A Metric for Quantifying Product-Level Circularity

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Summary

Circularity metrics are useful for empirically assessing the effects of a circular economy in terms of profitability, job creation, and environmental impacts. At present, however, there is no standardized method for measuring the circularity of products. We start by reviewing existing product-level metrics in terms of validity and reliability, taking note of theoretically justified principles for aggregating different types of material flows and cycles into a single value. We then argue that the economic value of product parts may constitute a useful basis for such aggregation; describe a set of principles for using economic value as a basis for measuring product circularity; and outline a metric that utilizes this approach. Our recommendation is to use the ratio of recirculated economic value to total product value as a circularity metric, using value chain costs as an estimator. In order to protect value chain actors' sensitive financial data and facilitate neutrality regarding outsourcing or insourcing, we suggest a means to calculate product-level circularity based on sequential approximations of adding one product part and activity at a time. We conclude by suggesting potential avenues for further research, including ways in which the proposed metric can be used in wider assessments of the circular economy, and ways in which it may be further refined.

Introduction

The circular economy has been billed as a way to decouple economic growth from environmental degradation (Kama 2015; Webster 2013; Stahel 2006, 2013); boost firm profitability (Ellen MacArthur Foundation 2013); increase competitive advantage (Webster 2013; Stahel 2006; Heese et al. 2005; Giuntini and Gaudette 2003); and create new job opportunities at the local level (Stahel 2006, 2013; Webster 2013). Robust and legitimate measures of circularity are needed to evaluate such claims. Metrics currently exist for macro- and meso-level circularity. Of special note is the recent special edition on socioeconomic metabolism in *Journal of Industrial Ecology* (*JIE*) (Schandl et al. 2015), which examined various methods for measuring material flows, including material flow analysis (MFA). However, there is no standardized or well-established method for measuring circularity at the micro level that includes businesses and products (Geng et al. 2012). The development of a product-level circularity metric is useful for business stakeholders given the old idiom: "What gets measured gets managed."

Several metrics that may be applicable to product-level circularity are currently in circulation (see, e.g., C2C 2014; Gehin et al. 2008; Scheepens et al. 2016; Di Maio and Rem 2015). Until recently, the Ellen MacArthur Foundation and Granta (2015, 4) argued that "there is no recognized way of measuring how effective a product or company is in making the transition from 'linear' to 'circular'", and developed a metric that assesses product-level circularity using mass-flow analysis. The European Commission (EC) is currently examining how product labels can support the transition to a circular economy (EC 2015a). Newly

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developed eco-labels are set to include information on the amount of raw materials used in products and their "recyclability" (EC 2015b). Existing attempts to develop standardized metrics use different types of units (e.g., material mass, emergy) to quantify product-level circularity.

Given the clear need for a robust and valid circularity metric, there is an urgent need to carefully review the available options for measuring circularity at the product level and try to find solutions to the varying weaknesses inherent to each of these options. How should product-level circularity be measured, and which units represent the most fruitful approach? In this article, which consists of eight sections, we review the concept of circularity and outline a definition of product-level circularity (in the second section) that can be used to evaluate existing metrics and provide a basis for a new circularity metric. We argue that a robust product-level circularity metric should focus exclusively on measurements of circularity. That is, a robust metric should not include consideration for other aspects of product quality, such as environmental performance. In the third section, we outline a set of criteria for assessing circularity metrics, and we apply these criteria to a set of existing metrics in the fourth section. In the fifth section, we make a case for basing circularity metrics on economic units and outline a new, product-level circularity metric based on these principles in the sixth section. In the seventh section, we discuss the advantages and limitations of our proposed metric and outline topics for future research. The final section offers conclusions.

