a system will produce comparatively lower ΔRSE_{cum}-values as the dilution of material flows is avoided to a larger degree, consequently saving effort for separation and concentration at later stages. In the scenarios proposed here, improvements in the ELV system are implemented both in upstream processes and in the processes further downstream (see Table 12). The overall effect is a reduction in ΔRSE_{cum}-values that need to be undertaken to produce material fractions of high purity.

Third, the reduction in the vehicle stock in those scenarios with a demand reduction from the year 2020 onwards leads to an additional reduction in the slope of the ELV scenario curves. The slopes of the scenarios with a demand reduction flatten and become negative towards the year 2050, with the decreasing demand reinforcing the decline in the future number of ELVs to be processed. The delay of ELV outflows that is the result of the vehicle lifetime is also present here so that the number of ELVs entering ELV treatment is reduced, showing increasing effects from the year 2030 onwards. Further, the continuous increase in the occupancy rate that is implemented in the year 2020 leads to a reduction in ELV flows with a delay in time.

Analogous to a demand reduction, an increase in the vehicle lifetime will result in an additional decrease in ΔRSE_{cum}-values. The lifetime increase reduces the demand for new vehicles and delays the outflows of ELVs to ELV treatment, which reduces the slope of the scenario curves even further. Combined with other strategies, such as demand reduction (*S70D-LFT*), increasing the vehicles' lifetime by two years is very effective in reducing effort in the ELV system. Putting in place additional CE strategies beyond the strategy of lifetime extension, such as increasing the reuse of components, improved recycling and demand reduction, will further decrease future recycling effort to a minimum. The scenario with an accelerated EV uptake that is accompanied by the full implementation of the CE strategies employed (*S100D-REU-REC-LFT*) shows that an accelerated transition to electric mobility can be undertaken with decreased effort but requires an intensified implementation of CE strategies. The low ΔRSE_{cum}-values after the year 2040 can be explained not only by the higher reuse of EV batteries, but also by a higher potential for their uptake in the increasing EV vehicle stock.

The results for the ELV system show that with the CE strategies employed, a combination of multiple CE strategies is required to preserve functionality and thereby keep overall effort that is related to the processing of components and materials low. Further, it is shown that electrification of the vehicle fleet alone not only leads to increased effort in the production system but also, although delayed in time, to greater effort in the ELV system. The results also indicate that a demand reduction and/or lifetime increase are effective measures in decreasing recycling effort, especially if combined with additional CE strategies.

4.3.3.3 Production and ELV system

The combined effect of the production and the ELV system represents the aggregated ΔRSE_{cum}-values of both systems for each year. Consequently, the patterns that have been described for the production and ELV systems based on Figure 21Figure 21A and 9B can also be recognised. The effect of an accelerated electrification of the vehicle stock without any further system changes is indicated by the steep increase in the ΔRSE_{cum}-values towards the year 2050. It is also shown that each of the CE strategies proposed here will reduce the ΔRSE_{cum}-values, e.g. an increased reuse of components in the year 2025 or an improved ELV recycling system in the year 2030, both clearly represented by the ΔRSE_{cum}-value reductions in these years. Figure 21Figure 21C also shows the effectiveness of a demand reduction and/or lifetime increase in reducing overall effort in the aggregated production and ELV systems. Both strategies show immediate as well as long term effects by minimising the increases in ΔRSE_{cum}-values that are related to an increased share of EVs making up vehicle demand. Moreover, the effectiveness of non-technological CE strategies, such as the increase in the occupancy rate per vehicle and an increase in the vehicle lifetime (being partially governed by so-called soft factors such as the 'want' to drive a new vehicle), need to be taken into consideration in conjunction with CE strategies that target materials management.

5. Conclusion and outlook

One key characteristic of the economic process is represented by the qualitative changes between the inputs into an economic process and the outputs resulting from it (Georgescu-Roegen, 1971). With the current largely linear mode of production and consumption, the transformation of resources includes processes from mining to final production and consumption, with the generation of waste and emissions along large parts of the value chain. Confronted with environmental, economic and resource constraints, an increasing number of societies and organisations aims at transforming the largely linear mode of production and consumption towards a more circular system.

One central enabler of the CE transition is the ability to measure and evaluate the progress towards a more circular system. Therefore, at first, an overview of CE metrics and their most prevailing perspectives of how the CE transition can be measured is provided. The results indicate that large parts of the assessments are dominated by resource efficiency and resource productivity approaches, including the consideration of waste and primary vs. secondary resource use accounting. Based on the identified metric clusters, it is shown that assessment perspectives are closely linked to the scale of assessment (macro-, meso-, micro-scale) while being weakly integrated. Despite the main goal of the CE to preserve value and functionality in a system, CE perspectives related to the preservation of value and functionality such as retention, embedded stocks and lifetimes, value change and quality-related aspects such as downcycling, cascading, including the potential for recycling or remanufacturing, are assessed to a lower degree. In addition to the performed analysis, the reflection on recent CE metrics reviews reveals that existing metrics mostly focus on few CE strategies and often lack a systemic perspective, thereby increasing the risk of optimising only selected elements that might not necessarily lead to a better performance of the overall system.

Considering the existing gaps, the complementarity of assessment perspectives and the derived potentials for further CE metrics, the main contribution of the thesis is the further development of the Statistical Entropy Analysis method. Originally developed to measure the substance concentration and dilution potential of material flow systems, SEA is further extended to a multilevel SEA that allows considering combinations of material-, component- and product-related CE strategies including reuse, product lifetime extension, remanufacturing, and recycling. As any SEA application is based on a previously performed and underlying MFA, the method represents an inherently systemic evaluation perspective, with increases in statistical entropy being associated with the consumption of resources that should be avoided in an ideal circular system.

The extension of the method is undertaken by employing a case example of a simplified vehicle life cycle. By applying different CE strategies and their combinations over multiple system cycles, it is demonstrated how multilevel SEA allows quantifying the degree of circularity of material flow systems, while not only identifying system stages that impede the achievement of an ideal CE state, but also quantifying each of the interventions.

Besides assessing the circularity of a system, the multilevel SEA also provides a novel perspective for evaluating resource systems based on the effectiveness of resource use. Resource effectiveness stands in contrast to commonly applied resource efficiency thinking, representing a state that maximally preserves functionality over time while reducing the overall effort measured in terms of changes in statistical entropy (ΔRSE). Applying the method to several, consecutive product life cycles and different CE strategy combinations, it shows that some systems require lower ΔRSE to achieve the same or a similar level of system functionality, thereby representing systems of higher resource effectiveness. Further, the SEA method demonstrates that it can assess diverse interactions between CE strategies while taking into account the composition of components, products, and the overall system structure (e.g. product-system fit). As the evaluation of several material flow systems may result in a complex task, a resource effectiveness framework is derived that allows to concurrently visualise the performance of several material flow systems in relation to a defined ideal system state.

An important element in acquiring a better understanding of a system's transition is the consideration of time-dynamics. For this reason, the method is extended by a time dimension through the implementation and integration of the method with a stock-driven model and a generic MFA of a simplified European automotive system. A set of transition scenarios is employed that models the electrification of the vehicle fleet under different combinations of CE strategies until the year 2050. The combination of methods allows additional CE strategies such as increased vehicle lifetimes, or an absolute reduction of the vehicle stock to be modelled. Depending on the CE strategy employed, multilevel SEA also allows identifying material and component hot-spots that are most likely to increase effort within the system, thereby, demonstrating how the method can be employed to assess the various elements of production-consumption systems and related system changes over time.

Based on the case study employed, the results indicate that the largest effort for preserving and restoring functionality is required in the case of a rapid electrification of the vehicle stock without any further system adaptations. In order to achieve the electric mobility transition with lowest resource consumption and effort, a combination of different CE strategies must be implemented, with the most effective measure representing a reduction in demand for new vehicles, strategy that can be achieved by a higher intensity of vehicle use, i.e. a higher occupancy rate per vehicle, or by an increase in the vehicle lifetimes. The effectiveness of these measures is related to an overall stock reduction and system downsizing. Even though other CE strategies like reuse and recycling are less effective, they lead to more immediate results and are of high importance when it comes to selected components and materials. The highest resource effectiveness is observed for scenarios that combine stock reducing measures with CE strategies that aim to preserve functionalities at all levels, from the product (lifetime extension), component (reuse), to the material (recycling) level. Therefore, an accelerated CE transition will require a combination of technical system improvements (e.g. reuse, recycling, lifetime increase) and sufficiency-oriented adaptations that will directly impact people's routines.

In this context, it is important to state that even though the case examples can only serve as simplified representations of real systems, the application of multilevel SEA has demonstrated to provide guidance by considering the interdependencies within material systems, especially when it comes to the joint consideration of quantitative and qualitative aspects of resource use that deserve special attention (e.g. Moraga et al., 2019). In this regard, it is to note that the resource effectiveness perspective is opposed to the commonly applied resource efficiency approaches that are mostly concerned with relative reductions of, e.g., environmental impacts, energy use, or economic costs per unit of output produced. The resource effectiveness perspective does not discriminate between the means of how the effort is delivered within the system to provide a specific functionality, as opposed to resource efficiency thinking (that can be influenced by factors and system conditions such as the energy-mix employed). Therefore, it is proposed to employ the multilevel SEA as an initial step in a system evaluation, to first identify resource effective systems and in a second step to optimise these for efficiency, e.g., to improve their environmental, energetic or economic performance. In this regard, commonly applied and complementary methods such as life cycle assessment, cost-benefit-analysis, or techno-economic assessments could be used. Hence, further research should explore a combined analysis of multilevel SEA with established resource efficiency methods (e.g. LCA or CBA). The joint assessment could provide insights for specific system applications, providing a further and more refined CE strategy formulations. Moreover, such research could establish relationships between different types of effort required to achieve ΔRSE while exploring relationships between effort and the direction and relative location (y-axis) of the ΔRSE performed.

Even though the multilevel SEA method has been applied to the product-, component-, and material level, the method is not limited to assessing these three levels. Given the conceptual similarity, other applications could include higher or lower hierarchical levels, e.g. household-product-component, or region-product-material levels. Here, the method provides further potential to evaluate specific aspects of waste and resource management systems, ranging from the waste collection systems, to the recoverability of hibernating stocks, or the comparison of specific processes (e.g., mechanical recycling of plastics, feed stock recycling or dissolution).

Even though the case studies employed use simplified vehicles models and propose only basic CE strategies, it is to note that the results are subject to the uncertainty that is inherently present to the transfer-coefficients derived for the MFA. Here it is noteworthy that the extension of the method requires the accounting of multiple substances within an MFA, including process parameters such as transfer coefficients that considerably increase data collection efforts. Therefore, data availability and data quality remain important issues that might reduce the methods use. In contrast, governmental agencies prefer using metrics or indicators that ideally do not need additional data gathering, preferably based on existing statistical data (e.g. Potting et al., 2018). Here, the multilevel SEA is likely to remain a method applied to specific case studies, even though it would represent an interesting research direction to normalise ΔRSE to an absolute reference level so that ΔRSE could be compared across systems and application contexts.

It is clear that the multilevel SEA method represents a technical metric with a clearly defined scope that does not account for environmental impacts or social consequences, requiring additional methods to be performed to account for these perspectives. On the other hand, it represents an entirely material-based method that is 'neutral' in its approach when evaluating systems regarding their resource use. In this regard, the method shows that if the goal is to attain a more circular and resource effective system, the rollout of CE strategies at all stages and levels is required to maximally preserve functionality, including the increase of the residence time of stocks, recycling, reuse, remanufacturing, changes in product design, not to forget the influence of expansion or contraction of stocks. Here, the multilevel SEA method represents an important perspective that could assess and facilitate the transition towards a more CE. Nevertheless, many challenges remain and require attention as they have an equally important stake in the CE transition, going beyond technical feasibility and include issues of ownership, regulation, standards, control of technologies and resources, related risks, and the distribution of costs and benefits of a CE transformation (e.g., Calisto Friant et al., 2020).

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7. Supplementary information

In addition to the supplementary information that is presented in the following, the published and/or submitted aritcles (Parchomenko et al., 2020, 2019, Parchomenko 2021 submitted), also include the references to the digital version of the supplementary information provided.

Supplementary information - chapter 2

Excluded metrics from consideration in MCA (SI 1)

Authors and Year	Title
Greyson, (2007)	An economic instrument for zero waste, economic growth and sustainability
Gehin et al., (2008)	A tool to implement sustainable end-of-life strategies in the product development phase
Xu et al., (2009)	Optimizing Circular Economy Planning and Risk Analysis Using System Dynamics
Grosse, (2011)	Quasi-Circular Growth: A Pragmatic Approach to Sustainability for Non-Renewable Material Resources
Geng and Sarkis, (2013)	Measuring China's Circular Economy
Li, (2012)	The Research on Quantitative Evaluation of Circular Economy Based on Waste Input-Output Analysis
Jiliang et al., (2013)	Building and Application of a Circular Economy Index System Frame for Manufacturing Industrial Chain
Thomas and Birat, (2013)	Methodologies to measure the sustainability of materials – focus on recycling aspects
Di Maio and Rem, (2015)	A Robust Indicator for Promoting Circular Economy through Recycling
Smol et al., (2017)	Circular economy indicators in relation to eco-innovation in European regions
Birat, (2015)	Life-cycle assessment, resource efficiency and recycling
Castellani et al., (2015)	Beyond the throwaway society: A life cycle-based assessment of the environmental benefit of reuse
Machacek et al., (2015)	Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties
Wang et al., (2015)	Promoting regional sustainability by eco-province construction in China: A critical assessment
Favot et al., (2016)	The evolution of the Italian EPR system for the management of household Waste Electrical and Electronic Equipment
Ng et al., (2016)	A multilevel sustainability analysis of zinc recovery from wastes
Salemdeeb et al., (2016)	The UK waste input-output table: Linking waste generation to the UK economy
Diez et al., (2017)	Regeneration Management Tool for Industrial Ecosystem
Fang et al., (2017)	Carbon footprints of urban transition: Tracking circular economy promotions in Guiyang, China
Jiménez-rivero and García-navarro, (2017)	Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union
Kalmykova et al., (2017)	Circular economy - From review of theories and practices to development of implementation tools
Mendoza et al., (2017)	Integrating Back casting and Eco-Design for the Circular Economy: The BECE Framework
Milios, (2017)	Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix
Mulrow et al., (2017)	Industrial Symbiosis at the Facility Scale
Nasir et al., (2017)	Comparing linear and circular supply chains: A case study from the construction industry
Niero et al., (2017)	Combining Eco-Efficiency and Eco-Effectiveness for Continuous Loop Beverage Packaging Systems: Lessons from the Carlsberg Circular Community
Pomberger et al., (2017)	Dynamic visualisation of municipal waste management performance in the EU using Ternary Diagram method
Prosman et al., (2017)	Closing Global Material Loops: Initial Insights into Firm-Level Challenges

Reike et al., (2017)	The circular economy: New or Refurbished as CE 3.0? - Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options
Silva et al., (2017)	From waste to sustainable materials management: Three case studies of the transition journey
Talens Peiró et al., (2017)	Design for Disassembly Criteria in EU Product Policies for a More Circular Economy: A Method for Analysing Battery Packs in PC-Tablets and Subnotebooks
Tisserant et al., (2017)	Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and Waste Footprints
Tolio et al., (2017)	Design, management and control of demanufacturing and remanufacturing systems
Voskamp et al., (2017)	Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban Metabolism: A Material Flow Analysis of Amsterdam
Winning et al., (2017)	Towards a circular economy: Insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry
Zeng et al., (2018)	Uncovering the evolution of substance flow analysis of nickel in China
Brouwer et al., (2018)	Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy
Gálvez-Martos et al., (2018)	Construction and demolition waste best management practice in Europe
Hahladakis and Iacovidou, (2018)	Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity?
Mahpour, (2018)	Prioritizing barriers to adopt circular economy in construction and demolition waste management
Milios et al., (2018)	Plastic recycling in the Nordics: A value chain market analysis
Nowakowski and Mrówczyńska, (2018)	Towards sustainable WEEE collection and transportation methods in circular economy - Comparative study for rural and urban settlements

Note: The articles were not included in the analysis either because it is difficult to precisely assess the categorised CE elements, an insufficient case study is presented, study has a different scope of assessment, e.g. environmental footprints, there is an absence metric, or because a highly similar metric was already included more than once in the assessment.

Metrics categorisations with the provision of a code example SI 2

1 DYNAMIC-PML

Primary vs. secondary materials, parts, products	"raw material inventory, […] material recovery ratio, […]" as processes in the model
Resource productivity or process efficiency	"Material recovery ratio"
Potential for recycling or remanufacturing	"Quantity of material per product "
Cascading use of resources	"product multiple life cycle" model, "In this research it is considered that the decision whether [product multiple life cycle] is more favourable than single life cycle"
Stock availability or concentration	"Raw material inventory" as part of the model
Modelling of materials cycles	"Enterprise dynamics under influence of material scarcity" model includes multiple cycles including "material consumption rate", "material recovery ratio", etc.
Longevity or residence time	"potential gain of product multiple life cycles" part of the model
Supply risk and scarcity of resources	"Dynamics of material scarcity" as one part of the simulation model
Embedded stocks or distinct lifetimes	Use of "stock and flow diagram[s]" together with "time to exhaust material reserve"
System stability	"enterprise dynamics under the influence of material scarcity" are modelled, "delay in material supply, […] gap in manufacturing, […]" are modelled

2 TSSFM

Primary vs. secondary materials, parts, products	Modelling of "virgin inflow, recycled inflow, recovery fraction", "volume of recycled material can be greater than virgin material by 2030 if recycling facilities are in place before then"
Waste disposal	"technology components are split in the model into waste flow, recycling/ reuse flow, and embedded flow"
Potential for recycling or remanufacturing	"Material stocks that are contained in the technology stocks described above, e.g., lithium contained in an electric vehicle Li-ion battery […, in] kg/unit"
Recycling efficiency	"recycling rates of 70% for lithium, 90% for cobalt, 70% for platinum, and 80% for neodymium"
Cascading use of resources	Material flows between different technologies "switch from [plug-in hybrid electric vehicles] to [electric vehicles] results in no further increase in material inflow"
Product, part, material retention	"Total in-use stocks of vehicles for the UK deployment [over time until 2050]"
Stock availability or concentration	"Technology stocks […] are further disaggregated into technology structures"
Modelling of materials cycles	"lifetime function that gives the fraction of stock added in [specific] year"
Longevity or residence time	Residence time of different vehicle types projected from 2010 to 2050
Supply risk and scarcity of resources	"we have shown how the potential for reuse can be used to mitigate potential supply bottlenecks", "supply disruption"
Embedded stocks or distinct lifetimes	"Technologies and their components are explicitly included with their own dynamic stocks and flows", "embedded inflow [of materials]"
System stability	"the high estimate scenario results in […] 160% […] for lithium […] of world production [to serve UK demand in 2030]"

3 Reman-SF

Primary vs. secondary materials, parts, products	“The purchased parts (new parts) account for one-third of the parts on a fully remanufactured item resulting in waste.” Remanufactured part viewed as partly substituting new parts, as it“ can reduce the life cycle costs for the [original equipment] manufacturer.’’
Energy consideration	
Potential for recycling or remanufacturing	“Potential for re-use “, “Reman market demand”, “Market size”, “Core market”
Reuse, remanufacturing, recycling complexity	Consideration of “reverse logistics, core requirements, distribution, buy-back incentives, profitability, [etc.]”
Value change or productive use	“Product core value”

4 MARKOV-CHAIN

Waste disposal	“disposal” as part of the markov chain
Potential for recycling or remanufacturing	“volume of disposed products and filtering out anything that is still of use can be an effective way to reduce waste volumes”, transition probabilities provide indication of relative size of product flow potentially accessible (Figure)
Cascading use of resources	Product cascades include the following stages: “consumer, collector, second hand market, dealer and disposal” product cascades through different stages based on transition probabilities (Figure)
Destination of flows	“matrix, representing the transient states” includes direction of transition
Product, part, material retention	“75% of the vendors sell products within half a year”, retention based on fractions of products kept at different stages
Modelling of materials cycles	Products pass through multiple stages based on “matrix of transition probabilities”
Longevity or residence time	Residence time as “counting time steps […] vector t indicates that the number of transitions to absorption takes between 4.4 and 7.9 steps”

5 Product-RRR

Waste disposal	“Waste type” categorisation: “industrial, post-consumer, mixed, or waste prevention”
Energy consideration	“energy recovery” as separate category for classification of products
Potential for recycling or remanufacturing	Studied cases, categorised into “remanufacture, recycle, reuse, energy recovery […]” groups.
Destination of flows	Product destination categorised into “reuse, maintenance, remanufacture,” or to different waste types “industrial, post-consumer, mixed”
Product, part, material retention	Relative fraction kept in the system from overall 55 assessed products through recovery routes
Reuse, remanufacturing, recycling complexity	Consideration of material composition , potential recovery route based on quality of product to be recovered, e.g. “worn out garments”, “not exactly the same product”, “handmade/serial”, etc.
Downcycling and quality loss	Remanufactured, maintained, recycled products are categorised according to their change in value (Table)
Value change or productive use	Three value categories (diminished, equal, increased) (classification table)

6 CE-DEA	
Resource productivity or process efficiency	"environment efficiency additionally involves the impact of economic activity on environment through considering emission of pollutants, namely undesirable outputs", other outputs are among others "GDP per capita", "industrial solid waste generated", etc.
Waste disposal	"Industrial solid wastes disposed"
Energy consideration	"process of utilising energy inputs (e.g., coal, oil, gas)"
Spatial dimension	"[assessment of] efficiency of regional Circular Economy in China [based on] decision making units (DMUs), each of which represents an administrative region of China"
Additional process inputs	"Labour, Capital, […] Water" used as variables and system inputs
Value change or productive use	"Output value of products made from solid waste"

7 CEECI	
Resource productivity or process efficiency	"iron resource efficiency", "SO2 emissions"
Energy consideration	"Coal injection rate" in the operation
Additional process inputs	"fresh water consumption"
Sharing of infrastructure and utilisation of resource streams	"second indicator is the comprehensive utilisation level of materials such as coke oven gas, blast furnace gas, […, etc.]" in other sectors, e.g. "blast furnace slag was being reused in the cement industry"

8 CEIS	
Primary vs. secondary materials, parts, products	"Higher values of these indicators represent increased materials recycling […]result would be reduction in total consumption of virgin materials"
Resource productivity or process efficiency	"Output of main mineral resource"
Waste disposal	"Total amount of industrial solid waste for final disposal"
Energy consideration	"Output of energy ", "Energy consumption per unit GDP"
Recycling efficiency	"Recycling rate of iron scrap ", "Recycling rate of industrial solid waste", "Recycling rate of non-ferrous metal recycling [, waste paper, plastic, rubber]"
Spatial dimension	"national circular economy indicator system in China"
Additional process inputs	"Water withdrawal"
Sharing of infrastructure and utilisation of resource streams	"Industrial water reuse ratio"

9 REERF	
Primary vs. secondary materials, parts, products	"phosphate rock" and recycled, reutilised products considered simultaneously in one large process chain, see substance-flow-analysis (SFA)
Resource productivity or process efficiency	Phosphorus (P) resource efficiency per US dollar per tonne, as y-axis for different scenarios, "P utilisation efficiency was 81.1%"
Waste disposal	"[phosphorus process] loss in waste water and ash"
Energy consideration	"the energy chain […] are considered"
Potential for recycling or remanufacturing	Size of waste flows (SFA)
Recycling efficiency	System includes: "phosphorite accompanying resource comprehensive recycling and solid waste comprehensive utilisation" separate groups of processes. Further recycling efficiencies are considered: "the recycling efficiency was 15.9% and 2.2%, respectively", "comprehensive utilisation efficiency was only 4.7%, and sulphur recycling efficiency was only 0.024%"
Additional process inputs	"Liquid [ammonia, and sulfuric acid] as additional inputs into phosphorus products production", "water chain […] are also considered"
Destination of flows	Application of SFA and CE system illustration provides direction and destination of material flows
Product, part, material retention	Fractions of solid waste recovered in "solid waste comprehensive utilisation" process group
Stock availability or concentration	"More than 95.3% of phosphor gypsum […] still piled up in the gypsum factory"
Reuse, remanufacturing, recycling complexity	Over 20 processes and more than 13 different production outputs are considered simultaneously (SFA and process figure)
Downcycling and quality loss	P resource efficiency in monetary values per tonne, over different production processes (sections) and different scenarios (fraction as value) indicates quality/downcycling over subsequent process sections (Figure 5a, 5b)
Value change or productive use	"total economic benefit increases from US$235.3 million to US$638.2 million, to US$771.5 million from the status quo to scenario 2, and to scenario 4, [under different resource reutilisation options]"
Sharing of infrastructure and utilisation of resource streams	Utilisation of various side products (SFA figure), "P-CCES involves industrial chains of the sulphur phosphorus chemicals, coal chemicals, fluorine chemicals, and architectural materials"

10 RES	
Primary vs. secondary materials, parts, products	"Domestic material consumption (DMC) per capita", "circular model with less primary material input"
Resource productivity or process efficiency	"resource productivity for EU28 has improved from 1.52 EUR/kg in 2002 to 1.95 EUR/kg in 2014", provision of a map showing resource productivity in the European Union per country
Waste disposal	"Generation of waste excluding major mineral waste" , "Landfill rate of waste excluding major mineral wastes"
Energy consideration	"Energy productivity"
Recycling efficiency	"Recycling rate of municipal waste"
Spatial dimension	"EU Resource efficiency"

11 MSIASM	
Energy consideration	"Joule based exosomatic energy throughput" as basis for the analysis, "exosomatic energy in the industrial sector", "exosomatic energy in the service and government sector" and other sectors are compared
Spatial dimension	National study, with regional resolution: "regions in mainland China, namely, Beijing, Tianjin, Hebei, Shanxi"

12 EIP-Indicator-Set

Primary vs. secondary materials, parts, products	“conservation of natural resources” under “key benefits of applying [the] standard”, as a result of “more efficient materials and energy use”
Resource productivity or process efficiency	“COD or SO2emissions per added industrial production value”, “Freshwater consumption per added industrial production value”
Waste disposal	“industrial solid waste generation/annual added industrial production value”
Energy consideration	“Energy consumption per added industrial production value”
Recycling efficiency	“[Industrial solid waste integrated utilisation / (generation + utilisation)]”
Additional process inputs	“industrial freshwater consumption”
Sharing of infrastructure and utilisation of resource streams	“industrial repetitive water use Q/industrial water consumption”, “[reuse of water] from local waste water treatment plant [which] could be reused within the park]”