Defining Circularity

The modern-day characterization of a circular economy is derived from key insights in the field of industrial ecology, including cradle-to-cradle design (McDonough and Braungart 2002) and biomimicry (Benyus 2002). It also draws upon Boulding's (1966) concept of "Spaceship Earth"; Daly's (1980) "steady-state economy"; and Stahel and Reday's (1981) "loop economy." These ideas have gained traction in policymaking spheres within the European Union (EU), China, and Japan and have been popularized by think tanks and nongovernmental organizations such as the Green Alliance and the Ellen MacArthur Foundation. The ultimate goal of a circular economy is sustainable development (Bonciu 2014; Kopnina 2014; Mathews et al. 2011; Qiao and Qiao 2013; Lowe 2015). Whereas the Chinese interpretation of a circular economy encompasses social factors under the broader political goal of a more "harmonious society" (Naustdalslid 2014), other countries focus more specifically on marrying the environmental and economic dimensions of sustainability (Webster 2013).

A shift to a circular economy presents the challenge of recirculating direct and indirect material flows in a manner that can promote eco-effectiveness (Webster 2013). The shift requires changes at the micro level (individual companies and consumers), meso level (eco-industrial parks), and macro level (city, province, region, and nation) (Geng et al. 2016a; Ghisellini et al. 2016; Qiao and Qiao 2013; Geng et al. 2009; Geng and Doberstein 2008). Micro-level activities that can support this change include eco-design, waste minimization, cleaner production, environmental management systems, product-life extension, new business models, and new modes of consumption. Three material recirculation strategies (reuse, remanufacture, and recycle) that seek to transform the way manufactured goods are produced and consumed have been identified. It is widely argued that two key elements of this strategy include the servitization of manufactured products through new business models that incentivize material recirculation and products that are designed to have extended life spans (Tukker 2015; Bakker et al. 2014; Kopnina 2014; Stahel 2006, 2013; Webster 2013; Lowe 2015). Some argue that this strategy is both environmentally motivated and a source of economic gains. The Ellen MacArthur Foundation, for example, reports that an advanced circular economy will deliver resource productivity gains in the order of €500 billion in the form of cost savings levied by European manufacturing industries (Ellen MacArthur Foundation 2013).

Whereas some definitions include the concepts of economic value and reduced energy consumption, the essence of a circular economy is related to the introduction of closed-loop product, resource, and material cycles as a means to improve resource efficiency. Several definitions of the circular economy focus on closed-loop cycles:

- "A self-sufficient economic regime conducted through 'closed loops' of materials" (Kama 2015, 19; see also Su et al. 2013);
- "A closed cycle of material and energy flows" (Mathews et al. 2011, 467);
- "The core of CE [circular economy] is the circular (closed) flow of materials" (Yuan et al. 2006, 5)
- "A CE is an industrial system focused on closing the loop for material and energy flows" (Geng et al. 2013, 1526);
- "In a circular economy, resources are kept in use for as long as possible, extracting their maximum value" (special issue call from *JIE*, 2015);
- An economy ". . . in which the conceptual logic for value creation is based on utilizing economic value retained in products after use" (Linder and Williander 2015, 2)
- "[CE] . . . aims at reducing both input of virgin materials and output of wastes by closing economic and ecological loops of resource flows" (Haas et al. 2015, 765);
- An economy ". . . where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized" (EC 2015a, 2)

At a product level, focusing on closed-loop cycles implies that materials, components, and products must be reused, remanufactured, or recycled. However, materials can also be recirculated within open-loop cycles. We argue that a robust product-level circularity metric should focus exclusively on measuring circularity as a single attribute of product quality, given that other aspects of quality are captured by other metrics and indicators (e.g., environmental product labels). Hence, we define circularity at the product level as *the fraction of a product that comes from used products* (i.e., from closed- or open-loop cycles). A well-designed product-level metric may arguably be aggregated as a measure for the entire economy, though, in practice, a product metric may not encompass all of the features linked to a circular economy (e.g., industrial symbiosis [IS]).