13 CE-enterprise-index

Primary vs. secondary materials, parts, products	“Resource exploiting” as separate category for overall score. A high score means that a higher amount of secondary resources is used
Resource productivity or process efficiency	“SO2 emissions per unit of industrial output”, “Wastewater emissions per unit industrial output”
Waste disposal	“Solid waste emissions per unit of industrial output”
Energy consideration	“Energy consumption per unit of industrial output”
Recycling efficiency	“Comprehensive utilisation of industrial solid waste”
Additional process inputs	“Water consumption”
Sharing of infrastructure and utilisation of resource streams	“Recycling rate of industrial water”

14 CET

Primary vs. secondary materials, parts, products	“percentage of virgin, non-recycled materials”
Resource productivity or process efficiency	“Materials are highly eco-efficient (low energy and carbon emissions to produce)”
Waste disposal	“Significant waste sent to landfill from factory”
Energy consideration	“energy [required to] produce”
Potential for recycling or remanufacturing	“refurbishment/ remanufacturing costs “, ““market for second hand sales”, “easy to identify parts once disassembled”, “damage caused to product or part when disassembling”
Product, part, material retention	“Recycled materials used“
Reuse, remanufacturing, recycling complexity	“Complex workings, difficult to understand”, “no components, connectors, modules or leads are standardized”, “Many mechanical connections” , “Many tools required to disassemble”
Longevity or residence time	“Product has a very long lifetime”
Value change or productive use	“refurbishing or remanufacturing currently undertaken”
Supply risk and scarcity of resources	“scarce materials used in product”
Sharing of infrastructure and utilisation of resource streams	“products currently sold as a service”
Materials mixing and dilution	“number of material combinations used in the product”
Toxicity and clean material cycles	“toxic materials in product“

15 LONGEVITY-I

Primary vs. secondary materials, parts, products	“initial lifetime” vs. “refurbished lifetime”
Potential for recycling or remanufacturing	“Handsets [or products] outside market control” implies products within market control
Recycling efficiency	“C describes the contribution in terms of additional time that recycling makes to material use. Recycled material will be used in new products”, “Precious material lost through imperfect recycling methods”
Product, part, material retention	“longevity indicator seeks to show the length of time for which a material is retained in a product system”
Stock availability or concentration	“Between 75 and 90% of phones in the US remain outside market control”, overall stock is known from these fractions
Longevity or residence time	“Overall longevity is therefore calculated as the sum of initial lifetime of the product, refurbished lifetime contribution and recycled lifetime contribution”
Value change or productive use	“An alternative that keeps a resource x-times longer in the system than another alternative, is also x-times more value-creating”

16 RRs

Primary vs. secondary materials, parts, products	“secondary polymers”, “secondary products”, “recyclates”, considered with the perspective of “[using recycling rates] and inherent material qualities […] to model replacement rates of primary materials more realistically than has been done in previous studies”
Resource productivity or process efficiency	
Waste disposal	Material flows directed to “municipal solid waste” or “municipal solid waste incineration”
Energy consideration	
Potential for recycling or remanufacturing	Size of material flows indicates potential of recycling in tonnes per year (MFA system)
Recycling efficiency	“for closed-loop recycling of PET is 45%, but only 26% of the PET waste generated is later avail-able as granulate for further bottle production”
Spatial dimension	“Material flow analysis of the Swiss waste management system”
Additional process inputs	
Cascading use of resources	“output of the system are useful secondary materials and exports of material fractions to other countries”, outputs distinguished into “open-loop” recycling
Destination of flows	MFA shows destination of each flow in the system (Figures)
Modelling of materials cycles	MFA used to model “closed-loop” and “open-loop” recycling
Reuse, remanufacturing, recycling complexity	Swiss system is modelled through more than 28 processes and more than 100 flows (MFA system)
Downcycling and quality loss	Fractions of flows show level of downcycling through destinations (similarly also for other flows such as glass, aluminium, […], e.g. paper and cardboard is directed to “municipal solid waste” “incineration”, “fibres for cardboard production”, “export of mixed paper”, “fibres for paper production”, etc.

17 CEENE	
Resource productivity or process efficiency	Consideration of "conversion efficiencies" of (natural) processes, e.g. "maximally 10.8% of the solar exergy is effectively metabolised"
Waste disposal	
Energy consideration	"Exergy calculation of energy and materials", consideration of different energy types for calculation of the CEENE score based on energy mix, including "fossil energy, nuclear energy, biomass energy, [etc.]"
Spatial dimension	"exergy values are weighed by the shares of the different countries in the European gas consumption"
Additional process inputs	Additional inputs from the natural environment are accounted e.g. "difference in scores can be explained by the fact that solar input in the CEENE method is accounted for through the land use"
Cascading use of resources	"exergy in overburden and tailings are returned to the environment and potentially utilisable in the future"
Stock availability or concentration	"exergy stocks in the natural environment [have to be calculated first]"

18 LCA-ENV	
Resource productivity or process efficiency	"environmental impacts […] per unit of service", additionally "fuel efficiency" of different options
Energy consideration	"required energy in a week is delivered by the national power grid", "for the full electric system, the assumption is made that 100% of the energy is generated at a windmill park or the national grid"
Spatial dimension	"design objective at a regional scale" with consideration of "regional pollution", case study of "Friesland Lake District"
Additional process inputs	"diesel", "electrical power" considered as inputs
Value change or productive use	Aim to "relative enhancement of the value of the regional business model ", "enhancing the perceived value" (in this case of a service offered)

19 VA-ED	
Waste disposal	"Percentage of harmless treatment for living garbage"
Energy consideration	"Energy consumption of unit GDP (TCE/10,000 yuan)"
Recycling efficiency	"Ratio of industrial solid wastes utilised (%)"
Additional process inputs	"Water consumption per unit industrial added value (m3/10,000 yuan)"

20 HE-ELFM	
Primary vs. secondary materials, parts, products	"waste-to-material – new resources for techno sphere replacing primary resources", "secondary materials" as separate flow
Resource productivity or process efficiency	Treatment of "18 million metric tons of waste" requires "investment of ~230 M€"
Energy consideration	"green energy" recovery from the project, "waste to energy"
Potential for recycling or remanufacturing	waste composition e.g. "paper, plastics, metals, [etc.]"
Recycling efficiency	"directly recyclable streams" quantified in relation to overall flows
Cascading use of resources	"cement substitution can theoretically be as high as 95 wt% […] the produced plasmarok could, hypothetically, replace […] million metric ton of cement"
Destination of flows	Flow sheets provide system structure and flows direction (Figures)
Product, part, material retention	"approximately 90% of the ash from the SRF will be captured in the slag bath […] it is concluded the material is safe to be used as an aggregate/gravel replacement"
Stock availability or concentration	"18 million metric tons of waste" with specific composition, e.g. "almost 6.3 million tons (as-received) is industrial waste such as shredder material from the car industry, metallurgical slags"
Reuse, remanufacturing, recycling complexity	"25 valorisation (utilisation) categories, including plastics, metals, glass, textiles, organics, sludge, slags, sand, etc."

21 RMS	
Primary vs. secondary materials, parts, products	“Metal mine production in the EU” vs. “Recycling’s contribution to meeting materials demand” and “trade in secondary raw materials” (the letter as subchapters
Resource productivity or process efficiency	Recycling efficiency as recycled material flow and fraction of material input (1 Gt / 4.2 Gt)
Waste disposal	“2.4 bn tonnes of End-of-life waste”
Energy consideration	“fossil fuels” as separate flow, distinguished between imports and domestic extraction
Recycling efficiency	Recycling as fraction of materials used presented
Spatial dimension	Perspective of Raw Materials Scoreboard on EU, to be seen in data, graphics, etc.
Destination of flows	“model of economy-wide material flow” provides general flow direction to “stocks, material use [processes], energetic use [processes], [end-of-life waste processes]”, etc.
Supply risk and scarcity of resources	“import dependence for selected raw materials”, “geographical concentration [of resources] and governance (as sub-chapter)”

22 GDM-reman	
Primary vs. secondary materials, parts, products	“Amount of material used for production in period t”, “number of cores entered to process in period t”, “amount of cores remanufactured”
Resource productivity or process efficiency	“Amount of emissions (CO2, water, sewage) per one regenerated core (product)”, “Remanufacturing process flow”
Waste disposal	“Amount of waste generated”
Energy consideration	“Energy consumption per one core”
Recycling efficiency	“Material recovery rate”
Additional process inputs	“availability of machines and tools”
Stock availability or concentration	“Availability of materials (overall out of stock)”

23 EMERGY	
Resource productivity or process efficiency	“EYR=U/F=(R+N+F)/F is the ratio of total emergy used and exploited by the process (U) to the emergy (F) invested from outside the system” (N = renewable energy, R = local free environmental emergy)
Waste disposal	“waste” as separate flow in energy flow diagram, “waste-to-total emergy ratio”, “if waste flow is landfilled, no longer available as by-product, there is a loss of emergy”
Energy consideration	“Emergy is defined as the total direct and indirect energy of one source type”, calculation base of emergy metric
Recycling efficiency	“waste-to-total emergy ratio” as recycling efficiency of waste streams
Spatial dimension	“energy system diagram of the whole system […] mandatory”, application on specific industrial park
Additional process inputs	Additional inputs into the process are mapped in the energy diagram and include: “water, fuel and electricity, materials and goods, machinery and buildings [etc.]”
Cascading use of resources	flows of materials are reutilised in the industrial park system at different processes
Modelling of materials cycles	Use of energy flow diagram, which includes all important inputs and reutilisation in the industrial park
Sharing of infrastructure and utilisation of resource streams	Utilisation of material flows in the industrial park is mapped in flow diagram, additionally it is referred to utilisation of waste streams: “the smaller the waste emergy, the more efficient the industrial park.”
Recycled material value	“waste reutilisation's profit based on the emergy accounting”

24 RP-I

Primary vs. secondary materials, parts, products	"substitution ratio between fly ash and […] […]substitution ratio [in %]"
Waste disposal	Evaluation processes and their potential with perspective of "reusing waste materials"
Energy consideration	
Potential for recycling or remanufacturing	"actual amount of fly ash reuse in 2009, […] further use potential, […] concrete production in 2009, typical range of fly ash content in concrete, potential demand estimated based on technical specification"
Recycling efficiency	"substitution ratio [in %]"
Cascading use of resources	Evaluation of a secondary resource over utilisation categories in other sector applications: fly ash to be used as "road base", "waste stabilisation", "mining applications", etc.
Stock availability or concentration	"Amount of fly ash that qualifies for the ASTM requirements for use in concrete (1/3 of fly ash generated in the United States)"
Reuse, remanufacturing, recycling complexity	Technological capabilities, potential of national economy for reusing secondary resource are evaluated: "Per reuse category, the most widely applied technology was selected and considered in the calculation"
Downcycling and quality loss	Reuse category A, B, C, D (decreasing reuse potential)
Value change or productive use	"y-axis represents the net marginal revenue earned by selling processed materials minus disposal costs at capacity."

25 MD-business-value

26 CE-STRATEGY-M

27 SSCN

Additional process inputs	"the manufactured product or service receives a 'backpack' full of the environmental effects of the production processes from earlier stages, and the environmental effects of the current production stage are added into the 'backpack'
Destination of flows	"organising closed process chains [based on LCA] for identifying useful network partners for the establishment of a [sustainable supply chain network]"

28 RE-EW-MFA

Primary vs. secondary materials, parts, products	Direct material input (DMI) vs. reutilised material (RU)
Resource productivity or process efficiency	Domestic Processed Output (DPO) vs material reutilised (RU)
Waste disposal	"TG is the total waste generation amount from both the production and final use"
Recycling efficiency	"RC is the amount of recycled and recovered materials after the final use (recycled consumption wastes)"
Spatial dimension	Economy-wide MFA, applied on the national economy of China
Modelling of materials cycles	Based on the established relationships between reutilisation rates, direct material inputs, etc. the material flows are calculated for various years
Sharing of infrastructure and utilisation of resource streams	"RU indicates the material reutilised in productive activities that consists of two flows: agricultural reutilisation (ARU) and industrial reutilisation (IRU), RU = ARU + IRU"

29 Recycling-indicator-set	
Primary vs. secondary materials, parts, products	"Degree of material cycle closure " as separate indicator with the perspective of "avoided mining and metallurgic processes of virgin ore [through recycling process]"
Resource productivity or process efficiency	"avoided environmental burdens" through recycling process, "environmental burden associated with the production of the material that is avoided by the recycled output fraction [divided by] environmental burden associated with the production of the material present in the EEE"
Waste disposal	"recycled material weight" indicates waste produced, additionally, "waste" as separate flow in system definition diagram
Potential for recycling or remanufacturing	"Material composition of [product]" is provided/needed for calculating the indicators
Recycling efficiency	"weight recovery of target material" as separate indicator
Downcycling and quality loss	"current market price of output fraction [vs] current market price of material [used as input]"
Supply risk and scarcity of resources	"recovery of scarce materials" and "SR: supply risk of the material" as separate indicator
Recycled material value	"current market price of output fraction"

30 IS-LCA	
Primary vs. secondary materials, parts, products	Scenarios proposed include different intensity of primary resource utilisation, e.g. industrial symbiosis scenario with by-product exchange uses solely residue for electricity generation, whereas in the reference case, fuels are used to produce electricity (Figure 2)
Resource productivity or process efficiency	"emissions and raw material usage are partitioned among the main products and by-products by means of an allocation key, such as mass, energy, or economic value."
Waste disposal	"residue" as separate flow from the process
Energy consideration	"Power plant", "electricity" and "power" are integral part of the system
Potential for recycling or remanufacturing	"it requires several assumptions on the potential utilisation of the by-products if they are not used in the symbiosis"
Recycling efficiency	Different degrees of reutilisation of resource streams in the scenarios proposed
Spatial dimension	
Additional process inputs	"fuels", "electricity" as inputs into the system
Cascading use of resources	"it requires several assumptions on the potential utilisation of the by-products if they are not used in the symbiosis"
Destination of flows	"simplified by-product exchange takes place between a power plant and a pulp mill"
Sharing of infrastructure and utilisation of resource streams	provision of "a general framework for quantifying the environmental performance of by-product exchange"

31 ITPR	
Primary vs. secondary materials, parts, products	"various products and metal ore deposits" compared in terms of concentrations of target material
Resource productivity or process efficiency	"number of materials counted for the four different material counting schemes" to decrease material mixing
Potential for recycling or remanufacturing	"number of target materials M", "apparent recycling boundary" (based on material mixing and single product recycled material value"
Recycling efficiency	"recycling rate" for 20 different products
Downcycling and quality loss	Downcycling as "recycled material values [..., based on] market data on recycled materials [, … and] amounts of the materials and their concentrations"
Embedded stocks or distinct lifetimes	"concentration of a target material"
Recycled material value	"recycled material values 9 (for 20 different products) ", "relationship between the concentration of a target material in a feed stream and the market value of the target material"
Materials mixing and dilution	"H as a measure of material mixing", […] n_i is the number of separation steps necessary to isolate material i", "material mixing" (as separate axis in result plot)

32 IS-RP-indicator

Primary vs. secondary materials, parts, products	Direct material inputs “DMI” vs. “copper-containing sludge and waste copper are recycled by resource utilisation enterprises”
Resource productivity or process efficiency	Resource productivity (RP) of copper in yuan/ton for different scenarios, figure: “[RP] of different segments within the PCB industrial symbiosis system”
Waste disposal	“Waste flow” as separate flow in (MFA)
Energy consideration	Resource productivity for energy “RP-energy”
Potential for recycling or remanufacturing	Quantification of waste flows: “waste etching solution (120 tons) , waste copper foil (65.30 tons), [etc.]”
Recycling efficiency	“Regenerated copper” and “Loss of copper” considered in one table
Spatial dimension	Assessment of “National Hi-Tech Industrial Development Zone”
Additional process inputs	Water as direct material input “DMI water”
Cascading use of resources	Utilisation cascades of waste streams within industrial park (from MFA)
Destination of flows	Application of MFA, with specific flow destinations entering processes (Figure)
Stock availability or concentration	“C stocks is the copper that stays in production like copper foil [, etc]”
Modelling of materials cycles	Material utilisation cycles provided in MFA
Reuse, remanufacturing, recycling complexity	14 flows and 13 processes used to model material and output specific utilisation (MFA), including specific utilisation companies
Sharing of infrastructure and utilisation of resource streams	Utilisation of waste streams such as “waste etching solution, waste copper foil, waste PCB, sludge containing copper [etc.]”

33 EMF

Primary vs. secondary materials, parts, products	“Mass of virgin feedstock used in a product”
Waste disposal	“Mass of unrecoverable waste associated with a product”
Recycling efficiency	“Efficiency of the recycling process used to produce recycled feedstock”
Product, part, material retention	“fraction of mass of a product’s feedstock from recycled sources”
Longevity or residence time	“average lifetime of a product”
Value change or productive use	“Utility of a product”, “Actual average number of functional units achieved during the use phase of a product”
Sharing of infrastructure and utilisation of resource streams	“recycled feedstock may come from sources other than the original product. Hence, E_C is not necessarily equal to E_F”

34 CEIP

Primary vs. secondary materials, parts, products	“Use of recovered material”
Resource productivity or process efficiency	“Product’s materials reintroduction. […] recycling a high portion of the reclaimed materials […]”
Waste disposal	“bill of solid waste for the manufacturing process”
Energy consideration	“Energy Identification – Presence of Bill of Energy”
Potential for recycling or remanufacturing	“Product recovery – availability of take back schemes”
Stock availability or concentration	“Material Identification – Presence of Bill of Materials”
Longevity or residence time	“Product life-time extension”
Materials mixing and dilution	“Is the product separated out from other products at the end of its life?”

35 ZWI

Primary vs. secondary materials, parts, products	“DFi = Substitution factor for different waste management systems based on their virgin material replacement efficiency”
Resource productivity or process efficiency	“virgin material replacement efficiency”
Waste disposal	“Total waste managed in the city”
Energy consideration	“Energy substitution efficiency”
Potential for recycling or remanufacturing	“potential amount of waste managed by the city” as part of enumerator in the material diversion rate formula
Recycling efficiency	“amount of waste avoided, recycled, […]” divided by “total amount of waste generated”
Spatial dimension	“indicator to measure the performance of a city”
Destination of flows	Waste flows are quantified based on the following process destinations: “Recycling, Composting, Landfilling”

36 PCM

Primary vs. secondary materials, parts, products	“sum of market prices for virgin materials contained in the product “, “economic value of recirculated parts” divided by “economic value of all parts”
Product, part, material retention	“fraction of a product that comes from used products”
Value change or productive use	“economic value of recirculated parts”, “when work is done on a product part, its circularity (c) stays the same whereas its value (v) increases.”
Supply risk and scarcity of resources	“[prices as] relative scarcity”

37 EW-MFA

Primary vs. secondary materials, parts, products	“domestic extraction” and “EoL waste as share of processes materials […] 31%”
Waste disposal	Waste disposal quantified: 2.4Gt/year
Energy consideration	“Fossil energy carriers as share of processed materials”
Potential for recycling or remanufacturing	Overall waste flow and stock outflow (MFA)
Recycling efficiency	“Recycling as share of EoL waste”
Spatial dimension	Global and EU economy material flows assessed (MFA)
Destination of flows	“model of economy-wide material flow” provides general flow direction to “stocks, material use [processes], energetic use [processes], [end-of-life waste processes]”, etc. (MFA)
Modelling of materials cycles	“recycling” contributes to re-entering of materials into production (MFA)

38 C2C

Resource productivity or process efficiency	“direct on-site emissions associated with the final manufacturing stage of the product”, “percentage of the purchased energy is renewably sourced or offset with renewable energy projects”
Waste disposal	“waste streams will need to be shown to the certification assessor”
Energy consideration	“Annual purchased electricity […] with the final manufacturing stage of the product are quantified”, “Addressing Embodied Energy Use with Offsets or Other Projects”
Potential for recycling or remanufacturing	“Cyclability rating system [based on categorised] technical cycle: recyclable […], partially recyclable […], not recyclable”, “future targets and timeline for number of units or volume of materials to be collected and recycled or composted”
Additional process inputs	“Water Stewardship Requirements […, e.g.] include all water inputs”
Product, part, material retention	“Percent recycled content”, “% of recycled or rapidly renewable content in the product”
Stock availability or concentration	“Bill of Materials […]: part number, part description, number of parts per product, generic material, part weight, total weight (all parts), and percent of total weight.”

Reuse, remanufacturing, recycling complexity	Identification of background system capable of treating the materials, e.g. whether "[technical systems] may be dismantled and reused, or physically or chemically transformed"
Downcycling and quality loss	Assessment through categorisation: "A material that is only downcyclable […], material is not downcyclable"
Value change or productive use	[relative assessment included in cyclability rating]: "A material that may be recycled into a material of similar quality and/or value."
Materials mixing and dilution	"concentration of the banned chemical within each homogeneous material", "threshold for metals in [biological nutrients/materials or products that are usable by living organisms to carry on life processes] is equal to the maximum background concentrations found in soils"
Toxicity and clean material cycles	"Environmental Health Endpoints Used for Chemical Profile Evaluation", Assessing absence of banned "chemicals considered harmful to humans or the environment are not intentionally added to [the certified] product", assessment of certain material groups for specific substances from banned list category to ensure safety of recycled content (Table 5)

39 DYNAMIC-SFA	
Primary vs. secondary materials, parts, products	Primary copper, secondary copper within the system is modelled
Resource productivity or process efficiency	Mining loss, refining loss, […] is considered
Waste disposal	Waste management loss is projected in the results
Potential for recycling or remanufacturing	"imbalance of copper demand and domestic scrap supply will shrink to 2Mt […] supply of domestic old scrap will play a central role in the future development of the copper industry"
Recycling efficiency	"ratio between output of mining, smelting, and fabrication was […]"
Spatial dimension	estimating futures of copper use for China
Cascading use of resources	Inflows and outflows of different value chains such as buildings, machinery, are considered
Destination of flows	Material flows within the Chinese economy are mapped
Product, part, material retention	Copper of in use stocks in infrastructure, transportation, equipment and building is modelled
Stock availability or concentration	"stocks-driven model is used to forecast future copper metabolism"
Modelling of materials cycles	Stock-driven model of copper cycle in China
Supply risk and scarcity of resources	"[…] net import reliance (NIR) as high as 60% […]" (as result of modelling)
Embedded stocks or distinct lifetimes	we further divide copper use into four categories (i) with specific product lifetimes: "Infrastructure" (such as electric power transmission and distribution, i=1), "Transportation" (such as motor vehicles, i=2), "Equipment" (such as household equipment, i=3), and "Buildings" […] calculation of in-use stocks…
System stability	"the import copper re- source will be very huge […]. The gap between copper demand […] and domestic supply will enlarge continuously in the coming decades. […] demand– supply gap will drop consistently as a result of increasing scrap supplies."

40 TOXIC-CYC	
Waste disposal	“In the relevant WEEE categories, the annual plastics flow was around 72,000 t, while ELVs have an annual plastics flow of around 20,000 t.”
Spatial dimension	“0.20 t per year in automotive waste in the Netherlands”
Destination of flows	“Plastic waste flow data was collected”
Reuse, remanufacturing, recycling complexity	Contamination and accumulation of recycled plastics as limitation of plastics recycling
Downcycling and quality loss	Contamination of recycled plastics is quantified, e.g. “in the automotive sector, this is 14%, while an additional 19% is expected to end up in second-hand parts (reuse)”
Materials mixing and dilution	“BDE concentrations were considerably higher in purified ABS than in polystyrene (PS) pellets”
Toxicity and clean material cycles	“POP-BDEs […], reaching levels up to 330 μg/g, […] 22% of all the POP-BDE in WEEE is expected to end up in recycled plastics.”

41 AGRI-FOOD-IO	
Resource productivity or process efficiency	Undesirable outputs: GHG emissions, total emissions by sector
Waste disposal	“food wastes generated by the industry”, Table on “waste generated” and table on “Waste sent to landfill”
Energy consideration	Primary energy demand (TJ)
Recycling efficiency	“Waste generated […] of the Australian processed food industry subsectors”, Table on “recycling rates in %”
Spatial dimension	Food producing sector of Australia
Additional process inputs	Absolute water use in different production sectors

42 PERFORM-ECON-M	
Primary vs. secondary materials, parts, products	Extraction and processing of virgin materials is determined by the remanufacturing and recycling rates in order to maintain the stock
Resource productivity or process efficiency	Material intensity (material flow per capital stock), product-service intensity (required stock to provide a service unit), emission intensity (ratio of GHG emissions used energy used)
Waste disposal	Outflow of goods that is not remanufactured and recycled
Energy consideration	“energy intensity of production” to produce a flow of materials
Potential for recycling or remanufacturing	Consideration of stock S (manufactured capital), which needs to be maintained
Recycling efficiency	Modelled as outflows from the stock, which are reprocessed at a certain rate
Destination of flows	Material flows and stocks used as diagrams which indicate the direction of flows
Stock availability or concentration	Central role of the stock for used materials and used goods flows in material flow system
Modelling of materials cycles	Cycles are modelled by establishing relations, e.g. remanufacturing rate determines recycling rate and virgin material inputs
Downcycling and quality loss	Downcycling considered as separate flow in the model
Longevity or residence time	Service lifetime is set in relation to the stock, “T is the average service life of the stock”
Value change or productive use	“product-service intensity; i.e. the quantity of stock required to deliver the required service”
Sharing of infrastructure and utilisation of resource streams	Product-service intensity as separate term in calculations (in the sense that the capital stock is shared by multiple users)
System stability	Maintenance of stock, “the change of stock over time […] $dS/dt \approx 0$ and $p \approx q$” (S=stock, p=material input flows to stock, q=outflow of materials from stock)

43 MATERIAL-RI	
Primary vs. secondary materials, parts, products	Overall system performance is also affected by amount of virgin material added
Resource productivity or process efficiency	Environmental impact affected by resource recovery, losses, and emissions
Waste disposal	Waste streams from recycling process losses
Energy consideration	Optimisation for energy efficiency
Recycling efficiency	“calculation of recycling rates”
Additional process inputs	“amount of virgin material” required to produce correct alloy
Cascading use of resources	
Destination of flows	Use of flow sheets
Modelling of materials cycles	Flow sheet modelling
Reuse, remanufacturing, recycling complexity	“produced recyclates will flow depending on the actual material mixture”
Downcycling and quality loss	“Recyclate quality of all recyclates”
Materials mixing and dilution	System performance “determined by the mix of materials flowing into [recyc. system]”

44 SCI	
Primary vs. secondary materials, parts, products	“Quantity of the inputs that are coming from virgin and recycled materials and reused components”
Waste disposal	“Waste generated at the time of collection for each sub-assembly, part, and/or material”
Energy consideration	“Amount of energy used per year”
Recycling efficiency	“Quantifies how efficient are the recycling processes used to produce recycled input and to recycle material after use”
Additional process inputs	“Amount of water consumed per year in industrial processes”
Product, part, material retention	“Fraction of mass of a product’s feedstock x from recycled sources, […] fraction of mass of a product’s feedstock x from reused sources”
Longevity or residence time	“L/Lav—accounts for any reduction (or increase) in the waste stream in a given amount of time for products that have a longer (or shorter) lifetime L than the industry average”
Value change or productive use	“U/Uav—Reflects the extent to which a product is used to its full capacity”

45 FW-LCI	
Resource productivity or process efficiency	Water balance, […] consideration of “Emissions to biosphere, […] “cumulative substance emissions (per functional unit)”
Waste disposal	“*Disposed* was the mass (dry weight) of waste disposed to air, soil and water”, “Percentage of MGB waste as refuse (sent to landfill)“
Energy consideration	Calculation of “energy balance” as separate subchapter
Potential for recycling or remanufacturing	Quantities of waste collected
Recycling efficiency	Recycled waste as percentage, compared to other treatment options
Spatial dimension	Municipal waste management systems
Additional process inputs	“quantity of diesel and trucks required for each WMS’ collection regime”
Cascading use of resources	“Substitution of synthetic fertiliser generation”
Destination of flows	Waste and material flows are mapped for different waste treatment systems
Reuse, remanufacturing, recycling complexity	“a number of waste types defined as FW, GW, paper/cardboard, textiles, nap-pies/sanitary items, rubber/leather and other/inert materials […] the manner in which the waste was collected, sorted, treated and disposed of, depending on the system”
Value change or productive use	Recycled waste is divided into “recycled (valued) ” and “recycled (other)” for estimating the value added between the different recycling systems
Recycled material value	“recycled (valued) and recycled (other), was to distinguish between elements within the mass-balance that have a clear and inferable market price”
Materials mixing and dilution	“The manner in which an ‘organic’ waste is separated from other wastes makes a big difference in the purity and characteristics of that waste.”
Toxicity and clean mat. cycles	

46 EOU-VR	
Resource productivity or process efficiency	"Operation cost", "Machine cost", "Tool change cost" used to evaluate process efficiency
Additional process inputs	"labour cost", "tool cost"
Stock availability or concentration	"Bill of materials"
Reuse, remanufacturing, recycling complexity	"product architecture information", "subassemblies", "connectivity relationships among parts must be characterised"
Recycled material value	"Revenue of components"

47 ECOENV-INVEST-I	
Primary vs. secondary materials, parts, products	"Wi is the amount of secondary raw materials used as input in the production process; Mi is the total amount of raw materials used as input in the production process."
Resource productivity or process efficiency	"quantity of materials (kg), the specific weight (kg/m3) […] necessary to fulfil the mandatory requirements", "Embodied Carbon for the i-th material or component used in the j-th building system [kg CO2 eq/kg]."
Waste disposal	wastes production [kg]
Energy consideration	"Embodied Energy"
Potential for recycling or remanufacturing	"Level of Disassembly (LD) assumes that […], materials and components used in a building can be separated in order to maximise the amount of demolition wastes delivered to reuse or recycling."
Recycling efficiency	"recycled materials index [%]"
Recycled material value	"residual value of the component j"

48 REG-ENV-IO	
Primary vs. secondary materials, parts, products	"virgin resource used" and "recovered waste"
Resource productivity or process efficiency	"carbon emissions [kg CO2/kg]" or "direct emissions intensity" [kg CO2-eq/€]
Waste disposal	"waste management [category in m^3]
Energy consideration	"electricity is the main hotspot"
Recycling efficiency	Fraction of recovered waste and overall inputs
Spatial dimension	Use of multi-regional input-output (MRIO) model
Additional process inputs	"mix of supply chain inputs" (water, equipment, chemicals, etc.)
Destination of flows	"input-output (IO) model" modelling the "mix of supply chain inputs […] required to produce a unit of output", and "descries the total requirements to produce the output [for a given demand]"
Sharing of infrastructure and utilisation of resource streams	"recovery of value and reused in the production of secondary products."

49 ARMC	
Primary vs. secondary materials, parts, products	"PPPR consumption is first converted to its corresponding primary resource consumption using equivalent coefficients", "secondary resource consumption"
Resource productivity or process efficiency	"resource productivity [as coefficient of] real GDP [and products produced directly by primary resources]", "the raw iron mine required for 1 ton steel production can be calculated as: 1 t×98%/(85×85.2×89.5%×33.1%)=4.56 t"
Waste disposal	
Energy consideration	"energy consumption", "energy consumption should first be converted to standard coal equivalents (tce)"
Spatial dimension	Application to defined industrial zone: "TEDA is a special development zone located in [China's third largest city]"

50 CE-PERFORM-I	
Primary vs. secondary materials, parts, products	“substitute the virgin original material”, “expressed in terms of natural resource consumption,”
Resource productivity or process efficiency	“environmental benefit of option I is thus the avoided impact of virgin production V multiplied with recycling rate r, minus impact R.”
Waste disposal	“In option IV, the waste can only be incinerated”
Energy consideration	“obtained amount of energy (E), including both heat and electricity”, “total exergy that is contained in the various resources extracted”
Recycling efficiency	Treatment options result in different contents of recycled materials, e.g. “end-product consists of […] 20% recycled material”
Reuse, remanufacturing, recycling complexity	“if the plastic is of high quality, it can substitute the virgin original material in a 1:1 ratio […]. If the quality is lower, there are two possibilities: (1) the recycled material can still substitute the original virgin material, but not in a 1:1 ratio […]”
Downcycling and quality loss	“recycled plastic can only be used in low-grade applications [if quality is low]”, “based on the quality factor, the waste should go […]”
Materials mixing and dilution	“Based on the interfacial tension, four compatibility classes are defined: perfectly compatible, reasonably compatible, limited compatible and incompatible [plastics].” “For a contamination of $<5\%$, the quality factor is on average 0.87”

51 GLOBAL-MAT-STOCKS-MODEL	
Primary vs. secondary materials, parts, products	“amount of primary material inputs, […] global resource extraction by uses” vs. “recycling input rate”
Resource productivity or process efficiency	“material stock productivity”, “analyse stocks, inflows, and outflows and their relation […] to energy use and CO2 emissions”
Waste disposal	Quantification of “waste output”
Energy consideration	“analyse […] energy use”
Potential for recycling or remanufacturing	“global in-use material stocks [per material group]”
Recycling efficiency	“recycling rates”, “for nonmetallic minerals we estimate that 37% of all end-of-life outflows from stocks are recycled”
Spatial dimension	“stocks by region”, “Energy and emissions intensity of stocks”
Stock availability or concentration	“global in-use material stocks”, “quantify the mass of all materials stored in buildings, infrastructure, and durable goods, distinguishing 11 types of stock-building materials”
Downcycling and quality loss	“total of 4.8 Pg/yr of re- or downcycled secondary materials added to the inflow of primary materials”
Embedded stocks or distinct lifetimes	“mean lifetimes”, “lifetimes and detailed cohorts for each material”
System stability	“global economy far from steady state or a circular economy. This would essentially require a stabilisation of material stocks”, consideration of “stock growth dynamics” and “recycling input rate”

52 SEA

Primary vs. secondary materials, parts, products	"input of secondary raw material flows [explicitly considered]", "P import"-flows vs. "P recycling"- flows
Resource productivity or process efficiency	"evaluating the efficiency of resource use patterns", "providing useful information regarding the patterns of resource use and the losses of materials entering the environment"
Waste disposal	"Hmax is reached when all of the P is directed to surface waters, […] also, P lost to surface waters can be considered non re- coverable and therefore Hmax defines a stage at which recoverable P resources do not exist"
Potential for recycling or remanufacturing	Potential for recycling shown through overall size of material flows: "four solid waste flows are directed to waste management (P6), two flows to waste water treatment (P5), one recycling flow (residues from bioenergy) to crop farming (P1) […]"
Recycling efficiency	"In order to evaluate the resource efficiency gains achieved by implementing the three groups of measures, SEA is applied to the P use system after [implementation]."
Spatial dimension	"Austrian P resource system"
Cascading use of resources	Cascading use of process outputs shown in MFA model through cycling loops
Destination of flows	"material flows used for SEA", (MFA system as precondition for SEA)
Stock availability or concentration	Material flow model (MFA) includes flows, SEA methodology requires concentrations for each flow, and includes material stocks
Modelling of materials cycles	"several internal P recycling loops exist within the P resource system"
Sharing of infrastructure and utilisation of resource streams	"resource utilisation in an economy", consideration of P resource utilisation from various processes
Materials mixing and dilution	"the concentration of the substance in the receiving environmental compartment is used to highlight the dilution of the emissions in the environment [and the] concentration in the emission flow itself (cij)"

53 MINING-MFA-I

Primary vs. secondary materials, parts, products	"projects processing virgin ores, the new waste is simply the waste generated by initial mining and mineral processing" vs. "total production from waste"
Resource productivity or process efficiency	"material efficiency indicator […] is the ratio between production and total material moved (TMM)", "Extraction Inefficiency"
Waste disposal	"total mineral losses to waste"
Energy consideration	"total energy input"
Potential for recycling or remanufacturing	"Production with waste material as the feedstock"
Recycling efficiency	"discounted by the amount of waste that is being processed for mineral recovery."
Additional process inputs	"total water input"
Destination of flows	Use of MFA
Stock availability or concentration	"Ore deposit"
Sharing of infrastructure and utilization of resource streams	"extract more value and extend the life of a mine while recovering mineral losses"
Recycled material value	"total production from waste […] and mineral losses to new waste […] represent the total mineral value of waste being reprocessed"

54 MATRACE

Primary vs. secondary materials, parts, products	"secondary metal" flows calculated, […] "using coefficients that distinguish between applications for primary and secondary steel"
Resource productivity or process efficiency	"maximal value 1 if no losses occur", "reduction of remelting yield losses by 50%, 20–22% of the steel will get lost by 2100, 38–42% will be used in construction"
Waste disposal	"losses in landfills or slag piles are weighted"
Potential for recycling or remanufacturing	"Total steel in the system" along different product categories is provided
Recycling efficiency	"recovery rates of postconsumer scrap in the waste management industries, and the recovery rates of fabrication scrap in the manufacturing industries"
Spatial dimension	"distinguishes between […] 25 regions"
Cascading use of resources	"metric for assessing the circularity of material use from the perspective of a unit of metal passing through different applications throughout its life cycle."
Destination of flows	Flows to different applications in the system e.g. construction, cars, machinery, etc. are calculated, "to derive multiregional distribution matrices […] whose coefficients tell the percentage of an incoming EoL product/scrap/metal/final product in region r"
Product, part, material retention	"unit of metal passing through different applications throughout its life cycle" [and] "[different] age-cohorts"
Stock availability or concentration	Simulation of stocks over time and composition shows stock availability (e.g. Figure 5)
Modelling of materials cycles	Scrap goes back to remelters and model consists of 86 model years
Reuse, remanufacturing, recycling complexity	"postconsumer scrap […] is remelted in the EAF route and subsequently used in construction only"
Downcycling and quality loss	"postconsumer scrap, whose largest contributors are steel scrap flows from vehicles and machinery […] is remelted in the EAF route and subsequently used in construction only"
Longevity or residence time	"once the steel ends up in construction there is not much additional turnover before 2100."
Embedded stocks or distinct lifetimes	"material content of product […] process data including product lifetimes"
System stability	"only 40–50% of the steel in registered passenger cars will still be in the country by 2100"
Recycled material value	"factor w that measures purity, quality, and recoverability ($0 \leq w \leq 1$)"

55 EOL-ECO-EFFICIENCY	
Primary vs. secondary materials, parts, products	“avoiding the production of new [lithium-ion battery] packs”, “potentially avoid 130 t of metal inputs, primarily by avoiding primary and secondary lead production”
Resource productivity or process efficiency	Relation of process inputs and process outputs provided
Waste disposal	“ultimate disposal of materials not reused or recycled (in landfills)”, “eventually entering the landfill is expected to account for 70% of the of the total waste stream”
Energy consideration	„cumulative energy demand“
Potential for recycling or remanufacturing	“maximum recycling capacity (34,000 tonnes [t] annually)”, “reusing the maximum feasible number of EV LIBs packs in automotive application (37.2% of the 1,000 packs entering the waste stream) only offsets […]”
Recycling efficiency	“recovery efficiencies in recycling”, “metal recovery from the hydrometallurgical process was 29% less, leading to 40 t of net avoided metals by both routes”
Spatial dimension	“EV battery packs in the United States”
Additional process inputs	“additional materials” as separate flow in MFA
Cascading use of resources	“open-loop cascaded use. […] cascaded use pathways would include some level of testing and refurbishment to bring batteries back to a usable condition or prepare packs for new applications”
Destination of flows	MFA of lithium-ion batteries
Product, part, material retention	Retention within the system depending on the recycling route “C2 [n years +4.5 years] and C3 [n years +9.5 years]”
Stock availability or concentration	“bill of materials of LIB cell and pack components”
Modelling of materials cycles	Reuse, recycling and cascading flows provided
Reuse, remanufacturing, recycling complexity	“maximum of 35% of the EV LIB outflows in year n may have remaining capacity for use in EV”, “Additional comparisons were made to determine sensitivity of results to alternate battery technology, specifically cathodes currently used or previously studied”
Downcycling and quality loss	“efficiency loss calculations were based on Zackrisson and colleagues (2010). A direct correlation between capacity decay and battery charge-discharge efficiency was applied, and after reuse in EVs, the capacity and efficiency was reduced to 80%”
Longevity or residence time	“(ld), Life span of EV LIB in reuse application”
Value change or productive use	“resale value of the new EV battery at vehicle EOL […], Cost of buying a refurbished EV LIB […], and resale value of refurbished [lithium-ion battery]”, “resale value of the new EV battery at vehicle EOL (SLIBused,new), Cost of buying a refurbished EV LIB (BLIB, refurb), and Resale value of refurbished LIB”
Supply risk and scarcity of resources	“scarcity […] of contained materials”
Embedded stocks or distinct lifetimes	“for year n, 40% (by weight) of the EOL EV LIBs would not meet technical criteria required for direct or cascaded reuse and would therefore be recycled in the same year (C1 recycling), whereas the rest of the waste would be recycled in later years after reuse and/or cascaded use denoted by C2 [n+4.5] and C3 [n+9.5] recycling”
Recycled material value	“economic cost or benefit of EV LIB recycling […] was calculated from the total cost of recycling operations […] and value of recovered materials”
Toxicity and clean material cycles	“Eco-toxicity impacts were based on empirical and database estimates”, “eco-toxicity characterisation factor (comparative toxic units eco-toxicity per kilogram; CTUe/kg) for that metal.”

56 C-MFA	
Primary vs. secondary materials, parts, products	“the proportions of [recycled aggregates] used to substitute natural aggregate”
Waste disposal	“Disposal” as separate process in MFA
Energy consideration	
Potential for recycling or remanufacturing	“total output of recycling relevant mineral products”, “Equation (11) determines the regional annual maximum amount of nonmetallic mineral materials that can be used for high-grade recycling”
Recycling efficiency	“taking into account the typical proportions of material lost during material capture and processing”
Spatial dimension	“processes are calculated at the regional level”
Destination of flows	Use of MFA approach
Stock availability or concentration	“Material compositions of multifamily houses”
Modelling of materials cycles	Calculation of material flows for multiple years, including recycled material flows
Reuse, remanufacturing, recycling complexity	“material composition indicator of building type”, “There will always be capture losses when material cannot be separately extracted to a high level of purity; the resulting low quality makes such material unsuitable for recycled aggregate production.”
Downcycling and quality loss	“guideline (DAfStb 2010) specifies that the finest particles (<2 mm) must not be used in the production of concrete, thereby ensuring the removal of most impurities. […] resulting processing losses can be quantified by a reduction factor”
Longevity or residence time	“describe the physical size of the building stock and its dynamic”
Sharing of infrastructure and utilisation of resource streams	“Outflows and inflows of recycling-relevant material in the German building stock in 2020, classified by material and region type”
System stability	“Comparison of supply and demand of [recycled concrete aggregates] and [recycled masonry aggregates] within region types RT (left) and resulting mismatch regarding admixtures”

57 ECOENV-REMAN-MODEL	
Primary vs. secondary materials, parts, products	“sufficient used products will be sourced to satisfy remanufactured product demand without the need to buy new components.”
Resource productivity or process efficiency	“to maximise the output of the remanufacturing process”, “The remanufacturing process starts by buying c used products that are disassembled in their n major components. For each component type i, a fraction Ri of components are reusable.”, “Environmental impact of collection, [assembly, refurbishing, etc]”
Waste disposal	“faulty components are identified and discarded during the refurbishment step.”, “components are recycled or land filled”
Recycling efficiency	“Environmental impact of recycling component i.”, “recycling costs”, “components recycled”
Additional process inputs	“refurbished components bi are assembled with di = a − bi new components,”
Cascading use of resources	“Number of refurbished components of type I”
Reuse, remanufacturing, recycling complexity	“reusable (Ri) and non-reusable still to be identified as faulty […] components, is based on the number of refurbished components needed in the assembly process (bi), which is decided based on the demand.”

58 EDIM

Resource productivity or process efficiency	"Disassembly times" per task
Stock availability or concentration	"material composition of 28 LCD monitors"
Modelling of materials cycles	
Reuse, remanufacturing, recycling complexity	"disassembly tasks", e.g. tool change, identifying connectors, etc.

59 BWPE

Primary vs. secondary materials, parts, products	"Total volume of building materials" vs "Recyclable [/reusable] component of building"
Waste disposal	"Fraction of building that goes to landfill"
Potential for recycling or remanufacturing	"Reusable component of building", "Recyclable component of building"
Product, part, material retention	"structural components largely made of steel has 0.93 reusability and 0.07 recyclability, while the building with timber structure has 0.65 reusability and 0.35 recyclability."
Reuse, remanufacturing, recycling complexity	"Total number of connections", "Ratio of demountable connections to total connections", "total number of possible building elements"
Longevity or residence time	"Life expectancy of building"
Value change or productive use	"Deterioration function of the building"
Recycled material value	"function is useful to determine the best time at which the optimal value could be derived from a building when it gets to its end-of-life."
Toxicity and clean material cycles	"Volume of material without hazardous content", "Ratio of volume of materials without toxic content to the total volume of materials"

60 PRODUCT-ECOSYS-MFA

Primary vs. secondary materials, parts, products	"figure 8 shows the net system demand versus secondary material supply", "Demand only met by primary material supply", Demand potentially met by theoretical secondary material supply"
Resource productivity or process efficiency	"decreasing average product mass", "per-product dematerialisation"
Waste disposal	"household waste"
Potential for recycling or remanufacturing	"Excess secondary material supply"
Recycling efficiency	"Fewer than 10% of small products, such as smartphones, are collected for recycling"
Spatial dimension	"US households"
Destination of flows	Use of simple MFA model
Stock availability or concentration	"Change in household stock", "number of products in stock"
Embedded stocks or distinct lifetimes	"Household stock disaggregated by material"
System stability	Unbalanced in- and outflows from households "demonstrates demand mismatch"
Materials mixing and dilution	Dilution of material in overall material stock shown over time: "While total mass of gold in the household waste stream is increasing, the weighted average gold per product is decreasing as many small products are consumed."

61 WASTE-VALUE	
Primary vs. secondary materials, parts, products	"The production of paper and cardboard from waste paper and cardboard requires the introduction of virgin fibres in the process., [which] displaces the production of new cardboard"
Resource productivity or process efficiency	"economic value of the items for reuse is 806 euros per ton"
Waste disposal	"Landfilling with household waste amounts to 1.7%"
Energy consideration	"energy recovery from incineration"
Spatial dimension	"municipalities, Hjørring and Brønderslev"
Cascading use of resources	"collection of items for reuse nearly doubled […], comprising 3.23%"
Destination of flows	"determine to which other waste fractions the waste "missing" in the combustible fraction had been diverted."
Reuse, remanufacturing, recycling complexity	"quality of polymers decreases during recycling, the result being that secondary plastics do not compete directly with primary plastics and thus do not displace virgin plastic in the production of new things"
Value change or productive use	"Value of the diverted materials", "economic value of the items for reuse is 806 euros per ton"
Recycled material value	"the prices of plastic films fluctuate greatly: between 157 and 306 euros per ton", "economic value of the items for reuse is 806 euros per ton", "company sells the cardboard to a large international recycling company at 13 EUR per ton"

62 ESTM-STOCK-DYNAMICS	
Primary vs. secondary materials, parts, products	Estimation to which degree end-of-life copper could satisfy demand
Recycling efficiency	"Even in an ideal situation where recycling rates as high as 70 or 90% are achieved, […]"
Spatial dimension	Modelling of "global" copper demand
Stock availability or concentration	"With the bottom-up stock dynamics method, detailed projections of demand per category and even per appliance have been conducted."
Longevity or residence time	"residence time of the application"
Embedded stocks or distinct lifetimes	"in-use-stock of the copper-containing products is the essential variable", life-span (in years) is used as input into model
System stability	"Even with large scale new mine explorations and extensive urban mining activities, it would be unlikely, that such an amount of copper would be available"

63 LONGEVITY-CIRCULARITY-I	
Primary vs. secondary materials, parts, products	Initial use vs. refurbishment and recycling (formula)
Potential for recycling or remanufacturing	"sum of the products and the goods returned"
Recycling efficiency	"variable p reflects the fraction of the initial material that will be recovered through recycling [and ratio p/1-p] shows the percentage of material that is recycled"
Product, part, material retention	"proportion of those that are returned, which are then refurbished"
Modelling of materials cycles	"variable n shows the total number of cycles there are, [for] each cycle i the amount of material that passes through each cycle preceding and including cycle i must be considered"
Longevity or residence time	"Longevity is determined in three ways: the time for which a resource is first used (A); the time for which a resource is used due to product refurbishment (B), and due to recycling (C).", "resources are used again, and, in turn, create an additional initial lifetime"
Value change or productive use	"This value is expressed in the unit of time and thus is a non- monetary unit" (Franklin-Johnson et al., 2016) (as Figge et al. 2018 update and correct the previous approach)

Contribution of CE elements to principal component axis – (SI3)

CE elements	Dim 1	Dim 2	Dim 3	Dim 4
system stability	8.19	0.01	8.21	0.05
embedded stocks lifetimes	7.34	0.01	4.02	3.26
longevity	6.30	3.34	0.04	7.19
modelling cycles	6.28	0.79	1.66	0.10
recycling	5.85	0.15	0.58	0.02
retention	5.82	2.83	1.64	1.00
stock availability concentration	4.42	0.60	0.25	0.50
supply risk scarcity	3.19	1.76	0.10	0.72
downcycling	3.17	1.11	4.55	0.96
cascading	3.11	1.69	0.57	1.42
additional inputs	2.16	4.74	1.06	2.62
flow destination	2.03	4.22	0.24	0.21
primary vs. secondary use	1.95	0.28	0.29	0.61
energy	1.44	4.14	0.72	2.28
reuse reman complexity	1.12	0.14	13.14	2.85
recyc material value	0.93	1.19	4.16	1.88
recycling efficiency	0.92	3.63	0.81	1.07
toxicity	0.88	0.83	15.85	0.03
value change	0.46	1.96	10.09	6.22
recycling efficiency	0.42	0.10	0.74	0.06
waste disposal	0.24	2.95	0.15	1.38
materials mixing	0.14	0.36	4.79	4.73
sharing	0.13	5.88	0.00	7.06
retention	0.12	0.38	0.02	12.6
resource efficiency productivity	0.03	4.68	0.06	0.34
spatial	0.01	3.25	1.06	3.43

Contributions of the CE metrics to the first four principal component axes (SI4)

Metric	Dim 1	Dim 2	Dim 3	Dim 4
Dynamic-PML	12.77	9.21	5.41	1.01
MATRACE	11	0.82	0.12	2.2
EOL-ECO-EFFICIENCY	8.6	0.96	6.4	0.03
TSSFM	7.6	1.6	4.2	0.25
Dynamic-PML	5.9	2.6	3.3	0.19
DYNAMIC-SFA	5.2	0.05	4.9	0.37
PERFORM-ECON-M	4.7	1.8	0.32	17
CEECI	3.7	0	0.04	0.19
C-MFA	3.6	0.43	0.7	0.04
LCA-EVR	3	0.18	0.06	0.01
EIP-indicator-set	2.6	0.82	0.12	1.4
CE-enterprise-index	2.6	0.82	0.12	1.4
MSIASM	2.5	1.3	0.48	0.71
AGRI-FOOD-IO	2.4	0.65	0.3	0
VA-ED	2.3	0.03	0.16	0.5
RES	1.9	0.3	1.9	0.11
SSCN	1.9	1.4	0.13	0.31
CE-DEA	1.9	0.12	0.03	0
RRs	1.9	0.11	0.17	0.69
MD-business-value	1.9	4	0.46	0.68
CE-strategy-model	1.9	4	0.46	0.68
Markov-chain	1.8	1.7	0.71	0.06
CEIS	1.7	2.1	0.53	1

ARMC	1.7	0.18	0.61	0.6
PRODUCT-ECOSYS-MFA	1.5	0.62	2.6	3.4
CEENE	1.3	0.52	0.05	0.48
GDM-reman	1.2	0.06	0.11	0.09
REG-ENV-IO	1.1	3.3	0.39	0.8
GLOBAL-MAT-STOCKS-MODEL	1	0.86	2.4	0.96
RP-indicator	0.87	0.17	2.7	0.72
EDIM	0.84	1.4	0	2.5
SEA	0.83	1.6	0.31	2.3
BWPE	0.82	4.7	7.6	0.46
REERF	0.76	2.6	3.8	1.5
ESTM-STOCK-DYNAMICS	0.75	1.5	6.9	0.58
LONGEVITY-CIRCULARITY-I	0.68	4.2	0.11	2.1
CET	0.67	1.1	8.9	2.5
Emergy	0.59	3.7	0.04	0.03
Duration-indicator	0.57	4.3	0.03	1.5
EOU-VR	0.57	0.92	0.25	3.8
SCI	0.55	1.2	0.04	24
HE-ELFM	0.43	0.08	0.26	0.36
IS-LCA	0.37	1.1	0.05	0.49
ECOENV-INVEST-I	0.37	0.06	0.28	0.18
ECOENV-REMAN-MODEL	0.34	0.19	0.04	0.11
ITPR	0.26	0.03	0.01	4.4
CE-PERFORM-I	0.24	0.89	0.61	1.6
RMS	0.21	0.4	0.81	0.01
EMF	0.21	4.5	0.03	4
RE-EW-MFA	0.2	0.56	2	0.08
TOXICS-CYC	0.17	1.2	4.5	7
Recycling-indicator-set	0.15	0.01	0.01	0.12
IS-RP-indicator	0.15	4.2	0	0.07
Reman-SF	0.14	3.9	0.53	0.11
WASTE-VALUE	0.06	0.54	2.1	0.84
PCM	0.05	7.4	0	0.39
MINING-MFA-I	0.05	9.4	0	1.8
C2C	0.05	0.07	15	0.08
FW-LCI	0.02	2.8	5.1	1.1
MATERIAL-RI	0.01	2.3	1.1	0.23
Product-RRR	0.01	0.81	4.2	0.06
EW-MFA	0	0.34	0.99	0.03
ZWI	0	0.48	0.15	0.05
CEIP	0	0.1	0.01	0
Dynamic-PML	12.77	9.21	5.41	1.01

Multiple Correspondence Analysis – interpretation guidance (SI5)

After the calculation of distances between the data points and the location of data points in the best fitting principal component space, the geometry and location of objects can be interpreted. In the following the interpretation rules as provided by Le Roux and Rouanet, (2010) will be followed. Each cell in the contingency table consists of a metric i and a circular economy element category k. Only entries of $\delta_{ik} = 1$ and $\delta_{ik} = 0$ are possible[11]. If two different metrics i and i' have the same entry for a category, the contribution of this category to the distance between the data points is zero. The partitioning of data points is the result of different entries for the same category (Le Roux and Rouanet, 2010). The total distance between individuals i and i' is determined by the number of overall classification elements Q and the difference in categorisation for each individual. In our case, the number of classification elements Q is equal to the number of categories, further $(n = Q)$. It follows, that the more diverse the categorisation pattern, the larger the distance between points, which is calculated as the squared distance between two metrics *(1)* (Le Roux and Rouanet, 2010).

$$d_k^2(i, i') = \frac{1}{n} \sum_{k \in K_i} (\delta_{ik} - \delta_{i'k})^2 / f_k \qquad (1)$$

The mean point of the cloud of points is G and represents the mean coordinates of the cloud. The distance of a point M^i of individual i to point G is defined as the squared distance between the points, K_i being the categorisation pattern of individual i, while f_k represents the relative frequency of category k *(2)* (Le Roux and Rouanet, 2010).

$$(GM^i)^2 = \left(\frac{1}{n} \sum_{k \in K_i} \frac{\delta_{ik}}{f_k}\right) - 1 \qquad (2)$$

Further, sub-clouds can be constructed with a mean point for each sub-cloud, by considering the variance within the sub-cloud and the distance of individuals to the mean point. The variance of the cloud, also referred to as inertia, is calculated by taking the squared sum of the distance between each point and the mean point of the cloud, dividing it by the number of individuals in the cloud *(3)*.

$$V_{Cloud} = \sum (GM^i)^2 / n. \qquad (3)$$

Besides the calculation of the cloud of objects, in our case the circular economy metrics, it is also possible to calculate the cloud of categories, in our case the elements assessed by the circular economy metrics. Each circular economy element k is represented by a point M^k and has a weight n_k, representing the number of metrics considering the category. The overall sum of weights is n, resulting in the relative weight *(4)*.

$$p_k = \frac{n_k}{n} = f_k \text{ and } \sum_{k \in K} p_k = 1 \qquad (4)$$

As for the distance calculation for metrics, the distance between two different elements is null, if two different metrics have the same entry for that element. The larger the similarity of assessed elements between the circular economy metrics, the smaller is the distance between the metrics. At the same time, the less frequent the element is present within the set of metrics, the larger the distance of the point from the centre of the cloud (Le Roux and Rouanet, 2010). The contribution of each category to the variance results in the overall variance of the cloud. The contribution of a category can be calculated as a ratio of a data point over the total cloud variance *(5)* (Le Roux and Rouanet, 2010).

[11] The algorithm by (Husson et al., 2010), utilizes categorical entries. Therefore, initial categorizations of (1,0) are translated into (Y=yes, N=No).

$$Ctr_k = \frac{p_k(GM^k)^2}{\sum p_k(GM^k)^2} \quad (5)$$

It follows, that the less frequent a category is present, the more it contributes to the variance of the cloud (Le Roux and Rouanet, 2010). The quality of representation of a point on the principal component axis is given by the cosine between the point and the projected point on the principal component axes (Le Roux and Rouanet, 2010).

The main limitations of the method are the potentially low value for the explained variance, which is a result of projecting a large number of dimensions into a two-dimensional space. Nevertheless, the two dimensions explain a much larger fraction of the data than each single dimension on its own. Further, the rotation of the principal component space along the maximum variance, makes the method sensitive to outliers (Le Roux and Rouanet, 2010). The reduction of variables can lead to difficulties in the interpretation in the principal component space (Clausen, 1998). Besides the methodological limitations, further limitations can be attributed to the data quality.

Visualisation framework for assessed circular economy elements (SI6)

The visualisation of CE elements has three objectives. First, it provides an overview of the CE elements that already can be assessed with existing metrics. Second, the framework allows classifying existing CE metrics in a simple way, providing a detailed account on the complementarity or dissimilarity of different metrics. Third, the framework can be used to identify substantial gaps in currently applied CE assessment methodologies (Figure 22).

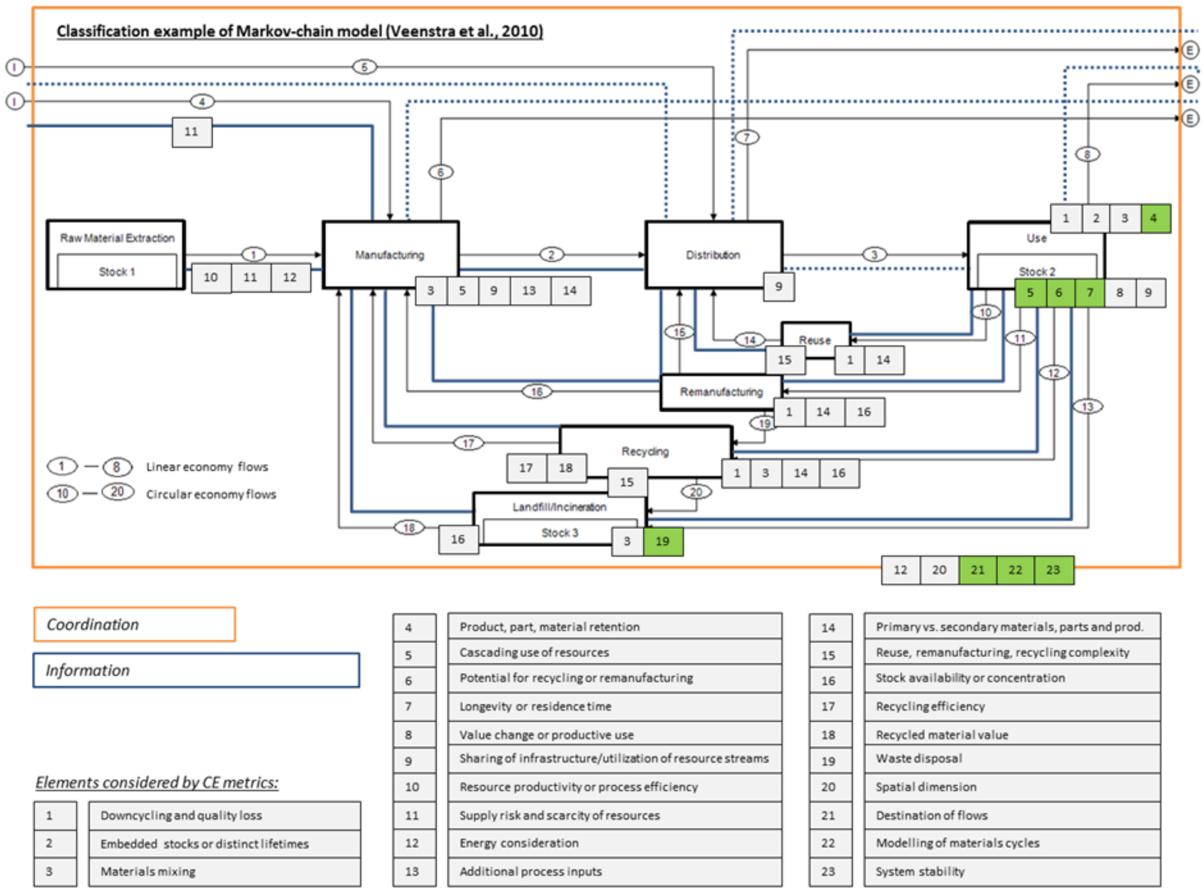


Figure 22: Visualisation of assessed circular economy elements (framed numbers) with main processes and material flows (encircled numbers). Dashed blue lines indicate information flows that are not considered by the assessed metrics[12].

The visualisation represents a simplified diagram of a metabolic production-consumption system, which is based on the visualisation of Liu et al., (2014) and the Raw Materials Scoreboard European Commission, (2016) and is a complementary extension to the MCA results to serve a more specific analysis of a subset of metrics. It maps the main processes, material flows (black) and information flows that can be potentially assessed (blue). Elements that refer to more systemic features are also indicated (orange). The linear economy is represented by five main processes: raw material extraction, manufacturing, distribution, use and landfilling/incineration. These processes are connected by so-called linear flows (encircled flows 1-10). Additional processes, such as reuse, remanufacturing, recycling, and the corresponding flows, are added to the framework and represent return flows through which the circularity is achieved that characterises a circular economy (encircled flows 10-20).

[12] Note: Basic structure based on Raw Materials Scoreboard (European Commission, 2016; Liu et al., 2014), additional attributes have been added with the STAN software (Cencic and Rechberger, 2008).

The framed numbers represent the 24 identified CE elements. Within the visualisation framework, each metric can be assessed by providing a simple colour code of the elements assessed. Thereby, the visualisation framework provides a simple visual representation of the assessed CE elements with the opportunity for a potential extension of metrics by considering additional CE elements, or by combining complementary metrics.

The reasoning behind the application of the visualisation framework is shown in the following by the parallel mapping of the CEIS, RRs and Longevity-Circularity-I metrics (Figure 23). The visualisation framework clearly shows a shift in focus from the CEIS metric, to the RRs and to the Longevity-Circularity-I metric. The distinguishing quality of the CEIS metric is the measurement of the CE elements 9 (Sharing or utilisation of resource streams), 10 (Resource productivity) and 12 (Energy consideration). The RRs metric does not consider these CE elements and has a stronger focus on the assessment of elements related to the process of recycling, such as CE element 1 (Downcycling and quality loss), 5 (Cascading use of resources), 6 (Potential for recycling or remanufacturing), 15 (Reuse, remanufacturing, recycling complexity), 21 (Destination of flows), and 22 (Modelling of material cycles). Further, the change in focus from the RRs metric to the Longevity-Circularity-I metric is based on the assessment of the inner reuse, remanufacturing circles, and the extension of the CE elements within the use phase, assessed by the elements 7 (Longevity or residence time) and 8 (Value change or productive use).

The different focus of the three metrics can also be observed from the MCA results, as the three metrics belong to three different clusters. The added value of the visualisation framework is a more explicit identification of assessed CE elements and a more precise identification of differences between CE metrics based on the colour coding of each CE element. The colour codes help to observe the shift in focus and identify the responsible CE elements for that shift. From the colour coding example, we observe that the CEIS metric has a stronger focus on the assessment of upstream processes and flows of the simplified metabolic system, while the focus of the Longevity-Circularity-I metric shifts to the use phase and related processes of the inner CE flows of reuse and remanufacturing.

Through the visualisation example, it is shown that the visualisation framework is useful for comparing a limited set of CE metrics and is, therefore, a complementary to the MCA results. It is seen especially useful, when it comes to choosing the right combination of CE metrics, identify further metric gaps, or to guide the development of additional CE metrics.

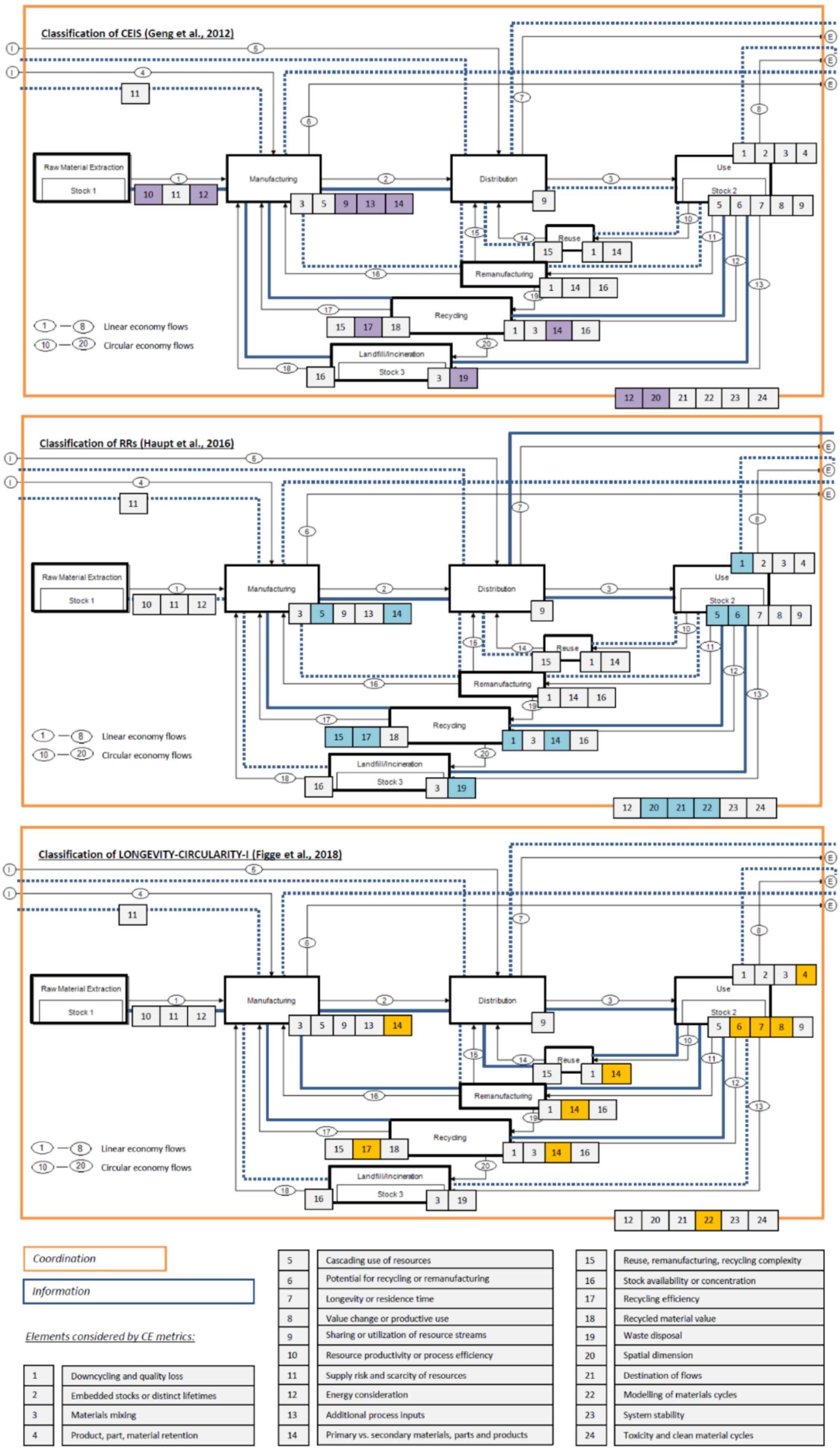


Figure 23: Comparative visualisation of the CEIS, RRs, and LONGEVITY-CIRCULARITY-I metrics, representing the first, second and third cluster of the MCA results.

Supplementary information - chapter 3

Statistical Entropy calculation examples (1-7) are provided in the following, combining different constellation of components, components and material flows and products, components and material flows.

Example 1 (SI 7): The supplementary excel file is provided under the following link:

https://doi.org/10.1016/j.resconrec.2020.104925

In this calculation example, the relative statistical entropy is calculated for three components, with all three components having an identical mass and composition, while each of the components is regarded as distinct (structurally not identical). This example is provided to show what happens if the number of distinct components is reduced while keeping the component composition equal (see Example 2).

Car	1000	kg
kg Fe	510	kg
kg Al	120	kg
kg OM	370	kg

Component 1	333.33	kg
Component 2	333.33	kg
Component 3	333.33	kg

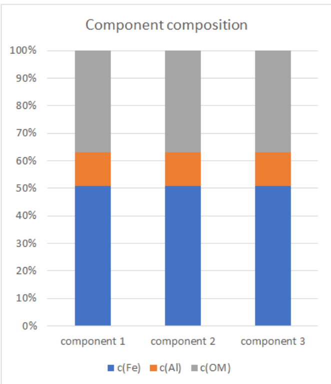
Eq 5	Eq 9
Eq 6	Eq 10
Eq 7	Eq 11
Eq 8	Eq12

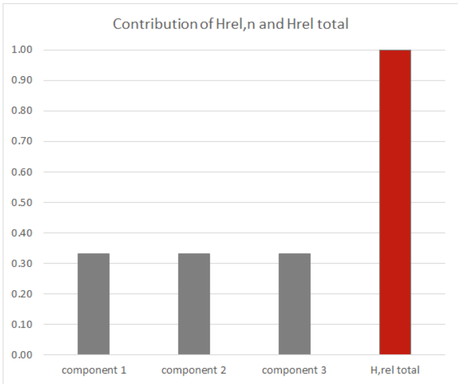
Component 1	kg Fe	170.00
	kg Al	40.00
	kg OM	123.33
	sum	333.33
Component 2	kg Fe	170.00
	kg Al	40.00
	kg OM	123.33
	sum	333.33
Component 3	kg Fe	170.00
	kg Al	40.00
	kg OM	123.33
	sum	333.33
Total:		
	kg Fe total	510
	kg Al total	120
	kg OM total	370

Calculation of Component Entropies:						
	cnj	mc,n = Mc,n/sum(sum(Xnj))	ld(cnj)		mc,n x cnj x ld(cnj)	H,rel
c1Fe	0.510	0.333	-0.97		-0.165	-0.119
c1Al	0.120	0.333	-3.06		-0.122	-0.088
c1OM	0.370	0.333	-1.43		-0.177	-0.127
			SUM	*Hc1*	0.464	**0.333**
c2Fe	0.510	0.333	-0.97		-0.165	-0.119
c2Al	0.120	0.333	-3.06		-0.122	-0.088
c2OM	0.370	0.333	-1.43		-0.177	-0.127
				Hc2	0.464	**0.333**
c3Fe	0.510	0.333	-0.97		-0.165	-0.119
c3Al	0.120	0.333	-3.06		-0.122	-0.088
c3OM	0.370	0.333	-1.43		-0.177	-0.127
			SUM	*Hc3*	0.464	**0.333**
					SUM(Hc,n)	***1.000***

Calculation of Product Entropy:			Hp,max =	1.58		
	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	*Hp,rel*
Component 1	1	0.333	0.3333	-1.58	-0.53	
Component 2	1	0.333	0.3333	-1.58	-0.53	
Component 3	1	0.333	0.3333	-1.58	-0.53	
N=	3				1.58	1.000

Hmax calculation - If all substances are mixed in one flow:						
		sum(Xj)	cj	mc	ld(cj)	mc x cj x ld(cj)
SUM SUM Xj (kg)	Fe	510	0.510	1.00	-0.97	-0.495
1000	Al	120	0.120	1.00	-3.06	-0.367
	OM	370	0.370	1.00	-1.43	-0.531
	SUM	*1000*	*1*		***H,max:***	***1.393***





Example 2 (SI 8): The supplementary excel file is provided under the following link:

https://doi.org/10.1016/j.resconrec.2020.104925

In this calculation example, it is shown that reducing the number of distinct components from three to two, while keeping everything else equal, reduces the relative statistical entropy of the product (Hp,rel), indicating how the number of *distinct* components (qn) is affecting the products structural complexity leading to a lower relative statistical entropy of the product.

Car	1000	kg
kg Fe	510	kg
kg Al	120	kg
kg OM	370	kg

Component 1	520	kg
Component 2	240	kg

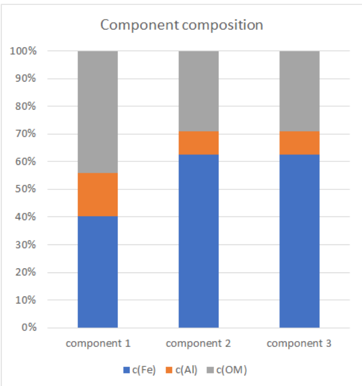
Eq 5	Eq 9
Eq 6	Eq 10
Eq 7	Eq 11
Eq 8	Eq12

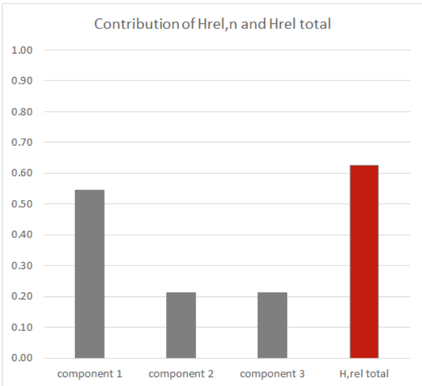
Component 1	kg Fe	210
	kg Al	80
	kg OM	230
	sum	520
Component 2	kg Fe	150
	kg Al	20
	kg OM	70
	sum	240
Component 2	kg Fe	150
	kg Al	20
	kg OM	70
	sum	240
Total:		
	kg Fe total	510
	kg Al total	120
	kg OM total	370

Calculation of Component Entropies:						
	cnj	mc,n = Mc,n/sum(sum(Xnj))	ld(cnj)		mc,n x cnj x ld(cnj)	H,rel
c1Fe	0.404	0.52	-1.31		-0.275	-0.197
c1Al	0.154	0.52	-2.70		-0.216	-0.155
c1OM	0.442	0.52	-1.18		-0.271	-0.194
			SUM	*Hc1*	0.761	**0.547**
c2Fe	0.625	0.24	-0.68		-0.102	-0.073
c2Al	0.083	0.24	-3.58		-0.072	-0.051
c2OM	0.292	0.24	-1.78		-0.124	-0.089
				Hc2	0.298	**0.214**
c3Fe	0.625	0.24	-0.68		-0.102	-0.073
c3Al	0.083	0.24	-3.58		-0.072	-0.051
c3OM	0.292	0.24	-1.78		-0.124	-0.089
			SUM	*Hc3*	0.298	**0.214**
					SUM(Hc,n)	***0.974***

Calculation of Product Entropy:			Hp,max =	1.585		
	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	Hp,rel
Component 1	1	0.333	0.547	-1.585	-0.866	
Component 2 (x 2)	**2**	0.667	0.214	-0.585	-0.125	
	3				0.991	0.625

Hmax calculation - If all substances are mixed in one flow:							
			sum(Xj)	cj	mc	ld(cj)	mc x cj x ld(cj)
Sum(Sum(Xj)) (kg)		Fe	510	0.510	1	-0.97	-0.495
	1000	Al	120	0.120	1	-3.06	-0.367
		OM	370	0.370	1	-1.43	-0.531
		SUM	*1000*	*1*		***H,max:***	***1.393***





Example 3 (SI 9): The supplementary excel file is provided under the following link:

https://doi.org/10.1016/j.resconrec.2020.104925

In this calculation example, relative statistical entropy is calculated for two components only.

Car	1000	kg
kg Fe	510	kg
kg Al	120	kg
kg OM	370	kg

Component 1	500	kg
Component 2	500	kg

Eq 5	Eq 9
Eq 6	Eq 10
Eq 7	Eq 11
Eq 8	Eq12

Component 1	kg Fe	255
	kg Al	60
	kg OM	185
	sum	500
Component 2	kg Fe	255
	kg Al	60
	kg OM	185
	sum	500
Total:	kg Fe total	510
	kg Al total	120
	kg OM total	370

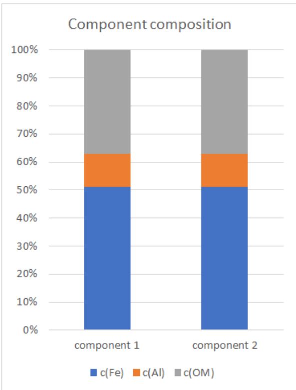
Calculation of Component Entropies:

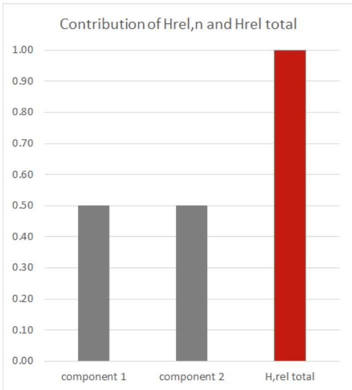
	cnj	mc,n = Mc,n/sum(sum(Xnj))	ld(cnj)		mc,n x cnj x ld(cnj)	H,rel
c1Fe	0.510	0.5	-0.97		-0.248	-0.178
c1Al	0.120	0.5	-3.06		-0.184	-0.132
c1OM	0.370	0.5	-1.43		-0.265	-0.190
			SUM	*Hc1*	0.697	**0.500**
c2Fe	0.510	0.5	-0.97		-0.248	-0.178
c2Al	0.120	0.5	-3.06		-0.184	-0.132
c2OM	0.370	0.5	-1.43		-0.265	-0.190
			SUM	*Hc3*	0.697	**0.500**
					SUM(Hc,n)	***1.000***

Calculation of Product Entropy:			Hp,max =	1.00		
	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	Hp,rel
Component 1	1	0.5	0.500	-1	-0.5	
Component 2	1	0.5	0.500	-1	-0.5	
N=	2				1	1.000

Hmax calculation - If all substances are mixed in one flow:

		sum(Xj)	cj	mc	ld(cj)	mc x cj x ld(cj)
SUM SUM Xj (kg)	Fe	510	0.510	1	-0.97	-0.495
1000	Al	120	0.120	1	-3.06	-0.367
	OM	370	0.370	1	-1.43	-0.531
	SUM	*1000*	*1*		***H,max:***	***1.393***





Example 4 (SI 10): The supplementary excel file is provided under the following link:

https://doi.org/10.1016/j.resconrec.2020.104925

In this calculation example, the number of components is increased to four and the respective statistical entropy values are calculated.

Car	1000	kg
kg Fe	510	kg
kg Al	120	kg
kg OM	370	kg

Component 1	250	kg
Component 2	250	kg
Component 3	250	kg
Component 4	250	kg

Eq 5	Eq 9
Eq 6	Eq 10
Eq 7	Eq 11
Eq 8	Eq12

Component 1	kg Fe	127.50
	kg Al	30.00
	kg OM	92.50
	sum	250.00
Component 2	kg Fe	127.50
	kg Al	30.00
	kg OM	92.50
	sum	250.00
Component 3	kg Fe	127.50
	kg Al	30.00
	kg OM	92.50
	sum	250.00
Component 4	kg Fe	127.50
	kg Al	30.00
	kg OM	92.50
	sum	250.00
Total:		
	kg Fe total	510
	kg Al total	120
	kg OM total	370

Calculation of Component Entropies:

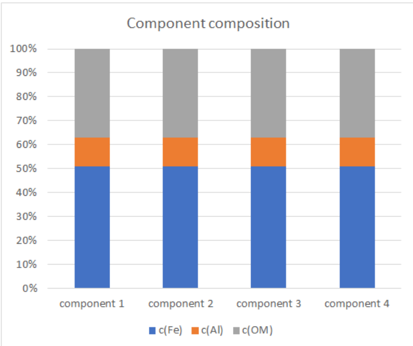
	cnj	mc,n = Mc,n/sum(sum(Xnj))	ld(cnj)		mc,n x cnj x ld(cnj)	H,rel
c1Fe	0.510	0.25	-0.97		-0.124	-0.089
c1Al	0.120	0.25	-3.06		-0.092	-0.066
c1OM	0.370	0.25	-1.43		-0.133	-0.095
			SUM	*Hc1*	0.348	**0.250**
c2Fe	0.510	0.25	-0.97		-0.124	-0.089
c2Al	0.120	0.25	-3.06		-0.092	-0.066
c2OM	0.370	0.25	-1.43		-0.133	-0.095
				Hc2	0.348	**0.250**
c3Fe	0.510	0.25	-0.97		-0.124	-0.089
c3Al	0.120	0.25	-3.06		-0.092	-0.066
c3OM	0.370	0.25	-1.43		-0.133	-0.095
				Hc3	0.348	**0.250**
c3Fe	0.510	0.25	-0.97		-0.124	-0.089
c3Al	0.120	0.25	-3.06		-0.092	-0.066
c3OM	0.370	0.25	-1.43		-0.133	-0.095
			SUM	*Hc4*	0.348	**0.250**
					SUM(Hc,n)	***1.000***

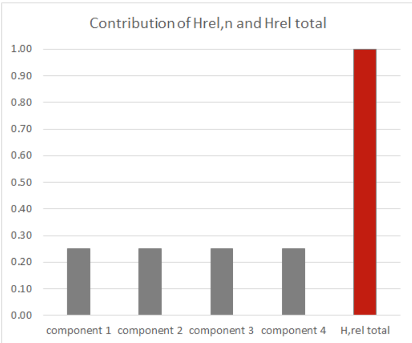
Calculation of Product Entropy: Hp,max = 2.00

	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	*Hp,rel*
Component 1	1	0.25	0.250	-2.000	-0.500	
Component 2	1	0.25	0.250	-2.000	-0.500	
Component 3	1	0.25	0.250	-2.000	-0.500	
Component 4	1	0.25	0.250	-2.000	-0.500	
N=	4				2.000	1.000

Hmax calculation - If all substances are mixed in one flow:

		sum(Xj)	cj	mc	ld cj	mc x cj x ld(cj)
SUM SUM Xj (kg)	Fe	510	0.510	1.000	-0.971	-0.495
1000	Al	120	0.120	1.000	-3.059	-0.367
	OM	370	0.370	1.000	-1.434	-0.531
	SUM	*1000*	*1*	***H,max:***		***1.393***





Example 5 (SI 11): The supplementary excel file is provided under the following link:

https://doi.org/10.1016/j.resconrec.2020.104925

In this calculation example, the number of components is N=3, with the presence of an additional material flow added to the calculation (grey).

Car	1000	kg
kg Fe	510	kg
kg Al	120	kg
kg OM	370	kg

Component 1	283.33	kg
Component 2	283.33	kg
Component 3	283.33	kg
Material flow 1	150.00	kg

Eq 5	Eq 9
Eq 6	Eq 10
Eq 7	Eq 11
Eq 8	Eq12

Component 1	kg Fe	136.00
	kg Al	32.00
	kg OM	115.33
	sum	283.33
Component 2	kg Fe	136.00
	kg Al	32.00
	kg OM	115.33
	sum	283.33
Component 3	kg Fe	136.00
	kg Al	32.00
	kg OM	115.33
	sum	283.33
Material flow 1	kg Fe	102.00
	kg Al	24.00
	kg OM	24.00
	sum	150.00
Total:		
	kg Fe total	510
	kg Al total	120
	kg OM total	370

Calculation of Component Entropies:

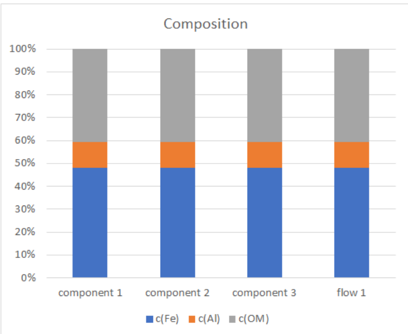
	cnj	mc,n = Mc,n/sum(sum(Xnj))	ld(cnj)		mc,n x cnj x ld(cnj)	H,rel
c1Fe	0.480	0.283	-1.06		-0.144	-0.103
c1Al	0.113	0.283	-3.15		-0.101	-0.072
c1OM	0.407	0.283	-1.30		-0.150	-0.107
			SUM	*Hc1*	0.394	**0.283**
c2Fe	0.480	0.283	-1.06		-0.144	-0.103
c2Al	0.113	0.283	-3.15		-0.101	-0.072
c2OM	0.407	0.283	-1.30		-0.150	-0.107
				Hc2	0.394	**0.283**
c3Fe	0.480	0.283	-1.06		-0.144	-0.103
c3Al	0.113	0.283	-3.15		-0.101	-0.072
c3OM	0.407	0.283	-1.30		-0.150	-0.107
				Hc3	0.394	**0.283**
c3Fe	0.480	0.15	-1.06		-0.076	-0.055
c3Al	0.113	0.15	-3.15		-0.053	-0.038
c3OM	0.407	0.15	-1.30		-0.079	-0.057
		1	SUM	*F1*	0.209	**0.150**
					SUM(Hc,n)	***0.999***

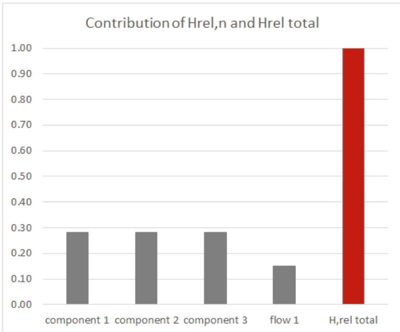
Calculation of Product Entropy: Hp,max = 1.58

	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	*Hp,rel*
Component 1	1	0.333	0.283	-1.585	-0.449	
Component 2	1	0.333	0.283	-1.585	-0.449	
Component 3	1	0.333	0.283	-1.585	-0.449	
N=	3		0.849		1.346	0.849
			H,rel			***Hrel total:***
Material flow 1			0.150			***0.999***

Hmax calculation - If all substances are mixed in one flow:

		sum(Xj)	cj	mc	ld cj	mc x cj x ld(cj)
SUM SUM Xj (kg)	Fe	510	0.510	1.000	-0.971	-0.495
1000	Al	120	0.120	1.000	-3.059	-0.367
	OM	370	0.370	1.000	-1.434	-0.531
	SUM	*1000*	*1.000*		***H,max:***	***1.393***





Example 6 (SI 12): The supplementary excel file is provided under the following link:

https://doi.org/10.1016/j.resconrec.2020.104925

In this calculation example, the statistical entropy calculation is demonstrated for the case of two products, that consist of two components each, with an additional material flow being present.

Car	1000	kg
kg Fe	510	kg
kg Al	120	kg
kg OM	370	kg

P1 Component 1	231.25	kg
P1 Component 2	231.25	kg
P2 Component 1	231.25	kg
P2 Component 2	231.25	kg
Material flow 1	75.00	kg

Eq 5	Eq 9
Eq 6	Eq 10
Eq 7	Eq 11
Eq 8	Eq12

P1 Component 1	kg Fe	114.75
	kg Al	27.00
	kg OM	89.50
	sum	231.25
P1 Component 2	kg Fe	114.75
	kg Al	27.00
	kg OM	89.50
	sum	231.25
P2 Component 1	kg Fe	114.75
	kg Al	27.00
	kg OM	89.50
	sum	231.25
P2 Component 2	kg Fe	114.75
	kg Al	27.00
	kg OM	89.50
	sum	231.25
Material flow 1	kg Fe	51.00
	kg Al	12.00
	kg OM	12.00
	sum	75.00
Total:		
	kg Fe total	510
	kg Al total	120
	kg OM total	370

Calculation of Component Entropies:

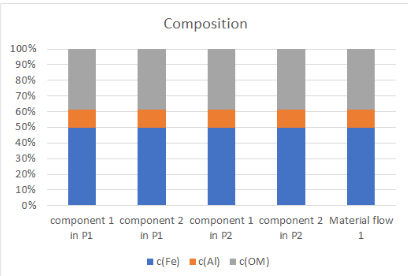
	cnj	mc,n = Mc,n/sum(sum(Xnj))	ld(cnj)		mc,n x cnj x ld(cnj)	H,rel
c1Fe	0.496	0.231	-1.01		-0.116	-0.083
c1Al	0.117	0.231	-3.10		-0.084	-0.060
c1OM	0.387	0.231	-1.37		-0.123	-0.088
			SUM	*Hc1*	0.322	**0.231**
c2Fe	0.496	0.231	-1.01		-0.116	-0.083
c2Al	0.117	0.231	-3.10		-0.084	-0.060
c2OM	0.387	0.231	-1.37		-0.123	-0.088
				Hc2	0.322	**0.231**
c3Fe	0.496	0.231	-1.01		-0.116	-0.083
c3Al	0.117	0.231	-3.10		-0.084	-0.060
c3OM	0.387	0.231	-1.37		-0.123	-0.088
				Hc3	0.322	**0.231**
c3Fe	0.496	0.231	-1.01		-0.116	-0.083
c3Al	0.117	0.231	-3.10		-0.084	-0.060
c3OM	0.387	0.231	-1.37		-0.123	-0.088
				Hc4	0.322	**0.231**
c3Fe	0.496	0.075	-1.01		-0.038	-0.027
c3Al	0.117	0.075	-3.10		-0.027	-0.019
c3OM	0.387	0.075	-1.37		-0.040	-0.029
		1	SUM	*F1*	0.105	**0.075**
					SUM(Hc,n)	***1.000***

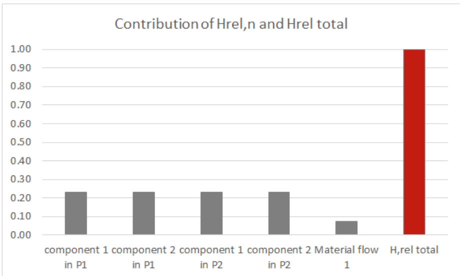
Calculation of Product Entropy: Hp,max = 1.00

	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	Hp,rel
Product 1	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	Hp,rel
Component 1	1	0.500	0.231	-1.000	-0.231	
Component 2	1	0.500	0.231	-1.000	-0.231	
N=	2				0.463	0.463
Product 2	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	Hp,rel
Component 1	1	0.500	0.231	-1.000	-0.231	
Component 2	1	0.500	0.231	-1.000	-0.231	
N=	2				0.463	0.463
					Sum (Hp1,Hp2)	0.925
Material flow 1			0.075			***1.000***

Hmax calculation - If all substances are mixed in one flow:

		sum(Xj)	cj	mc	ld cj	mc x cj x ld(cj)
SUM SUM Xj (kg)	Fe	510	0.510	1.000	-0.971	-0.495
1000	Al	120	0.120	1.000	-3.059	-0.367
	OM	370	0.370	1.000	-1.434	-0.531
	SUM	*1000*	*1.000*		***H,max:***	***1.393***





Example 7 (SI 13): The supplementary excel file is provided under the following link:

https://doi.org/10.1016/j.resconrec.2020.104925

In this calculation example, the statistical entropy calculation is demonstrated for the case of four components, with two identical components, represented as 3a and 3b. Their composition is set to be identical to show the effect of structurally identical components on the H,rel value.

Car	1000	kg
kg Fe	510	kg
kg Al	120	kg
kg OM	370	kg

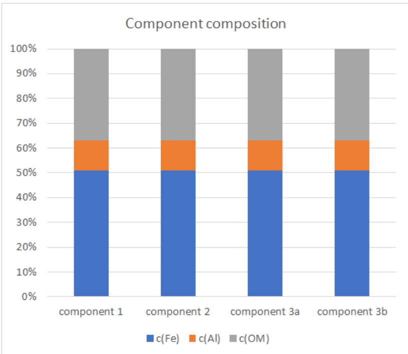
Component 1	333.33	kg
Component 2	333.33	kg
Component 3a	166.67	kg
Component 3a	166.67	kg
Eq 5	Eq 9	
Eq 6	Eq 10	
Eq 7	Eq 11	
Eq 8	Eq12	

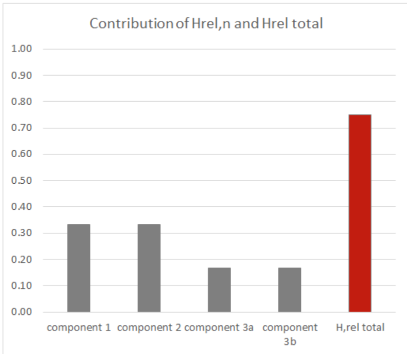
Component 1	kg Fe	170.00
	kg Al	40.00
	kg OM	123.33
	sum	333.33
Component 2	kg Fe	170.00
	kg Al	40.00
	kg OM	123.33
	sum	333.33
Component 3a	kg Fe	85.00
	kg Al	20.00
	kg OM	61.67
	sum	166.67
Component 3b	kg Fe	85.00
	kg Al	20.00
	kg OM	61.67
	sum	166.67
Total:		
	kg Fe total	510
	kg Al total	120
	kg OM total	370

Calculation of Component Entropies:						
	cnj	mc,n = Mc,n/sum(sum(Xnj))	ld(cnj)		mc,n x cnj x ld(cnj)	H,rel
c1Fe	0.510	0.333	-0.97		-0.165	-0.119
c1Al	0.120	0.333	-3.06		-0.122	-0.088
c1OM	0.370	0.333	-1.43		-0.177	-0.127
			SUM	*Hc1*	0.464	**0.333**
c2Fe	0.510	0.333	-0.97		-0.165	-0.119
c2Al	0.120	0.333	-3.06		-0.122	-0.088
c2OM	0.370	0.333	-1.43		-0.177	-0.127
				Hc2	0.464	**0.333**
c3Fe	0.510	0.167	-0.97		-0.083	-0.059
c3Al	0.120	0.167	-3.06		-0.061	-0.044
c3OM	0.370	0.167	-1.43		-0.088	-0.063
			SUM	*Hc3a*	0.232	**0.167**
c3Fe	0.510	0.167	-0.97		-0.083	-0.059
c3Al	0.120	0.167	-3.06		-0.061	-0.044
c3OM	0.370	0.167	-1.43		-0.088	-0.063
				Hc3b	0.232	**0.167**
					SUM(Hc,n)	***1.000***

Calculation of Product Entropy:			Hp,max =	2.00		
	qn	qn/N (Cn)	Hc,n	*ld(Cn)*	*Hp*	*Hp,rel*
Component 1	1	0.250	0.333	-2.000	-0.667	
Component 2	1	0.250	0.333	-2.000	-0.667	
Component 3/2 x 2	2	0.500	0.167	-1.000	-0.167	
N=	4				1.500	0.750

Hmax calculation - If all substances are mixed in one flow:						
		sum(Xj)	cj	mc	ld cj	mc x cj x ld(cj)
SUM SUM Xj (kg)	Fe	510	0.510	1.000	-0.971	-0.495
1000	Al	120	0.120	1.000	-3.059	-0.367
	OM	370	0.370	1.000	-1.434	-0.531
	SUM	*1000*	*1.000*		***H,max:***	***1.393***





Sensitivity results (SI 14)

Sensitivity results for four system cycles are presented. The input values for the calculations are reported in the first column of the table. The flows are indicated in the second columns, with the normalised regression coefficients, shown for each stage and system run in the rest of the table. The calculation was performed with @Risk 7.6 software (Palisade Corporation, 2018).

		Initial run				1st Cycle					2nd Cycle					3rd Cycle				
Distributions and input values	Name	Product	Comp. flows	Shredder output	Recycled fraction and rest	Prod. input	Product	Comp. flows	Shredder output	Recycled fraction and rest	Prod. input	Product	Comp. flows	Shredder output	Recycled fraction and rest	Prod. input	Product	Comp. flows	Shredder output	Recycled fraction and rest
RiskBernoulli(0.5;RiskStatic(1))	Reuse	n/a	n/a	-0.905	0.413	-0.554	-0.801	-0.801	-0.877	-0.453	-0.71	-0.823	-0.823	-0.851	-0.635	-0.768	-0.818	-0.818	-0.847	-0.7
RiskTriang(0.2;0.5;0.8;RiskStatic(0.5))	RR=	n/a	n/a	n/a	-0.864	-0.377	-0.545	-0.545	-0.441	-0.86	-0.45	-0.522	-0.522	-0.484	-0.735	-0.526	-0.56	-0.56	-0.518	-0.699
RiskNormal(203;20.3;RiskStatic(203);	Standard steel / Chassis	-0.537	-0.537	-0.3	-0.09	-0.037	-0.09	-0.09	-0.078	-0.067	-0.073	-0.11	-0.11	-0.099	-0.094	-0.035	-0.049	-0.049	-0.048	-0.044
RiskTriang(0.95;0.99;0.999;RiskStatic(0.99))	Purity after recycling=	n/a	n/a	n/a	-0.112	-0.007	-0.01	-0.01	-0.008	-0.071	-0.009	-0.011	-0.011	-0.01	-0.044	-0.01	-0.011	-0.011	-0.01	-0.036
RiskNormal(108;10.8;RiskStatic(108)	Others / Powertrain	0.023	0.023	-0.029	0.017	0.006	-0.029	-0.029	-0.03	-0.016	-0.013	-0.036	-0.036	-0.036	-0.03	-0.018	-0.032	-0.032	-0.032	-0.028
RiskNormal(182;18.2;RiskStatic(182)	HSS / Body	-0.149	-0.149	0.069	-0.018	-0.009	0.017	0.017	0.042	0.015	0.003	n/a	n/a	n/a	n/a	0.018	0.029	0.029	0.038	0.028
RiskNormal(99;9.9;RiskStatic(99)	Standard steel / Powertrain	0.056	0.056	-0.005	0.024	0.009	-0.021	-0.021	-0.023	-0.009	-0.006	-0.027	-0.027	-0.027	-0.02	-0.015	-0.028	-0.028	-0.028	-0.025
RiskNormal(173;17.3;RiskStatic(173)	Others / Interior	-0.554	-0.554	0.004	-0.024	-0.009	-0.04	-0.04	0.025	0.018	0	-0.014	-0.014	0.019	0.016	0.015	0.007	0.007	0.029	0.025
RiskNormal(12;1.2;RiskStatic(12)	Wrought Al / Interior	0.096	0.096	0.061	0.023	0.01	0.029	0.029	0.025	0.026	0.015	0.026	0.026	0.025	0.026	0.016	0.022	0.022	0.021	0.022
RiskNormal(94;9.4;RiskStatic(94)	Cast Fe / Powertrain	0.074	0.074	0.003	0.022	0.011	-0.017	-0.017	-0.02	-0.006	-0.007	-0.027	-0.027	-0.027	-0.021	-0.01	-0.022	-0.022	-0.023	-0.018
RiskNormal(222;22.2;RiskStatic(222)	Standard steel / Body	-0.37	-0.37	-0.221	-0.082	-0.036	-0.039	-0.039	-0.036	-0.041	0.003	n/a	n/a	n/a	n/a	-0.015	-0.011	-0.011	-0.012	-0.014
RiskNormal(10;1;RiskStatic(10)	Wrought Al / Chassis	0.102	0.102	0.05	0.02	0.008	0.017	0.017	0.013	0.012	0.017	0.032	0.032	0.028	0.029	0.01	0.013	0.013	0.012	0.013
RiskNormal(17;1.7;RiskStatic(17)	Cast Fe / Chassis	0.132	0.132	0.086	0.026	0.011	0.023	0.023	0.021	0.016	0.016	0.035	0.035	0.034	0.027	0.01	0.013	0.013	0.013	0.012
RiskNormal(8;0.8;RiskStatic(8)	Wrought Al / Body	0.101	0.101	0.04	0.013	0.006	0.023	0.023	0.017	0.016	n/a	n/a	n/a	n/a	n/a	0.008	0.013	0.013	0.012	0.011
RiskNormal(23;2.3;RiskStatic(23)	Cast Al / Chassis	0.15	0.15	0.1	0.024	0.012	0.027	0.027	0.025	0.02	0.019	0.041	0.041	0.039	0.031	0.008	0.012	0.012	0.012	0.01
RiskNormal(61;6.1;RiskStatic(61)	Standard steel / Interior	0.074	0.074	-0.061	-0.022	-0.01	0.011	0.011	-0.01	-0.012	-0.007	0.006	0.006	-0.007	-0.007	-0.007	0	0	-0.006	-0.007
RiskNormal(45;4.5;RiskStatic(45)	Others / Body	0.229	0.229	0	-0.006	-0.003	0.035	0.035	0.005	0	n/a	n/a	n/a	n/a	n/a	0.004	0.018	0.018	0.008	0.007
RiskNormal(37;3.7;RiskStatic(37)	Others / Chassis	0.169	0.169	0.041	0.017	0.008	0.021	0.021	0.008	0.011	0	0.023	0.023	0.005	0.003	0.004	0.008	0.008	0.004	0.005
RiskNormal(2;0.2;RiskStatic(2)	Cast Al / Interior	0.03	0.03	0.015	0.005	0	0.006	0.006	0.005	0	0	0.004	0.004	0.003	0	0.003	0.005	0.005	0.005	0.004
RiskNormal(0.3;0.03;RiskStatic(0.3)	Cast Al / Body	0.005	0.005	0	0	0	0	0	0	0	0	n/a	n/a	n/a	n/a	0	0	0	0	0
RiskNormal(4;0.4;RiskStatic(4)	Wrought Al / Powertrain	0.058	0.058	0.029	0.011	0.004	0.006	0.006	0.004	0.005	0.003	0.002	0.002	0.002	0	0	0	0	0	0
RiskNormal(41;4.1;RiskStatic(41)	HSS / Chassis	0.169	0.169	0.048	0.014	0.007	0.02	0.02	0.007	0.005	0.02	0.047	0.047	0.047	0.035	0	0.004	0.004	0	0
RiskNormal(41;4.1;RiskStatic(41)	Cast Al / Powertrain	0.176	0.176	0.078	0.041	0.016	0.01	0.01	0.005	0.012	0.006	0	0	-0.003	0	0	-0.003	-0.003	-0.004	0
	RSqr	*0.992*	*0.992*	*0.988*	*0.952*	*0.99*	*0.987*	*0.981*	*0.986*	*0.955*	*0.987*	*0.983*	*0.983*	*0.985*	*0.967*	*0.982*	*0.98*	*0.98*	*0.983*	*0.97*

Supplementary information - chapter 4

Stock-driven model (SI 15)

Calculation of inflows and stock of vehicles

The model simulates the vehicle inflows to stock (use phase) and outflows from stock, while distinguishing for electric vehicles (EVs) and internal combustion vehicles (ICEVs). All vehicle numbers, if not further indicated are in million units. The model closely follows the provided model by Pauliuk (2020), http://www.teaching.industrialecology.uni-freiburg.de/

The model represents a combined bottom-up and top-down approach. For the first decade the model utilised aggregated and reported statistical data on vehicle flows and stocks, while for the projection of the different scenarios into the future, the model employs the simulation of vehicle demand based on a constant functional unit to be provided for the population, so that several parameters such as population, occupancy rate per vehicle, etc., influence the demand for new vehicles produced. Further, the scenarios determine the fraction of ICEVs/EVs produced in a respective year.

Historical vehicle stock data are based on historical vehicle registrations (European Commission, 2019c), with the increase in the vehicle stock between the years 2017 – 2019 being based on the increase of vehicles of Germany[13], extrapolated to the European level. New vehicle registrations in the same time period are based on ACEA data[14].

Based on the number of vehicles (V) in the year 2019 ($S_{v,2019}$) and the population of the EU in the year 2019 (Pop_{2019} in persons (p)), the average vehicle ownership v_t is calculated.

$$v_{2019} = \frac{S_{v,2019}}{Pop_{2019}} = \frac{271.667*10^6\, v}{514.982*10^6\, p} = 0.5275\ \frac{v}{p}$$

For the scenarios without any change in the occupancy rate per vehicle (p/v), the projected population is multiplied with the vehicle ownership rate to estimate the stock of vehicles ($S_{v,t}$) for the base scenario.

The estimated stock of vehicles ($S_{v,t}$) in the base scenario is combined with the consideration of the average vehicle lifetime that allows calculating the average renewal rate (r_t) of vehicles per year, representing the inflows of overall vehicles per year into the stock ($S_{v,t}$). The average vehicle lifetime of 16 years, means that on average 1/16 of the vehicle stock is renewed each year, therefore the renewal rate $r_t = \frac{1}{16} = 0.0625$. The multiplication of the vehicle stock ($S_{v,t}$) with the vehicle renewal rate leads to the overall inflow or demand of vehicles in a specific year ($I_{v,t}$).

$$I_{v,t} = r_t * S_{v,t}$$

Based on the demand of new vehicles, the vehicle can represent an ICEV or an EV. The fraction of EVs build in a specific year is determined by the scenario employed, which are based on the scenarios developed by (Hill and Bates, 2018). The scenarios employed represent 'Ricardo energy low xEV', 'Ricardo energy medium xEV scenario' and 'Ricardo energy high xEV scenario' scenarios. The share of xEVs is multiplied with the vehicle demand in a specific year.

When calculating the inflows of vehicles to the vehicle stock ($S_{v,t}$), some scenarios as presented in section 4.2.4 include changes in vehicle lifetime. The vehicle lifetime directly influences the renewal

[13] Statista (last access 20.01.2021) https://de.statista.com/statistik/daten/studie/12131/umfrage/pkw-bestand-in-deutschland/
[14] ACEA (last access 20.01.2021) https://www.acea.be/statistics/tag/category/by-country-registrations

rate (r_t) in a specific year, thereby increasing or reducing the vehicle demand and the inflows of vehicles to stock.

In addition, some scenarios include a change in the demand of vehicles, based on an intensified use of vehicles, i.e. a higher occupancy rate per vehicle. These scenarios, require additional parameters that influence the vehicle stock evolution, allowing to model sufficiency strategies, while providing the same functional unit, that is measured in terms of the distance driven (with comfort of the distance driven being not considered). The increase in sufficiency is modelled by a higher occupancy rate O_c (p/v), which starts at 1.52 (p/v) and steadily increases to 2.14 (p/v).

With the functional unit of 12,000 (pkm/year) travelled by each person, the travelled distance travelled by the entire vehicle stock is calculated for the base year 2019. The distance travelled is then divided by the occupancy rate (p/v) so that the total distance travelled by the vehicle stock can be calculated.

$$D_{v,t}\left(\frac{vkm}{year}\right) = \frac{D_{pop,t}\left(\frac{pkm}{year}\right)}{O_{c,t}\left(\frac{p}{v}\right)}$$

For the year t = 2019 the calculation is:

$$D_{v,t}\left(\frac{vkm}{year}\right) = \frac{6.194*10^9\left(\frac{pkm}{year}\right)}{1.52\left(\frac{p}{v}\right)} = 4{,}075 * 10^9\left(\frac{vkm}{year}\right)$$

Based on the average distance a vehicle is driving per year (15,000 km), the vehicle stock (S_t) can be calculated, as $271.667*10^6$ vehicles. Therefore, with a higher occupancy rate, the stock of vehicles that allows providing the same travel distance for the population decreases.

In addition to the increase of the occupancy rate, the model also includes an increase in the average vehicle lifetime, which directly reduces the renewal rate (r_t), leading to a decreased demand for vehicles. Both effects, a reduction in the vehicle stock and a reduction in the renewal rate are able to independently reduce the demand for vehicles to be produced. Regarding the shares of EVs/ICEVs produced the same multiplication by the fraction of EVs or ICEVs is used, depending on the scenario employed.

Calculation of the outflows of the vehicles from stock

The next step after the calculation of the vehicle stock and the inflows of vehicles per year, the outflows of vehicles from stock are presented in the following. In this regard, the age-cohort model that is provided by Pauliuk, (2020) that is based on previous work by Pauliuk et al., e.g. Pauliuk et al., (2013).

The calculation employs a normal distribution to simulate the lifetime distribution of vehicles in the stock for each age cohort. The stock of vehicles is divided into age-cohorts with each of them having a year of production t', a mean lifetime τ (16 years) and a standard deviation σ (5 years). For the calculation of the lifetime function, a normal distribution is employed:

$$\lambda(t, t', \tau, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t-t'-\tau}{\sigma})^2}$$

In excel, the following function is employed to calculate the lifetime distribution:

=NORM.DIST(YEAR X; AVERAGE LIFETIME (const.); STANDARD DEVIATION (const.))

The outflow of vehicles O_t from a vehicle stock of a specific age-cohort ($S_{t'}$) is calculated as:

$$O_t = S_{t'}(\tau) * \lambda(t, t', \tau)$$

In excel the calculation is implemented for each age-cohort ($S_{t'}$) and year by the use of a V-lookup function calculating the outflows of vehicles per age-cohort by multiplying the probability of a vehicle existing an age cohort in as a function of its age:

*=VLOOKUP(YEAR;VEHICLES ENTERING STOCK)*VLOOKUP(YEAR;PROBABILITY FOR YEAR)*

The outflows of each age-cohort are aggregated for each year so that the overall outflow of vehicles can be calculated per year. The calculation is performed separately for EVs and ICEVs, with the supplementary information being provided in:

https://github.com/AlexejP/MFA_SEA_vehicles_model/blob/master/_SIA1.xlsx

Inflows of vehicles to the vehicle stock

Year	1 Inflow S70 EV	1 Inflow S70 ICEV	2 Inflow S100 EV	2 Inflow S100 ICEV	3 Inflow S70D EV	3 Inflow S70D ICEV	4 Inflow S70D-CE+ EV	4 Inflow S70D-CE+ ICEV	5 Inflow S100D-CE+ EV	5 Inflow S100D-CE+ ICEV
2010	0.0134	13.3595	0.0134	13.3595	0.0134	13.3595	0.0134	13.3595	0.0134	13.3595
2011	0.0263	13.1218	0.0263	13.1218	0.0263	13.1218	0.0263	13.1218	0.0263	13.1218
2012	0.0482	12.0036	0.0482	12.0036	0.0482	12.0036	0.0482	12.0036	0.0482	12.0036
2013	0.0831	11.7902	0.0831	11.7902	0.0831	11.7902	0.0831	11.7902	0.0831	11.7902
2014	0.1631	12.3794	0.1631	12.3794	0.1631	12.3794	0.1631	12.3794	0.1631	12.3794
2015	0.1781	13.5182	0.1781	13.5182	0.1781	13.5182	0.1781	13.5182	0.1781	13.5182
2016	0.2487	14.3812	0.2487	14.3812	0.2487	14.3812	0.2487	14.3812	0.2487	14.3812
2017	0.3326	14.7857	0.3326	14.7857	0.3326	14.7857	0.3326	14.7857	0.3326	14.7857
2018	0.4239	14.7166	0.4239	14.7166	0.4239	14.7166	0.4239	14.7166	0.4239	14.7166
2019	0.5542	15.7458	0.5542	15.7458	0.5542	15.7458	0.5542	15.7458	0.5542	15.7458
2020	0.7889	15.82	0.9965	15.6123	0.7872	15.7845	0.7872	15.7845	0.9943	15.5774
2021	1.0319	15.8841	1.4548	15.4612	1.0096	15.5418	0.9771	15.0404	1.3775	14.64
2022	1.2729	15.8126	1.9136	15.1719	1.2218	15.178	1.1534	14.328	1.7339	13.7475
2023	1.5062	15.61	2.362	14.7541	1.4277	14.7962	1.3249	13.7309	2.0777	12.9781
2024	1.7402	15.4043	2.8117	14.3327	1.6291	14.421	1.4857	13.1519	2.4006	12.2371
2025	1.9747	15.1967	3.2626	13.9088	1.8261	14.0531	1.6232	12.4917	2.6818	11.4331
2026	2.356	14.8413	3.9898	13.2075	2.1525	13.5591	1.9133	12.0525	3.2401	10.7258
2027	2.7383	14.4837	4.7188	12.5032	2.472	13.0749	2.1973	11.6221	3.7865	10.0329
2028	3.1214	14.1238	5.4495	11.7957	2.7846	12.6	2.4752	11.2	4.3214	9.3538
2029	3.5053	13.7623	6.1818	11.0858	3.0908	12.1347	2.7473	10.7864	4.8451	8.6886
2030	3.8901	13.3991	6.9156	10.3735	3.3906	11.6786	3.0138	10.381	5.3579	8.0369
2031	4.2858	13.0235	7.443	9.8663	3.693	11.2223	3.2827	9.9753	5.701	7.5571
2032	4.682	12.646	7.9709	9.3571	3.9891	10.7745	3.5459	9.5774	6.0367	7.0866
2033	5.0789	12.267	8.4995	8.8464	4.2792	10.3355	3.8037	9.1871	6.3655	6.6253
2034	5.4762	11.8865	9.0286	8.3341	4.5632	9.9049	4.0562	8.8043	6.6875	6.1731
2035	5.874	11.5046	9.5582	7.8204	4.8415	9.4824	4.3035	8.4288	7.0028	5.7296
2036	6.2685	11.1247	10.088	7.3051	5.1111	9.0707	4.5432	8.0628	7.3115	5.2945
2037	6.6632	10.7433	10.6179	6.7885	5.3751	8.6665	4.7779	7.7036	7.6137	4.8678
2038	7.0579	10.3605	11.1478	6.2706	5.6336	8.2697	5.0077	7.3509	7.9095	4.4491

2039	7.4526	9.9764	11.6774	5.7516	5.8867	7.8802	5.2326	7.0046	8.1989	4.0383
2040	7.8474	9.5912	12.207	5.2316	6.1346	7.4979	5.453	6.6648	8.4824	3.6353
2041	8.2872	9.1596	12.7361	4.7106	6.4123	7.0873	5.6999	6.2998	8.7598	3.2399
2042	8.7268	8.7268	13.2647	4.1888	6.6842	6.6842	5.9415	5.9415	9.0311	2.8519
2043	9.1658	8.2928	13.7923	3.6663	6.9503	6.2884	6.178	5.5897	9.2965	2.4712
2044	9.6041	7.8579	14.3189	3.1432	7.2106	5.8996	6.4094	5.2441	9.5558	2.0976
2045	10.0416	7.422	14.8441	2.6195	7.4651	5.5177	6.6356	4.9046	9.8092	1.731
2046	10.4781	6.9854	15.3679	2.0956	7.714	5.1427	6.8569	4.5713	10.0568	1.3714
2047	10.9134	6.5481	15.89	1.5715	7.9572	4.7743	7.0731	4.2439	10.2984	1.0185
2048	11.3476	6.1102	16.4104	1.0475	8.195	4.4127	7.2844	3.9224	10.5344	0.6724
2049	11.7804	5.672	16.9289	0.5236	8.4273	4.0576	7.4909	3.6067	10.7647	0.3329
2050	12.2119	5.2337	17.4456	0	8.6543	3.709	7.6927	3.2969	10.9896	0

Outflows of vehicles from the vehicle stock

Year	1 Outflow S70 EV	1 Outflow S70 ICEV	2 Outflow S100 EV	2 Outflow S100 ICEV	3 Outflow S70D EV	3 Outflow S70D ICEV	4 Outflow S70D-CE+ EV	4 Outflow S70D-CE+ ICEV	5 Outflow S100D-CE+ EV	5 Outflow S100D-CE+ ICEV
2010	0	14.0082	0	14.0082	0	14.0082	0	14.0082	0	14.0082
2011	0	13.8109	0	13.8109	0	13.8109	0	13.8109	0	13.8109
2012	0.0001	13.616	0.0001	13.616	0.0001	13.616	0.0001	13.616	0.0001	13.616
2013	0.0002	13.4424	0.0002	13.4424	0.0002	13.4424	0.0002	13.4424	0.0002	13.4424
2014	0.0004	13.3052	0.0004	13.3052	0.0004	13.3052	0.0004	13.3052	0.0004	13.3052
2015	0.0007	13.2138	0.0007	13.2138	0.0007	13.2138	0.0007	13.2138	0.0007	13.2138
2016	0.0013	13.1706	0.0013	13.1706	0.0013	13.1706	0.0013	13.1706	0.0013	13.1706
2017	0.0023	13.1714	0.0023	13.1714	0.0023	13.1714	0.0023	13.1714	0.0023	13.1714
2018	0.0039	13.2071	0.0039	13.2071	0.0039	13.2071	0.0039	13.2071	0.0039	13.2071
2019	0.0064	13.2661	0.0064	13.2661	0.0064	13.2661	0.0064	13.2661	0.0064	13.2661
2020	0.0103	13.3355	0.0104	13.3354	0.0103	13.3355	0.0042	13.2129	0.0042	13.2129
2021	0.0159	13.4041	0.0163	13.4038	0.0159	13.4039	0.0068	13.2718	0.0069	13.2717
2022	0.0241	13.4638	0.0251	13.4628	0.024	13.4632	0.0106	13.341	0.0109	13.3407
2023	0.0354	13.5108	0.0376	13.5085	0.0353	13.5092	0.0163	13.4089	0.017	13.4083
2024	0.051	13.5457	0.0554	13.5413	0.0507	13.5424	0.0245	13.4673	0.0257	13.4661
2025	0.0719	13.5736	0.0799	13.5656	0.0713	13.5674	0.0357	13.5119	0.0381	13.5095
2026	0.0993	13.6024	0.1134	13.5884	0.0983	13.5914	0.051	13.5427	0.0555	13.5383
2027	0.1348	13.6414	0.1584	13.6178	0.133	13.6227	0.0713	13.5637	0.0792	13.5558
2028	0.1799	13.6991	0.2179	13.6611	0.1767	13.6688	0.0978	13.5813	0.1112	13.5679
2029	0.2362	13.7817	0.2955	13.7225	0.2311	13.7343	0.1316	13.6026	0.1534	13.5807
2030	0.3056	13.8916	0.395	13.8022	0.2975	13.82	0.1738	13.6338	0.2085	13.5991
2031	0.3899	14.0263	0.5205	13.8956	0.3773	13.9219	0.2259	13.6778	0.2791	13.6245
2032	0.4906	14.1791	0.6763	13.9935	0.4719	14.0313	0.2888	13.7335	0.3681	13.6542
2033	0.6094	14.3395	0.8661	14.0828	0.5823	14.1365	0.3638	13.795	0.4784	13.6804
2034	0.7477	14.4947	1.0936	14.1488	0.7092	14.2238	0.4516	13.8524	0.6127	13.6914
2035	0.9065	14.6311	1.3614	14.1762	0.8531	14.2793	0.553	13.893	0.7735	13.6725
2036	1.0865	14.7364	1.6713	14.1517	1.0143	14.2912	0.6684	13.9029	0.9626	13.6087
2037	1.2882	14.8003	2.0237	14.0648	1.1925	14.2504	0.7981	13.8695	1.1812	13.4864
2038	1.5117	14.8155	2.4181	13.909	1.3872	14.1518	0.942	13.7832	1.4297	13.2955

2039	1.7565	14.7782	2.8523	13.6824	1.5975	13.9942	1.0998	13.6383	1.7074	13.0307
2040	2.022	14.6879	3.323	13.387	1.8223	13.7799	1.2711	13.4339	2.0129	12.6921
2041	2.3073	14.5467	3.8259	13.0281	2.0602	13.514	1.4554	13.1734	2.3437	12.2851
2042	2.6109	14.3588	4.3557	12.6141	2.3096	13.2035	1.6518	12.8637	2.6966	11.8189
2043	2.9314	14.1297	4.9067	12.1545	2.5688	12.8564	1.8594	12.5141	3.0678	11.3056
2044	3.267	13.8655	5.4729	11.6596	2.8359	12.4808	2.077	12.1346	3.4528	10.7588
2045	3.6158	13.5721	6.0486	11.1393	3.1091	12.0842	2.3034	11.735	3.847	10.1914
2046	3.976	13.2552	6.6286	10.6026	3.3863	11.6734	2.5371	11.3241	4.2455	9.6157
2047	4.3458	12.9198	7.2086	10.057	3.666	11.2538	2.7766	10.9088	4.6439	9.0415
2048	4.7237	12.5698	7.7854	9.5081	3.9466	10.8299	3.0203	10.4943	5.0382	8.4765
2049	5.1081	12.2084	8.3566	8.96	4.2269	10.4049	3.2668	10.0841	5.425	7.9259
2050	5.4981	11.8381	8.9211	8.4152	4.506	9.9812	3.5146	9.6802	5.8019	7.3929

Vehicle models and component compositions employed (SI 16)

The vehicle model employed is based on the Hawkins et al. (2013), who present an LCIA study of an internal combustion engine vehicle (ICEV) and an electric vehicle (EV), providing a detailed resolution of component compositions that are used to derive the vehicle models presented. The employed mass of the vehicle component group and its composition is related to the original mass of the component group. The difference in the mass is calculated as a fraction of mass employed in the vehicle model in the paper.

Internal combustion engine vehicle (ICEV) composition on the component level, with a comparison of the represented material mass of the model compared to the original vehicle model employed.

	ICEV	Component composition employed [kg]	Original mass [kg]	Component mass fraction employed of original mass [%]
Body and Doors	Steel	389.00		
	Glass	28.83		
	Plastic	25.00	443.26	99.90%
Brakes	Cast iron	18.16		
	Steel	10.59	31.03	92.68%
Chassis	Steel	172.46		
	Plastic	5.89		
	Copper	4.09	186.88	97.62%
Engine	Iron	89.26		
	Aluminium	29.83		
	Steel	29.04	150.67	98.31%
Tires and Wheels	Steel (wheels and tires)	46.95		
	Rubber	18.11		
	Carbon black	8.33	79.36	92.47%
ICEV Powertrain	Steel	53.15		
	Plastic	29.69		
	Copper	6.50	92.25	96.85%
Transmission	Steel	26.57		
	Aluminium	12.12		
	Plastic	4.00	44.90	95.08%
ICEV Battery	Lead	11.24		
	Plastic	0.66	16.14	73.73%
Interior and Exterior	Plastic	118.76		
	Steel	70.56		
	Aluminium	18.46		
	Paint	11.79		
	Copper	11.52		
	Rubber	5.29	237.67	99.46%
Total		**1255.86**	**1282.15**	**97.95%**

Electric vehicle (EV) composition on the component level, with a comparison of the represented material mass of the model compared to the original vehicle model employed.

	EV	Component composition employed [kg]	Original mass [kg]	Component mass fraction employed of original mass [%]
Body and Doors	Steel	389.00		
	Glass	28.83		
	Plastic	25.00	443.26	99.90%
Brakes	Cast iron	18.16		
	Steel	10.59	31.03	92.68%
Chassis	Steel	172.46		
	Plastic	5.89		
	Copper	4.09	186.88	97.62%
Tires and Wheels	Steel	46.95		
	Rubber	18.11		
	Carbon black	8.33	79.36	92.47%
EV motor and transmission	Aluminium	184.43		
	Copper	109.53		
	Steel	35.88		
	Plastic	8.15		
	Iron	4.52		
	Rubber	3.70		
	Neodymium	1.67	378.28	91.96%
Interior and Exterior	Plastic	118.76		
	Steel	70.56		
	Aluminium	18.46		
	Paint	11.79		
	Copper	11.52		
	Rubber	5.29	237.67	99.46%
ICEV Battery	Lead	11.24		
	Plastic	0.66	16.14	73.73%
EV Battery	Copper	57.93		
	$LiMn_2O_4$	56.70		
	Graphite	54.61		
	Ethylene carbonate	46.42		
	Aluminium	35.77		
	Plastic	21.27		
	LiPF6	5.51	300.00	92.74%
Total		**1601.77**	**1672.61**	**95.76%**

Uncertainty overview ranges of translated material flows in the ELV system (SI 17)

Flow	Goods	Flow Rate [kg]	Reliability [%]	Completeness [%]	Temporal [%]	Geographical [%]	Other [%]	Uncertainty absolute [kg]	Uncertainty relative total [%]	Data sources are provided by Andersson et al., (2017), SI
E0.01	ELVs	230000	0.02	0.00	0.07	0.14		35545	15.45%	Table S2
E1.01	Dismantled ELVs	163298	0.02	0.00	0.02	0.14		22933	14.04%	Table S2
E1.02	Iron and steel	8235	0.02	0.05	0.07	0.14		1326	16.10%	Table S15
E1.03	Engines, gearboxes and Al components	11864	0.02	0.05	0.07	0.14		1911	16.10%	Table S3
E1.04	Catalytic converters	1384	0.02	0.05	0.07	0.14		223	16.10%	Table S3
E1.05	Tyres, batteries, fluids, windows	7014	0.02	0.05	0.07	0.14		1130	16.10%	Table S3
E1.06	Spare parts	38204	0.02	0.05	0.07	0.14		6152	16.10%	Table S3
E2.01	Heavy fraction	120581	0.02	0.00	0.14	0.14		23477	19.47%	Table S7
E2.02	Light fraction	42717	0.02	0.00	0.14	0.14		8317	19.47%	Table S15
E3.01	Exported Al fraction	2090	0.02	0.05	0.02	0.14		308	14.76%	Table S7
E3.02	Exported Fe fraction	35587	0.02	0.05	0.02	0.14		5251	14.76%	Table S7
E3.03	Domestic Fe	66952	0.07	0.05	0.02	0.14		10782	16.10%	Table S7
E3.04	Non-Fe fraction	15952	0.21	0.05	0.14	0.14		4569	28.64%	Table S7
E4.01	Shredder fluff 1	18448	0.07	0.05	0.14	0.14		3875	21.00%	Table S7
E4.02	Fines (LFP)	12406	0.02	0.05	0.14	0.14		2480	19.99%	Table S7
E4.03	Domestic Al	1295	0.07	0.05	0.21	0.14		338	26.08%	Table S7
E4.04	Shredder fluff 2	9274	0.07	0.05	0.14	0.14		1948	21.00%	Table S7
E4.05	Exported Al fraction	1294	0.02	0.05	0.14	0.14		259	19.99%	Table S7
E5.01	Domestic Al fractions	2090	0.02	0.05	0.14	0.14		418	19.99%	Table S8
E5.02	Residues	6494	0.07	0.14	0.21	0.14		1890	29.10%	Table S8
E5.03	Exported Fe fractions	983	0.07	0.05	0.21	0.14		256	26.08%	Table S8
E5.04	Exported Al fractions	2070	0.07	0.05	0.21	0.14		540	26.08%	Table S8
E5.05	Exported mixed fractions	3018	0.07	0.14	0.21	0.14		878	29.10%	Table S8
E5.06	Residues	1297	0.07	0.14	0.21	0.14		377	29.10%	Table S8
E6.01	Slags	3251	0.02	0.05	0.05	0.14		496	15.27%	Table S10
E6.02	Flue gas residues	998	0.02	0.05	0.05	0.14		152	15.27%	Table S10
E6.03	To flue gas	6323	0.02	0.05	0.05	0.14		965	15.27%	Table S10
E7.01	Domestic Al fractions	7	0.21	0.05	0.14	0.14		2	28.64%	Table S20
E7.02	Bottom ash	1405	0.02	0.05	0.05	0.14		215	15.27%	Table S11
E7.03	Exported Fe fraction	967	0.21	0.05	0.05	0.14		247	25.57%	Table S11
E7.04	Exported Al fraction	7	0.21	0.05	0.05	0.14		2	25.57%	Table S11
E7.05	Evaporated water	865	0.21	0.05	0.05	0.14		221	25.57%	Table S11

E8.01	Crude steel (domestic steel production)	63678	0.02	0.05	0.02	0.14	9396	14.76%	Table S12
E8.02	Slags (domestic steel production)	8602	0.02	0.05	0.02	0.14	1269	14.76%	Table S12
E8.03	Dusts/Sludge	789	0.02	0.05	0.02	0.14	116	14.76%	Table S12
E9.01	Cast Al	8727	0.02	0.05	0.02	0.14	1288	14.76%	Table S13
E9.02	Slags (domestic aluminium production)	660	0.02	0.05	0.02	0.14	97	14.76%	Table S13
E11.01	Domestic Al	5995	0.02	0.14	0.14	0.14	1426	23.79%	Table S6
E11.02	Exported Al	5904	0.02	0.14	0.14	0.14	1405	23.79%	Table S6
E11.03	Exported Fe	2856	0.02	0.14	0.14	0.14	679	23.79%	Table S6
E11.04	Domestic iron	5344	0.02	0.14	0.14	0.14	1271	23.79%	Table S6
E12.01	Domestic steel from decanning	773	0.02	0.05	0.05	0.14	118	15.27%	Table S5
E12.02	Exported steel from decanning	411	0.02	0.05	0.05	0.14	63	15.27%	Table S5
E12.03	EAF and PGM refining slags	200	0.02	0.05	0.05	0.14	31	15.27%	Table S5
E12.04	Pd and Pt	0	0.02	0.05	0.05	0.14	0	15.27%	Table S5
E13.01	Slags (regulated components)	160	0.07	0.14	0.21	0.14	47	29.10%	Table S4
E13.02	Recycled materials	4486	0.07	0.14	0.21	0.14	1305	29.10%	Table S4
E13.03	Output from energy recovery	2369	0.07	0.14	0.21	0.14	689	29.10%	Table S4

This table represents the original mass flows (kg) (b) for the Swedish ELV system that is used to derive the transfer-coefficients (TCs) on the goods level (c). After classifying the uncertainty as presented in the table above (d), the model is mass-balanced by employing the total uncertainty derived (e). Employing a mass-balanced MFA model (f), the TCs are derived (g). The colour codes indicate the flow that enters a process (b) and the flows resulting from the process (c), e.g. ELVs enter a dismantling process. The process produces outflows of dismantled ELVs, and iron and steel fraction, engines, gearboxes and aluminium components, etc.

Code	(a) Flow	(b) Units discrete [kg]	(c) TCs original	(d) Mass fraction [%] of total flow	(e) Uncertainty total [%]	Code	(f) Units discrete [kg]	(g) TCs after mass establishing mass balance as fraction
E0.01	ELVs	230,000.00		100.00%	15.45%	E0.01	230,000.00	
E1.01	Dismantled ELVs	163,000.00	0.7087	71.00%	14.04%	E1.01	163,298.19	0.7100
E1.02	Iron and steel	8,270.00	0.0360	3.58%	16.10%	E1.02	8,234.99	0.0358
E1.03	Engines, gearboxes and Al components	11,900.00	0.0517	5.16%	16.10%	E1.03	11,864.11	0.0516
E1.04	Catalytic converters	1,380.00	0.0060	0.60%	16.10%	E1.04	1,384.41	0.0060
E1.05	Tires, batteries, fluids, windows	7,080.00	0.0308	3.05%	16.10%	E1.05	7,014.27	0.0305
E1.06	Spare parts	27,700.00	0.1204	16.61%	16.10%	E1.06	38,204.03	0.1661
E2.01	Heavy fraction	120,000.00	0.7362	52.43%	19.47%	E2.01	120,581.12	0.7384
E2.02	Light fraction	43,500.00	0.2669	18.57%	19.47%	E2.02	42,717.06	0.2616
E12.01	Domestic steel from decanning	773.00	0.5601	0.34%	15.27%	E12.01	773.27	0.5586
E12.02	Exported steel from decanning	411.00	0.2978	0.18%	15.27%	E12.02	410.70	0.2967
E12.03	EAF and PGM refining slags	200.00	0.1449	0.09%	15.27%	E12.03	200.17	0.1446
E12.04	Pd and Pt	0.28	0.0002	0.00%	15.27%	E12.04	0.28	0.0002
E11.01	Domestic Al	6,010.00	0.2980	2.61%	23.79%	E11.01	5,995.24	0.2983
E11.02	Exported Al	5,990.00	0.2970	2.57%	23.79%	E11.02	5,904.01	0.2937
E11.03	Exported Fe	2,870.00	0.1423	1.24%	23.79%	E11.03	2,855.70	0.1421
E11.04	Domestic iron	5,350.00	0.2652	2.32%	23.79%	E11.04	5,344.15	0.2659
E13.01	Slags (regulated components)	160.00	0.0226	0.07%	29.10%	E13.01	159.86	0.0228
E13.02	Recycled materials	4,540.00	0.6412	1.95%	29.10%	E13.02	4,485.56	0.6395
E13.03	Output from energy recovery	2,380.00	0.3362	1.03%	29.10%	E13.03	2,368.85	0.3377
E3.01	Exported Al fraction	2,090.00	0.0174	0.91%	14.76%	E3.01	2,090.10	0.0173
E3.02	Exported Fe fraction	35,000.00	0.2917	15.47%	14.76%	E3.02	35,586.80	0.2951

E3.03	Domestic Fe	66,500.00	0.5542	29.11%	16.10%	E3.03	66,952.12	0.5552
E3.04	Non Fe fraction	16,300.00	0.1358	6.94%	28.64%	E3.04	15,952.10	0.1323
E4.01	Shredder fluff 1	19,000.00	0.4368	8.02%	21.00%	E4.01	18,448.25	0.4319
E4.02	Fines (LFP)	12,600.00	0.2897	5.39%	19.99%	E4.02	12,405.93	0.2904
E4.03	Domestic Al	1,300.00	0.0299	0.56%	26.08%	E4.03	1,294.87	0.0303
E4.04	Shredder fluff 2	9,260.00	0.2129	4.03%	21.00%	E4.04	9,273.96	0.2171
E4.05	Exported Al fraction	1,300.00	0.0299	0.56%	19.99%	E4.05	1,294.06	0.0303
E8.01	Crude steel (domestic steel production)	63,200.00	0.8702	27.69%	14.76%	E8.01	63,678.00	0.8715
E8.02	Slags (domestic steel production)	8,600.00	0.1184	3.74%	14.76%	E8.02	8,602.34	0.1177
E8.03	Dusts/Sludge (domestic steel production)	789.00	0.0109	0.34%	14.76%	E8.03	789.19	0.0108
E9.01	Cast Al	8,740.00	0.9298	3.79%	14.76%	E9.01	8,726.91	0.9304
E9.02	Slags (domestic aluminium production)	660.00	0.0702	0.29%	14.76%	E9.02	659.59	0.0703
E5.01	Domestic Al fractions	2,090.00	0.1282	0.91%	19.99%	E5.01	2,089.88	0.1310
E5.02	Residues	6,730.00	0.4129	2.82%	29.10%	E5.02	6,493.91	0.4071
E5.03	Exported Fe fractions	986.00	0.0605	0.43%	26.08%	E5.03	983.29	0.0616
E5.04	Exported Al fractions	2,080.00	0.1276	0.90%	26.08%	E5.04	2,069.79	0.1298
E5.05	Exported mixed fractions	3,070.00	0.1883	1.31%	29.10%	E5.05	3,018.03	0.1892
E5.06	Residues to energy recovery	1,300.00	0.0798	0.56%	29.10%	E5.06	1,297.20	0.0813
E6.01	Slags	3,240.00	0.3068	1.41%	15.27%	E6.01	3,250.54	0.3075
E6.02	Flue gas residues	998.00	0.0945	0.43%	15.27%	E6.02	998.11	0.0944
E6.03	To flue gas	6,320.00	0.5985	2.75%	15.27%	E6.03	6,322.51	0.5981
E7.01	Domestic Al fractions	6.50	0.0020	0.00%	28.64%	E7.01	6.50	0.0020
E7.02	Bottom ash	1,410.00	0.4352	0.61%	15.27%	E7.02	1,405.19	0.4323
E7.03	Exported Fe fraction	963.00	0.2972	0.42%	25.57%	E7.03	966.85	0.2974
E7.04	Exported Al fraction	6.50	0.0020	0.00%	25.57%	E7.04	6.50	0.0020
E7.05	Evaporated water	862.00	0.2660	0.38%	25.57%	E7.05	865.50	0.2663

Aggregation of material flows of the ELV material flow system (SI 18)

Based on mass-balanced MFA that is introduced further above (S 17) and taking into consideration of literature that study specific flows in the ELV treatment system, the material flows have been aggregated, as presented in the following table. The table is a result of an iterative process of data classification considering the material resolution that is employed in the vehicle model while taking into account and matching where possible the resolution of material flows in the studies that contain more detailed compositional flows, e.g. studies on the evaluation of shredder fluff and their respective flow compositions to the ELV material flow structure employed.

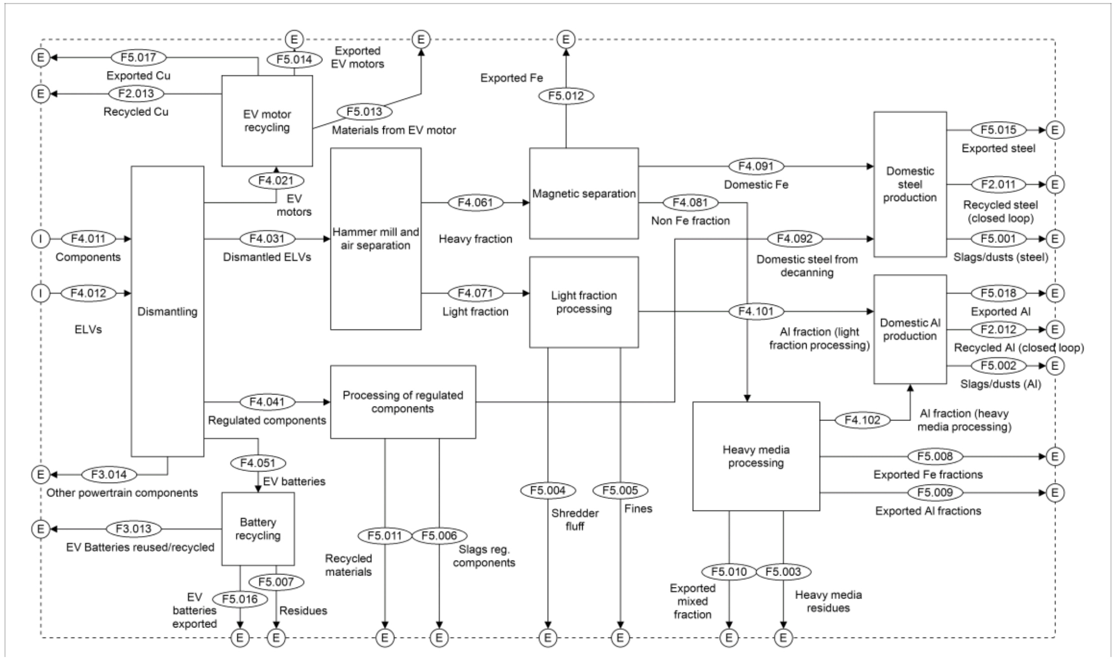
Code	Flow	Code original	Flow original	*mass new [kg]*	*TC as fraction*	*Uncertainty abs. combined [kg]*	*CV combined*
F4.031	***Dismantled ELVs***			***183397***	***0.7974***	***53133***	***28.97%***
	integrated	E1.01	Dismantled ELVs	163298	0.7100	52592	
	integrated	E1.02	Iron and steel	8235	0.0358	176	
	integrated	E1.03	Engines, gearboxes and Al components	11864	0.0516	365	
F4.041	***Regulated components***			***46603***	***0.2026***	***3918***	***8.41%***
	integrated	E1.04	Catalytic converters	1384	0.0060	5	
	integrated	E1.05	Tires, batteries, fluids, windows	7014	0.0305	128	
	integrated	E1.06	Spare parts	38204	0.1661	3785	
F4.061	***Heavy fraction***	***E2.01***	***Heavy fraction***	***120581***	***0.7384***		
F4.071	***Light fraction***	***E2.02***	***Light fraction***	***42717***	***0.2616***		
F4.081	***Non-Fe fraction***			***18042***	***0.1496***	***2098***	***11.63%***
	integrated	E3.01	Exported Al fraction	2090	0.0173	10	
	integrated	E3.04	Non-Fe fraction	15952	0.1323	2088	
F5.012	***Exported Fe***	***E3.02***	***Exported Fe fraction***	***35587***	***0.2951***	***2757***	***7.75%***
F4.091	***Domestic Fe***	***E3.03***	***Domestic Fe***	***66952***	***0.5552***	***11625***	***17.36%***
F4.101	***Al fraction (light fraction processing)***		***Domestic Aluminium***	***2589***	***0.0606***	***18***	***0.70%***
	integrated	E4.03	Domestic Al	1295	0.0303	11	
	integrated	E4.05	Exported Al fraction	1294	0.0303	7	
F5.004	***Shredder fluff***	***E4.01***	***Shredder fluff 1***	***27722***	***0.6490***	***1881***	***6.79%***
F5.009	***Fines***	***E4.02***	***Fines (LFP)***	***12406***	***0.2904***	***615***	***4.96%***

F4.112	*integrated*	E4.04	Shredder fluff 2	9274	0.2171	379	***4.09%***
F4.102	***Al fraction (heavy media processing)***	***E5.01***	***Domestic Al fractions***	***2090***	***0.1310***	***17***	***0.84%***
F5.003	***Heavy media residues***	***E5.02***	***Residues***	***7791***	***0.4884***	***357***	***4.58%***
F5.008	***Exported Fe fractions***	***E5.03***	***Exported Fe fraction***	***983***	***0.0616***	***7***	***0.67%***
F5.009	***Exported Al fractions***	***E5.04***	***Exported Al fraction***	***2070***	***0.1298***	***29***	***1.41%***
F5.010	***Exported mixed fraction***	***E5.05***	***Exported mixed fraction***	***3018***	***0.1892***	***77***	***2.56%***
F4.111	*integrated (in F5.003)*	*E5.06*	*Residues to energy recovery*	*1297*	*0.0813*		
F4.121	*excluded*	E6.01	Slags	3251			
F5.005	*excluded*	E6.02	Flue gas residues	998			
F5.020	*excluded*	E6.03	To flue gas	6323			
F5.006	*excluded*	E7.02	Bottom ash	1405			
F5.012	*excluded*	E7.03	Exported Fe fraction	967			
	excluded	E7.01	Domestic Al fractions	7			
	excluded	E7.04	Exported Al fraction	7			
	excluded	E7.05	Evaporated water	865			
F5.014	***Exported steel***	***E8.01***	***Crude steel (domestic steel production)***	***47758***	***0.6536***	***6622***	***13.86%***
F2.011	***Recycled steel (closed loop)***	***E8.01***	***Crude steel (domestic steel production)***	***15919***	***0.2179***	***2207***	***13.86%***
F5.001	***Slags/Dusts (steel)***	***E8.02***	***Slags (domestic steel production)***	***9392***	***0.1285***	***161***	***1.72%***
F5.003	*integrated (in F5.001)*	E8.03	Dusts/Sludge (domestic steel production)	789			
F5.017	***Exported Al***	***E9.01***	***Cast Al***	***2618***	***0.2789***	***116***	***4.43%***
F2.012	***Recycled Al (closed loop)***	***E9.02***	***Cast Al***	***6109***	***0.6508***	***50***	***0.81%***
F5.002	***Slags/dusts (Al)***	***E9.02***	***Slags (domestic aluminium production)***	***660***	***0.0703***	***1***	***14.76%***
	integrated (in F4.031)	E11.01	Domestic Al	5995			
	integrated (in F4.031)	E11.02	Exported Al	5904			
	integrated (in F4.031)	E11.03	Exported Fe	2856			
	integrated (in F4.031)	E11.04	Domestic iron	5344			
F4.092	***Domestic steel from decanning***			***1184***	***0.1444***	***2***	***30.54%***
	integrated (in F4.092)	E12.01	Domestic steel from decanning	773	0.5586	1	15.27%

	integrated (in F4.092)	E12.02	Exported steel from decanning	411	0.2967	0	15.27%
F5.017	*EAF and PGM refining*			200	0.1448	0	0.05%
	excluded	E12.03	EAF and PGM refining slags	200	0.1446	0	15.27%
	excluded	E12.04	Pd and Pt	0	0.0002	0	15.27%
F5.006	***Slags regulated components***	***E13.01***	***Slags (regulated components)***	***160***	***0.0195***	0	***0.14%***
F5.011	***Recycled materials***	***E13.02***	***Recycled materials***	***6854***	***0.8361***	170	***2.49%***
F5.013	*integrated (F5.011)*	E13.03	Output from energy recovery	2369	0.3377		

Derived transfer coefficients for ELV treatment (SI 19)

In the following, the transfer-coefficients are derived for the ELV treatment sector



Main sources employed for deriving the transfer-coefficients

[1] (Vermeulen et al., 2011)
[2] (Nakamura et al., 2012)
[3] (Gradin et al., 2013)
[4] (Bureau of International Recycling, 2017)
[5] (Passarini et al., 2014)
[6] (Simic and Dimitrijevic, 2012)
[7] (Passarini et al., 2018)
[8] (Diener and Tillman, 2016)
[9] (Cullen et al., 2012)
[10] (World auto steel, 2020)
[11] (Björkman and Samuelsson, 2014)
[12] (Løvik et al., 2014b)
[13] (Boin and Bertram, 2005)
[14] (Schau et al., 2011)
[15] (Kurdve et al., 2019)
[16] (Alfaro-Algaba and Ramirez, 2020)
[17] (Olsson et al., 2018)

*EV battery materials should not be diverted to the shredder, but if this should happen, it is modelled based on the values provided in the cells for the battery materials.

The transfer coefficients are derived for most processes, with some selected processes being controlled by a diversion rate applied to the total flow, as it is shown for the reuse of ‘other powertrain components’ (F3.014), shown in the python code that is following in Python vehicle model (SI 20).

While the estimation of the transfer-coefficients are presented in the following, the tables can be also accessed via _SIA2.xlsx by following the GitHub link: https://github.com/AlexejP/MFA_SEA_vehicles_model

Estimation from dismantled ELV to heavy and light fraction

Heavy and light fractions are estimated based on reported ASR data provided [1]. As the reported material resolution is not the same as the composition of the vehicle model, the composition of the ASR flow is further disaggregated based on the relative mass fraction, e.g. Iron is disaggregated to cast iron and steel, based on the relative fraction of iron and steel in the ELV, applying the condition that no extra mass of any other material flow is present (even though in reality shredders are fed with other resource streams), all material fractions have to be sourced from the ELV that is shredded. The derived relative composition value is used as the transfer-coefficient for the light fraction. The heavy fraction is derived by subtracting the value of the light fraction from the transfer-coefficients of the light fraction.

	Automotive shredder residue (ASR) composition in wt% [1]			ASR composition [1] normalized to 100%				Normalized average ASR composition based on [1]	
	min	average	max	min norm	***average norm****	max norm	STD		
Fe	2.20	7.00	12.00	8.03	***9.05***	10.07	0.83	Fe	0.09
Al	1.50	8.80	16.00	5.47	***9.45***	13.42	3.24	Al	0.09
Non-Fe	1.00	3.90	6.70	3.65	***4.64***	5.62	0.80	Non-Fe	0.05
Rubber	7.00	8.00	23.00	25.55	***22.42***	19.30	2.55	Rubber	0.22
Plastics	14.20	15.00	44.00	51.82	***44.37***	36.91	6.09	Plastics	0.44
Glass	1.50	8.00	17.50	5.47	***10.08***	14.68	3.76	Glass	0.10
Total	*27.40*	*50.70*	*119.20*	*100.00*	*100.00*	*100.00*		Total	1.00

After the normalisation of the average ASR fraction and its constituting flows to 100 wt%, the normalised average ASR composition is translated to the materials that are employed in the vehicle model. Battery materials are not included as it is assumed that batteries should not find their way to the ASR fraction. Further, the ASR studies employed are based on conventional vehicles as inputs. Therefore, assumptions are made for Pb, Ethylene carbonate, Graphite, Nd, LiMnO4 and LiPF6, as many of these materials represent EV-battery materials. Here it is to note that these materials do not find their way to the shredder and are therefore not simulated. Nevertheless, the following assumptions are made, namely that the transfer-coefficients for Ethylene carbonate are similar plastics, Graphite is maximally mixed, Nd follows the route of Fe, depending on the stage LiMnO4 and LiPF6 is maximally mixed or follow a similar route as Al.

The material resolution is extended based on the relative mass fraction of each material, e.g., for disaggregating aluminium into two different aluminium categories, the relative fraction is multiplied with the relative fraction, for cast Al: (0.58*0.04) and (0.42*0.04) for the overall aluminium category, that is presented in the first column of the table to the right.

	Mass [kg] of an ELV flow resulting from 99% ICEV, 1% EV	Relative to total ELV flow	Relative to material category reported [1]
Cast Fe	195.09	0.14	0.20
Steel	800.01	0.59	0.80
Plastic	157.70	0.12	0.87
Cu	15.76	0.01	1.00
Glass	28.98	0.02	1.00
Al	42.54	0.03	0.42
Cast Al	59.20	0.04	0.58
Paint	23.68	0.02	0.13
Rubber	23.56	0.02	0.74
Carbon black	8.38	0.01	0.26
Sum	1354.90		

	ASR composition, weighted, based on ELV composition.	Estimated composition disaggregated flows	Est. comp. with condition that mass flow stays const. to ELV composition	Relative fraction of est. comp. with condition that mass flow stays const. to ELV composition
Cast Fe	0.02	6.29	6.29	0.02
Steel	0.07	25.78	25.78	0.09
Plastic	0.39	136.72	136.72	0.50
Cu	0.05	16.43	7.88[1]	0.03
Glass	0.10	35.72	14.49	0.05
Al	0.04	14.00	14.00[2]	0.05
Cast Al	0.05	19.49	19.49[2]	0.07
Paint	0.06	20.53	20.53	0.07
Rubber	0.17	58.62	22.38	0.08
Carbon black	0.06	20.85	7.96	0.03
Total	1.00	354.43	275.53	1.000

[1]Copper is considered as heavy material by Gradin et al., (2013), but as it often appears in combination with rubber and plastic (cables, electronics), it is assumed that 50% of Cu is directed to the light fraction with the other 50% directed to the heavy fraction; [2]Assumption that Al is diverted to 50% to each fraction.

Estimation of the heavy fraction to exported Fe, domestic Fe and Non-Fe fraction

Based on the values reported [2], the separation of Fe and Non-Fe metals is set. The Non-Fe fraction is directed to heavy media processing and entails all materials that are not diverted to the ferrous fractions. The composition of the preceding flow is used to calculate ferrous fractions by multiplication with the reported data [2] and the EU-28 steel scrap export rate [4]. The remaining materials are diverted to the Non-Fe fraction. The transfer-coefficients d) are derived based on a) and multiplicated the material flows from preceding flow c) resulting in material flows e). The assumptions made relate to the transfer-coefficients regarding paint (assumed with 10% remaining on the Fe-metal fractions). Non-Fe fraction is calculated as the difference between 'Exported Fe' and 'Domestic Fe'. For example, the exported Fe fraction from Cast Fe (first cell in table e)) is calculated by employing the Cast Fe from heavy fraction in table c) (188.81kg), multiplicated with the fraction being exported b), (0.17), multiplicated with the transfer-coefficient for Fe in table d) (188.81kg x 0.17 x 0.99 = 32.27kg). The transfer-coefficient is calculated by dividing 'Exported Fe' by 'Total' (32.27kg/188.81kg).

a) [2]	Iron and steel scrap recycled	Relative mass fraction
Fe	407.80	0.99
Cu	1.10	0.00
Al	2.30	0.01
SUM	411.20	

b)

Steel scrap [4]	
Export	Domestic
0.17	0.83

c)	Dismantled ELV [kg]	Heavy fraction [kg]	Relative composition of heavy fraction
Cast Fe	195.09	188.81	0.17
Steel	800.01	774.23	0.72
Plastic	157.70	20.98	0.02
Cu	15.76	7.88	0.01
Glass	28.98	14.49	0.01
Al	42.54	28.54	0.03
Cast Al	59.20	39.72	0.04
Paint	23.68	3.15	0.00
Rubber	23.56	1.18	0.00
Carbon black	8.38	0.42	0.00
Sum	1354.90	1079.38	1.00
		0.80	***1.00***

d)	TCs ferrous fraction
Cast Fe	0.99
Steel	0.99
Plastic	0.00
Cu [2]	0.00
Glass	0.00
Al	0.01
Cast Al	0.01
Paint	0.10
Rubber	0.00
Carbon black	0.00

e) Exported Fe [kg]	Domestic Fe [kg]	Non-Fe fraction [kg]	Total [kg]
32.27	154.98	1.56	188.81
132.31	635.51	6.40	774.23
0.00	0.00	20.98	20.98
0.44	2.11	5.33	7.88
0.00	0.00	0.00	14.49
0.03	0.03	0.13	28.38
0.04	0.04	0.18	39.49
0.05	0.26	2.83	3.15
0.00	0.00	1.18	1.18
0.00	0.00	0.42	0.42
165.14	793.18	121.05	1079.38
0.15	0.73	0.11	1.00

Estimation of the light fraction to fines, shredder fluff and Al fraction (light fraction processing)

The flows resulting from light fraction processing are calculated based on [1]. As the material categories (e.g. 'metals') are not further disaggregated, the disaggregation is undertaken based on the relative mass fractions of the metals present in the dismantled ELV. Similarly, the disaggregation is undertaken for other material fractions. Based on the resulting relative composition of the flows 'fines' and 'shredder fluff', the transfer-coefficients are derived. On the example of 'Cast Fe' it is demonstrated how the transfer-coefficients of 'Fines', 'Shredder fluff' and the 'Al fraction' are calculated. Based on [1], the relative compositions of 'Fines' and 'Shredder fluff' are calculated, using the 'mid' column, to be later reused in f). Based on the upstream flows, Cast Fe that is present in the ELV b) is multiplicated with c) the TC of the light fraction that is already calculated, resulting in d) the Cast Fe content of the 'light fraction'. The disaggregation of the flows is based on the mass content and the relative relation between Cast Fe and Steel, resulting in e), where Cast Fe (0.2) and Steel (0.8) add up to 100% Fe metals. The disaggregated material categories e) are multiplicated with f) the relative composition of 'Fines' and 'Shredder fluff', resulting in g) that is employed to derive transfer-coefficients for Cast Fe provided in h).

a) [1]	Light ASR (or light fraction)	low	mid	max	rel. comp. mid values
Fines (light ASR)	Metals	0.30	10.65	21.00	0.22
	Wire	0.50	1.75	3.00	0.04
	Rubber	2.60	6.45	10.30	0.14
	Plastic	8.70	27.40	46.10	0.58
	Glass	0.00	1.15	2.30	0.02
		12.10	47.40	82.70	1.00
Shredder fluff (heavy ASR)	Metals	0.20	2.60	5.00	0.04
	Wire	0.70	6.70	12.70	0.09
	Rubber	14.10	34.55	55.00	0.47
	Plastic	8.00	20.30	32.60	0.28
	Glass	8.30	9.65	11.00	0.13

	b) Dismantled ELV [kg]	c) TC light fraction	d) Light fraction [kg]	e) Disaggregation of material categories[1]	f) Composition of Fines and Shredder fluff			g) Relative composition		h) TCs		Mass test		
								Fines	Shredder fluff	Fines	Shredder fluff	Fines [kg]	Shredder fluff [kg]	Domestic Al [kg]
Cast Fe	195.09	0.03	6.29	0.20		Fines	Shredder fluff	0.04	0.01	0.86	0.14	5.44	0.85	0.00
Steel	800.01	0.03	25.78	0.80	Metals	0.22	0.04	0.18	0.03	0.86	0.14	22.29	3.49	0.00
Plastic	157.70	0.87	136.72	0.87	Wire	0.04	0.09	0.50	0.24	0.68	0.32	92.64	44.08	0.00
Cu	15.76	0.50	7.88	0.03	Rubber	0.14	0.47	0.04	0.09	0.29	0.71	2.28	5.60	0.00
Glass	28.98	0.50	14.49	0.05				0.02	0.13	0.16	0.84	2.27	12.22	0.00
Al	42.54	0.33	14.00	0.42	Plastic	0.58	0.28	0.00	0.00	0.00	0.00	0.00	0.00	14.00
Cast Al	59.20	0.33	19.49	0.58				0.00	0.00	0.00	0.00	0.00	0.00	19.49
Paint	23.68	0.87	20.53	0.13	Glass	0.02	0.13	0.08	0.04	0.68	0.32	13.91	6.62	0.00
Rubber	23.56	0.95	22.38	0.74		1.00	1.00	0.10	0.35	0.23	0.77	5.04	17.34	0.00
Carbon black	8.38	0.95	7.96	0.26				0.04	0.12	0.23	0.77	1.79	6.17	0.00
Sum	1354.90		275.53					1.00	1.00			145.65	96.38	33.49
												0.53	0.35	0.12

[1]proportional to their mass

Estimation of flows from the Non-Fe fraction to the exported mixed fraction, exported Al and Fe fraction, the Al fraction (recycled) and residues

The flows from ‘Non-Fe fraction’ after separation after ‘heavy media processing’ are based on [4], [5] and [6], including assumptions for other material fractions such as plastics, rubber etc., employed to calculate the relative material fractions directed to each of the flows, resulting in the transfer-coefficients presented.

	Heavy fraction [kg]	TCs Non-Fe fraction	Non-Fe fraction	Sorting efficiency [6]			Exported mixed fraction [kg]	Exported Al fraction [kg]	Exported Fe fraction [kg]	Residues [kg]	Al fraction [kg]	Mass balance test [kg]	Mass balance test
Cast Fe	188.81	0.01	1.56	Al	0.98	Cast Fe	0.02[1]	0.02[1]	1.50	0.02[1]	0.02[1]	1.56	1.56
Steel	774.23	0.01	6.40	Cu	0.14	Steel	0.06[1]	0.06[1]	6.15	0.06[1]	0.06[1]	6.40	6.40
Plastic	20.98	1.00	20.98	Plastic	0.11	Plastic	2.23[2]	0.00	0.00	18.75[7]	0.00[1]	20.98	20.98
Cu	7.88	0.68	5.33	Rubber	0.11	Cu	0.77[2]	0.05[1]	0.05[1]	4.39[10]	0.05[1]	5.33	5.33
Glass	14.49	1.00	14.49			Glass	7.25[3]	0.00	0.00	7.25[3]	0.00	14.49	14.49
Al	28.54	0.99	28.38			Al	0.04[4]	7.09[10]	0.00	0.05[8]	21.19[9]	28.38	28.38
Cast Al	39.72	0.99	39.49	Steel scrap export and import [4]		Cast Al	0.08[2]	9.87[10]	0.00	0.08	29.47[9]	39.49	39.49
Paint	3.15	0.90	2.83			Paint	0.99[5]	0.28[5]	0.28[5]	0.99[5]	0.28[5]	2.83	2.83
Rubber	1.18	1.00	1.18	Export	Domestic	Rubber	0.13[2]	0.13	0.00	0.00	1.05[2]	0.00	1.18
Carbon black	0.42	1.00	0.42	0.25	0.75	Carbon black	0.04[6]	0.00	0.00	0.38[6]	0.00	0.42	0.42
Sum	1079.38		121.05			**Sum**	11.60	17.38	7.98	33.02	51.08	121.05	121.05

[1]assumption of 1% cross-contamination to other material flows, [2]based on recycling efficiency reported by [6], [3]assumption that half of the glass is directed to residues and the exported mixed fraction, [4]based on the Al content in light fraction [5], [5]assumed that paint remains on Fe and Al parts to some degree, assumption that 10% of the paint is distributed to each metal fraction, with the remaining 70% being equally distributed between residues and the exported mixed fraction, [6]assumption that 90% of carbon black is directed to residues, with 10% remaining in the mixed fraction, [7]mass balanced through the residue flow, [8]based on [5], estimation that 1000kg of light fluff contain 6.5 kg of aluminium, [9]cased on fraction of Al scrap exported [5], [10]mass balanced through other flows.

	TC Exported mixed fraction	TC Exported Al fraction	TC Exported Fe fraction	TC Residues	TC Al fraction
Cast Fe	0.01	0.01	0.96	0.01	0.01
Steel	0.01	0.01	0.96	0.01	0.01
Plastic	0.11	0.00	0.00	0.89	0.00
Cu	0.14	0.01	0.01	0.83	0.01
Glass	0.50	0.00	0.00	0.50	0.00
Al	0.00	0.25	0.00	0.00	0.75
Cast Al	0.00	0.25	0.00	0.00	0.75
Paint	0.35	0.10	0.10	0.35	0.10
Rubber	0.11	0.00	0.00	0.89	0.00
Carbon black	0.10	0.00	0.00	0.90	0.00

Estimation of flows from regulated components to recycled materials, slags of regulated components, and domestic steel from decanning

The flows resulting from regulated components are calculated based on [8], who report values for the ferrous fraction that is directed to steel recycling. The other materials leave the system either as a material flow that is entering a further recycling process or as a residue flow. The values for recycled and residue flows are to a large degree assumed.

Exported mixed fraction	Regulated components used to estimate TCs for lead battery and wheels of a car	Recycled materials	Residues regulated components	Domestic steel from decanning	Mass balance
Cast Fe	0.00	0.02[1]	0.02[1]	0.97[3]	1.00
Steel	46.95	0.02[1]	0.02[1]	0.97[3]	1.00
Plastic	0.66	0.50[2]	0.50[2]	0.00	1.00
Cu	0.00	0.98[4]	0.01	0.01	1.00
Glass	0.00	0.99[5]	0.01	0.00	1.00
Al	0.00	0.98[6]	0.01	0.01	1.00
Cast Al	0.00	0.98[6]	0.01	0.01	1.00
Paint	0.00	0.10[7]	0.80	0.10	1.00
Rubber	18.11	0.01[8]	0.99	0.00	1.00
Carbon black	8.33	0.01[8]	0.99	0.00	1.00
Pb	11.24	1.00[9]	0.00	0.00	1.00

[1] based on data from [8], with loss accounted with 1% (no mass balance); to ensure mass balance, 2% of materials are distributed equally to recycled materials and residues, [2] assumption that 50% of plastics are sorted and sent to recycling, [3] based on data from [8], [4] assumption that almost all Cu is sorted and sent to recycling, [5] assumption that glass is sorted and collected separately to be sent to recycling if it is diverted to regulated component flows, [6] assumption that Al is diverted to a dedicated Al flow, [7]assumption that 10% of paint remains on the component surface, [8] assumption that most rubber and carbon black is not recycled, [9]assumption that all Pb is diverted to dedicated recycling process

Estimation of flows from domestic Fe (incl. domestic steel from decanning) to exported steel, recycled steel and slags/dusts from steel production

The flows resulting from domestic Fe (and domestic Fe from decanning), to exported steel, steel slags/dusts and recycled steel (closed loop) based on [9, 11] and the closed-loop recycling rate of automotive steel and Fe fractions [8]. The Fe/steel recycling rates are calculated based on the difference between input and output flows. Considering the closed-loop recycling rates, the flow of domestic Fe and steel a) and the recycling efficiency, e.g. the exported steel flow b) can be calculated (1-0.11) x 0.75 x 682.46 = 455.06. Similarly, the other flows c) based on the losses in the recycling process, and d) closed-loop recycling rate can be calculated. References and assumption for the transfer-coefficients of other material flows that have to be defined, even though they might not be directed to the steel recycling process are provided in the footnotes.

Inputs [Mt]	Outputs [Mt]	Losses [Mt]	Losses [rel.]	Exported steel (directed to other applications)	Used in a closed-loop recycling
461.50	410.30	51.20	0.11	0.75	0.25

	a) Domestic Fe and domestic steel from decanning	b) Exported steel	c) Slags and dusts steel	d) Recycled steel	e) Mass balance test	f) Exported steel	g) Slags and dusts steel	h) Recycled steel	i) Mass balance test
Cast Fe	154.98	103.34	17.19	34.45	154.98	0.67	0.11	0.22	1.00
Steel	682.46	455.06	75.71	151.69	682.46	0.67	0.11	0.22	1.00
Plastic	0.66	0.00	0.66[2]	0.00	0.66	0.00	1.00	0.00	1.00
Cu	2.11	1.59[1]	0.00	0.53	2.11	0.75	0.00	0.25	1.00
Glass	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00
Al	0.13	0.00	0.13[1]	0.00	0.13	0.00	1.00	0.00	1.00
Cast Al	0.18	0.00	0.18[1]	0.00	0.18	0.00	1.00	0.00	1.00
Paint	0.26	0.00	0.26[2]	0.00	0.26	0.00	1.00	0.00	1.00
Rubber	18.11	0.00	18.11[2]	0.00	18.11	0.00	1.00	0.00	1.00
Carbon black	8.33	0.00	8.33[2]	0.00	8.33	0.00	1.00	0.00	1.00
Pb	11.24	10.12[1]	1.12[1]	0.00	11.24	0.90	0.10	0.00	1.00
Sum	878.47	570.10	121.70	186.66	878.47				

[1] based [9] and [8], [2] assumed oxidation

Estimation of flows from domestic Al production to the exported Al, recycled Al (closed-loop) and slags/dusts from Al production

Similar to steel recycling, the flows from domestic Al production to exported Al, recycled Al in a closed loop and the losses of Al and other materials to the slags/dusts fraction are estimated based on [12, 13]. The same calculation is employed as for the estimation of domestic Fe, exported steel flows, presented above.

The Al fraction is calculated based on the recycling efficiency and losses in the recycling process, including the consideration of open-loop/closed-loop recycling rates, both being multiplicated to calculate exported Al flows, Slags Al, and Recycled Al.

Inputs [Mt]	Outputs [Mt]	Losses [Mt]	Losses [rel.]	Recycled Al:	Open-loop RR (to automotive sector) incl. losses	Closed-loop RR (to other sectors) incl. losses
4.23	3.99	0.25	0.06	0.94	0.53	0.41

	a) A fraction (light fraction processing) and Al fraction (heavy media processing)	b) Exported Al	c) Slags Al	d) Recycled Al		Exported Al	Slags Al	Recycled Al
Cast Fe	0.02	0.00	0.02[1]	0.00	0.02	0.00	1.00	0.00
Steel	0.06	0.00	0.06[1]	0.00	0.06	0.00	1.00	0.00
Plastic	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Cu	0.05	0.02	0.02[1]	0.02	0.05	0.30	0.40	0.30
Glass	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Al	35.19	18.57	2.04	14.59[2]	35.19	0.53	0.06	0.41
Cast Al	48.96	25.83	2.83	20.29	48.96	0.53	0.06	0.41
Paint	0.28	0.00	0.28[1]	0.00	0.28	0.00	1.00	0.00
Rubber	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Carbon black	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Sum	84.56	44.41	5.26	34.90	84.56	0.00	1.00	0.00

[1] directed to slags fraction, even though recycled Al is attributed to the general Al fraction, it is considered that recycled Al results in cast Al, as reported by various sources, e.g. [12].

Estimation of flows from EV motor reuse/recycling to materials from EV motor, exported Cu, recycled Cu, or reused EV motor (fraction)

The flows resulting from EV motor recycling/reuse to exported Cu, recycled Cu (closed-loop) and reused EV motor are based on the remanufacturing data and the probability of material discarding [12]. As no data on the remanufacturing of EV motors has been found, the data for alternators was used and upscaled to derive transfer-coefficients. For recycling of Cu scrap within the EU and scrap being exported data based on [5] is used to derive the fraction of exported scrap.

Based on the sub-components b), main material constituents c), reported mass d) and the replacement probability e); first the overall mass of each material group is aggregated and in a second step, each material replacement is weighted with the replacement probability.

	a) Material composition	b) Sub-component	c) Main constituent	d) Mass [kg]		Materials from EV motor	EV motors	Recycled Cu (closed loop)	Exported Cu
Cast Fe	4.52	Stator	Steel	0.77	Cast Fe	0.19	0.81	0.00	0.00
Steel	35.88	Rotor coil	Cu	0.55	Steel	0.17	0.83	0.00	0.00
Plastic	8.15	Rotor	Cast Fe	1.09	Plastic	1.00[3]	0.00	0.00	0.00
Cu	109.53	Drive shaft	Steel	0.26	Cu	0.00	0.66	0.16	0.19
Glass	0.00	Belt fitting	Steel	0.52	Glass	1.00[1]	0.00	0.00	0.00
Al	184.43	Fan	Plastic	0.02	Al	0.40	0.60	0.00	0.00
Cast Al	0.00	Spacer	Al	0.00	Cast Al	0.40	0.60	0.00	0.00
Nd	1.67	Bearings	Steel	0.10	Nd	0.17[2]	0.83	0.00	0.00
Rubber	3.70	Slip ring S	Cu	0.10	Rubber	1.00[3]	0.00	0.00	0.00
Carbon black	0.00	Housing	Al	0.96	Carbon black	1.00[3]	0.00	0.00	0.00
Sum	347.86			4.38					

	f) Mass [kg]	g) Mass weighted replacement probability
Cast Fe	1.09	0.19
Steel	1.65	0.17
Plastic	0.02	1.00
Cu	0.65	0.34
Al	0.96	0.40
Sum	4.38	
Cu Scrap [7]	Cu [kt]	rel. fraction
Export	873.00	0.54
Dom. processed	730.00	0.46
	1603.00	

Assumption that [1]glass is not reused, [2]Nd follows steel reuse rate, [3]rubber, carbon black and plastic fully replaced, [4]recycled Cu (closed-loop) and exported based on [7].

Estimation of flows from EV battery to reused batteries, exported batteries, or Residues

The flows resulting from EV battery reuse, such as exports to other sectors, or the battery reuse in a second life application (e.g. for energy storage), represent highly uncertain future processes, as it depends on various factors that influence the level of reuse, remanufacturing and recycling [15]. The recovery rate of battery materials is set in accordance with the scenario employed, nevertheless here the value presented is 50%, with some metals such as Cu and Al, being reused to a higher degree [16], while 40% of batteries being directed in other sectors.

	Material composition	EV Batteries reused or recycled	EV batteries exported	Residues
Copper	109.53	0.60	0.40	0.00
LiMn2O4	0.00	0.50	0.40	0.10
Graphite	184.43	0.50	0.40	0.10
Ethylene carbonate	0.00	0.50	0.40	0.10
Aluminium foil	1.67	0.60	0.40	0.00
Polyethylene	3.70	0.50	0.40	0.10
LiPF6	0.00	0.50	0.40	0.10
Sum	347.86			

According [16], if disassembly will be pursued, the level of disassembly will be high, as the most profitable sub-components, the battery modules, are likely to be recovered late in the disassembly sequence. Depending on the state of the modules, it is assumed that 50% can be reused. By extension of the battery lifetime, it is also proposed to reuse vehicle batteries in other sectors, thereby repurposing them, while minimising the environmental effects of EV batteries, deriving a higher overall value and thereby contributing to other sector's sustainability performance [17]. Therefore, the values of 'exported' EV batteries to other sectors are set relatively high (40%).

Python vehicle model (SI 20)

The python model is provided on GitHub under the name MFA_SEA_vehicles_model, accessible under the following link: https://github.com/AlexejP/MFA_SEA_vehicles_model

The folder holds all necessary files that have to be downloaded to the python working directory, remaining accessible in the same folder as the main python code file. The following table shortly describes the files present in the repository.

Filename	Description
LICENSE	One of the default licenses provided by GitHub with 1) permissions for commercial use, modification, distribution, private use, 2) limitations of liability and warranty, and 3) license copyright notice
MFA_SEA_model_supplementary_python.ipynb	Main code file
README.md	A short description on how to change (activate/deactivate) scenarios is presented to run the model
Tks.csv	The file holds transfer-coefficients that determine the material flows in the model
Tks_improved.csv	Improved transfer-coefficients include improvements in the recycling processes
_Main_scenario_file.csv	Scenarios that are generated by the stock-based model can be called as inputs to the model
_components.csv	The file holds the flows of components that enter the ELV system per year being a result of the stock-flow model and the lifetime distribution of selected components
_components_empty.csv	The file holds the form of the 'components file' being empty to overwrite component flows if needed to simulate only the flows of vehicles
component_composition.csv	The file holds the material composition of each component
empty_df.csv	Imported to be used as an empty data frame providing a place holder for recycled material flows
imported_empty.csv	Imported to be used as an empty data frame is provided to be initialised and to be filled by material imports based on the scenario
in.csv	Empty data frame for appending the results of each year
_SIA1.xlsx	The file holds a data summary of the stock-flow model and the scenario data derived
_SIA2.xlsx	The file includes the generic MFA derived, EV and ICEV compositions, the transfer-coefficients and RSE values of components

Initial transfer coefficients employed in the python model and improved transfer coefficients (SI 21)

Initial transfer-coefficients employed

Flow name	Fe	Steel	Plastic	Cu	Glass	Al	Al cast	Paint	Rubber	Carbon black	Pb	Ethylene carbonate	Graphite	Nd	LiMnO4	LiPF6
Dismantled_ELVs	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Materials_from_EV_motor	0.19	0.17	1.00	0.00	1.00	0.40	0.40	1.00	1.00	1.00	1.00	1.00	1.00	0.17	0.40	0.40
Exported_copper	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Recycled_copper	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EV_motors	0.81	0.83	0.00	0.66	0.00	0.60	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.60	0.60
Slags_battery_recycling	0.97	0.97	0.00	0.00	0.00	0.01	0.01	0.10	0.00	0.00	0.00	0.10	0.10	0.40	0.10	0.10
EV_batteries_exported	0.02	0.02	0.50	0.60	0.99	0.98	0.98	0.10	0.01	0.01	1.00	0.50	0.50	0.30	0.50	0.50
EV_batteries_recycled	0.02	0.02	0.50	0.40	0.01	0.01	0.01	0.80	0.99	0.99	0.00	0.40	0.40	0.30	0.40	0.40
Heavy_fraction	0.97	0.97	0.13	0.50	0.20	0.67	0.67	0.07	0.00	0.00	0.50	0.13	0.13	0.97	0.67	0.67
Light_fraction	0.03	0.03	0.87	0.50	0.80	0.33	0.33	0.93	1.00	1.00	0.50	0.87	0.87	0.03	0.33	0.33
Exported_Fe_heavy	0.17	0.17	0.00	0.06	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00
Domestic_Fe	0.82	0.82	0.00	0.27	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.82	0.00	0.00
Non_Fe_fraction	0.01	0.01	1.00	0.68	1.00	0.99	0.99	0.90	1.00	1.00	1.00	1.00	1.00	0.01	0.99	0.99
Shredder_fluff_1	0.86	0.86	0.68	0.29	0.16	0.00	0.00	0.68	0.23	0.23	0.05	0.68	0.33	0.33	0.33	0.33
Shredder_fluff_2	0.14	0.14	0.32	0.71	0.84	0.00	0.00	0.32	0.77	0.77	0.95	0.32	0.33	0.33	0.33	0.33
Domestic_Aluminum	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.33	0.33
Exported_mixed_fraction	0.01	0.01	0.11	0.14	0.50	0.00	0.00	0.35	0.11	0.10	0.95	0.11	0.50	0.01	0.00	0.00
Exported_Al_fraction	0.01	0.01	0.00	0.01	0.00	0.25	0.25	0.10	0.00	0.00	0.00	0.00	0.00	0.01	0.25	0.25
Exported_Fe_fraction	0.96	0.96	0.00	0.01	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.96	0.00	0.00
Residues	0.01	0.01	0.89	0.83	0.50	0.00	0.00	0.35	0.89	0.90	0.05	0.89	0.50	0.01	0.00	0.00
Al_fraction	0.01	0.01	0.00	0.01	0.00	0.75	0.75	0.10	0.00	0.00	0.00	0.00	0.00	0.01	0.75	0.75
Exported_steel	0.67	0.67	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.67	0.00	0.00
Slags_and_dusts_steel	0.11	0.11	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.10	1.00	1.00	0.11	1.00	1.00
Recycled_steel	0.22	0.22	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.00
Exported_Al	0.00	0.00	0.00	0.30	0.00	0.53	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53
Slags_Al	1.00	1.00	1.00	0.40	1.00	0.06	0.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.06	0.06
Recycled_Al	0.02	0.02	0.50	0.01	0.01	0.01	0.01	0.80	0.99	0.99	0.00	0.50	0.00	0.02	0.01	0.01
Recycled_materials	0.97	0.97	0.00	0.01	0.00	0.01	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.97	0.01	0.01
Slags_regulated_components	0.02	0.02	0.50	0.01	0.01	0.01	0.01	0.80	0.99	0.99	0.00	0.50	0.00	0.02	0.01	0.01
Domestic_steel_from_decanning	0.19	0.17	1.00	0.00	1.00	0.40	0.40	1.00	1.00	1.00	1.00	1.00	1.00	0.17	0.40	0.40

Flow name	Description of changes	Sources, and assumptions
Materials_from_EV_motor Exported_copper Recycled_copper EV_motors	Replacement probability for metal parts decreased, it is assumed that 10% improvement in metal parts reuse is achieved in remanufacturing, improvements diverted from "materials_from_EV_motor"	The improvements assumed here represent the magnitude that is at the lower bound, given the market study of the European remanufacturing sector, improvements could be much higher [4], especially if additional improvements are fostered by dedicated policies given the positive green-house-gas saving potential and employment effects of the sector.
Slags_battery_recycling EV_batteries_exported EV_batteries_recycled	Recycling of battery materials doubled (Ethylencarbonate, Graphite, Nd, $LiMnO_4$, $LiPF_6$), with reductions of batteries exported	It is assumed that with larger amounts of spent EV batteries, recycling improvements can set in, that significantly improve the recovery of battery materials, as demonstrated recycling efficiencies can be higher for most battery materials [3]
Heavy_fraction Light_fraction	Diversion of Fe and Steel increased from 96,7% to 97%, and of Plastic from 86.7% to 90%	Improvements in hammer mill air separation are considered to be already optimized and therefore reach only minor, incremental improvements
Exported_Fe_heavy Domestic_Fe Non_Fe_fraction	Domestic recycling of Fe increased to by 10%. Diversion of Cu from ferrous fraction increased also by 10%.	Increases of the recycling efficiency by 10% is considered feasible for Cu as it is discussed by [2], for Fe the diversion of Fe scrap to European Fe recyclers is assumed to be feasible
Shredder_fluff_1 Shredder_fluff_2 Domestic_Aluminum	No changes	It is assumed that no improvements in shredder fluff recovery are achieved, as it is a highly contaminated output fraction with low economic value
Exported_mixed_fraction Exported_Al_fraction Exported_Fe_fraction Residues Al_fraction	Diversion of copper from 14.5% to 60.0%, and glass from 50.0% to 80.0%	With a higher share of ELVs and an improved recycling system, recovery of Cu is assumed to reach similar values as it is shown for the development of for platin-group metals in the case of catalytic converters [1]
Exported_steel Slags_and_dusts_steel Recycled_steel	Closed loop recycling to the automotive sector of steel is increased by 20% (potential uptake), with less Fe lost to slags and generally lower Cu content of Cu in recycled steel	The improvement of closed steel recycling by 20% might be optimistic, as high contamination by other metals, especially copper, lead to a downcycling of steel and limit its closed-loop use. Improvements in sorting technology and recycling processes could increase the share of recycled steel for automotive applications in the future [5].
Exported_Al Slags_Al Recycled_Al	Closed loop recycling to the automotive sector of Al increased by 70% (potential uptake), with less Al and higher contaminants diversion to slags	With only a few closed loop recycling systems in existence and the high downcycling of aluminium in its recycling process [6], high potential for closed loop recycling still exists and it is assumed that installation of modern sensor technology and pre-sorting of aluminium alloys can lead to a higher closed-loop recycling
Recycled_materials Slags_regulated_components Domestic_steel_from_decanning	No changes in the processing of regulated components	Regulated components already follow a special recycling process, so that it is assumed that no major improvements happen in this regard.

[1]	(Hagelüken, 2020)
[2]	(Richa et al., 2014)
[3]	(Levedeva et al., 2017)
[4]	(Parker et al., 2015)
[5]	(Hatayama et al., 2014)
[6]	(Modaresi, 2015)

Improved transfer-coefficients

Flow name	Fe	Steel	Plastic	Cu	Glass	Al	Al cast	Paint	Rubber	Carbon black	Pb	Ethylene carbonate	Graphite	Nd	LiMnO4	LiPF6
Dismantled_ELVs	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Materials_from_EV_motor	0.11	0.09	1.00	0.00	1.00	0.34	0.34	1.00	1.00	1.00	1.00	1.00	1.00	0.17	0.40	0.40
Exported_copper	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Recycled_copper	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EV_motors	0.89	0.91	0.00	0.72	0.00	0.66	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.60	0.60
Slags_battery_recycling	0.97	0.97	0.00	0.00	0.00	0.01	0.01	0.10	0.00	0.00	0.00	0.10	0.10	0.40	0.10	0.10
EV_batteries_exported	0.02	0.02	0.50	0.60	0.99	0.98	0.98	0.10	0.01	0.01	1.00	0.10	0.10	0.00	0.10	0.10
EV_batteries_recycled	0.02	0.02	0.50	0.40	0.01	0.01	0.01	0.80	0.99	0.99	0.00	0.80	0.80	0.60	0.80	0.80
Heavy_fraction	0.97	0.97	0.10	0.50	0.50	0.67	0.67	0.13	0.05	0.05	0.95	0.13	0.67	0.97	0.67	0.67
Light_fraction	0.03	0.03	0.90	0.50	0.50	0.33	0.33	0.87	0.95	0.95	0.05	0.87	0.33	0.03	0.33	0.33
Exported_Fe_heavy	0.09	0.09	0.00	0.06	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00
Domestic_Fe	0.90	0.90	0.00	0.20	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.82	0.00	0.00
Non_Fe_fraction	0.01	0.01	1.00	0.74	1.00	0.99	0.99	0.90	1.00	1.00	1.00	1.00	1.00	0.01	0.99	0.99
Shredder_fluff_1	0.86	0.86	0.68	0.29	0.16	0.00	0.00	0.68	0.23	0.23	0.05	0.68	0.33	0.33	0.33	0.33
Shredder_fluff_2	0.14	0.14	0.32	0.71	0.84	0.00	0.00	0.32	0.77	0.77	0.95	0.32	0.33	0.33	0.33	0.33
Domestic_Aluminum	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.33	0.33
Exported_mixed_fraction	0.01	0.01	0.11	0.60	0.20	0.00	0.00	0.35	0.11	0.10	0.95	0.11	0.50	0.01	0.00	0.00
Exported_Al_fraction	0.01	0.01	0.00	0.10	0.00	0.25	0.25	0.10	0.00	0.00	0.00	0.00	0.00	0.01	0.25	0.25
Exported_Fe_fraction	0.96	0.96	0.00	0.10	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.96	0.00	0.00
Residues	0.01	0.01	0.89	0.10	0.80	0.00	0.00	0.35	0.89	0.90	0.05	0.89	0.50	0.01	0.00	0.00
Al_fraction	0.01	0.01	0.00	0.10	0.00	0.75	0.75	0.10	0.00	0.00	0.00	0.00	0.00	0.01	0.75	0.75
Exported_steel	0.63	0.63	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.67	0.00	0.00
Slags_and_dusts_steel	0.10	0.10	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.10	1.00	1.00	0.11	1.00	1.00
Recycled_steel	0.27	0.27	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.00
Exported_Al	0.00	0.00	0.00	0.30	0.00	0.24	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53
Slags_Al	1.00	1.00	1.00	0.40	1.00	0.06	0.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.06	0.06
Recycled_Al	0.00	0.00	0.00	0.30	0.00	0.70	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.41
Recycled_materials	0.02	0.02	0.50	0.98	0.99	0.98	0.98	0.10	0.01	0.01	1.00	0.50	1.00	0.02	0.98	0.98
Slags_regulated_components	0.02	0.02	0.50	0.01	0.01	0.01	0.01	0.80	0.99	0.99	0.00	0.50	0.00	0.02	0.01	0.01
Domestic_steel_from_decanning	0.97	0.97	0.00	0.01	0.00	0.01	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.97	0.01	0.01