Desirable Qualities in a Circularity Metric

There are many potential uses of a circularity metric. Circularity metrics may be used as key performance indicators, as product labels, or as a basis for regulatory change. Combinations of metrics may also be used to support the shift toward eco-industrial developments (Geng et al. 2016b). By focusing on circularity as a social-scientific measure of the theoretical construct of circularity, we elect to evaluate circularity metrics against traditional methodological qualities, such as reliability and construct validity. Construct validity is defined as “the extent to which an operationalization measures the concept it is supposed to measure” (Bagozzi et al. 1991, 421), and hence a good circularity metric is capable of measuring circularity vis-à-vis *the fraction of new products that come from used products*. That is, a circularity metric should focus on the concept of circularity and not on other, ancillary concepts such as environmental performance or competitiveness. *Reliability* refers to the degree to which a metric gives similar values under consistent conditions (Riege 2003). For instance, if two separate measurements of circularity or the same product generate different results, the metric is considered to have low reliability.

Because of the social contexts within which a circularity metric is to be used, it is also important that it is robust against opportunistic behavior. There are plausible incentives for firms to try to present circularity values that are as high as possible. For instance, a high circularity value might be used to convince environmentally conscious customers to buy a product. Hence, we refer to the possibility of third-party verification in terms of the *transparency* of a metric. We expect that trade-offs exist between transparency and validity of the metric, given that detailed information about products and key processes probably relates to sensitive intellectual property.

One other way to reduce the risks of opportunistic behavior is to reduce the number of subjective judgments that are made when calculating circularity. In practice, judgments can involve the choice of suitable comparison values (such as the average life span of a product in a given industry) or the share of materials required to produce a product (such as industrial waste from upstream suppliers). To be robust against these types of problems, a metric should utilize *unambiguous methodological principles*. These principles should leave as little room as possible for judgments, focusing instead on literal interpretations.

We consider a high degree of *generality* of the metric to be desirable. Few products are perfect copies of one another, and there is a continuum of products from direct competitors to substitutes to completely different solutions to the same underlying customer need. The interpretation of the metric in comparisons of two similar products (e.g., two different bicycles) should ideally be the same as the interpretation of the metric in a comparison of two different products (e.g., a bicycle and a skateboard). Thus, for comparative purposes, a metric is preferable if the interpretation of it is independent of industry and technology. Because technology and products often change over time, this is also a precondition for useful comparisons of circularity over time in the same firm or industry.

Finally, metrics of low dimensionality (i.e., that translate circularity into a single number) are useful for correlation studies, customer prioritization, and managerial decision making. In contrast, in situations where separate circularity values exist for different materials within in a complex product, it is difficult to aggregate these values into an overall, summarizing value. We evaluate dimensionality in terms of the existence, consistency, and validity of *aggregation principles* for summarizing product circularity as a single value.

Existing Circularity Metrics

Circularity can be assessed at different spatial levels, ranging between macro (national, regional), meso (city, industrial park, and supply chain), and micro levels (company, product) (see Zhu et al. 2011) using different methods and techniques. Macro-level indicators measure the sociometabolic impact of a circular economy and are arguably better developed than micro-level indicators (Geng et al. 2012). For example, Haas and colleagues (2015) developed a circularity indicator based on the MFA approach and applied it to the European economy. MFA also underpins other efforts in China and the EU to develop economy-wide circularity indicators (Geng et al. 2011, 2012; Wang et al. 2012; Daniels and Moore 2001). The indicators currently being developed by the EC to monitor progress toward a circular economy are based on MFA.[1] MFA has reached maturity as a tool for measuring economy-wide direct material flows (see, e.g., Bringezu et al. 2003; Fisher-Kowalski et al. 2011; Allesch and Brunner 2015; Wood et al. 2009). At the meso level, MFA has been applied to measure IS in industries such as forestry (Karlsson and Wolf 2008), printed circuit boards (Wen and Meng 2014), highway traffic systems (Wen and Li 2010), and the agri-food industry (Pagotto and Halog 2015). Emergy-based assessments of energy and labor intensity have been applied to various industrial parks in China (Geng et al. 2014; Liu et al. 2015, 2016) and can be applied as supplement to MFA to measure the efficiency of IS within one industrial park.

The Ellen MacArthur Foundation has developed a metric that assesses circularity at product and company levels (Ellen MacArthur Foundation and Granta 2015). Their Material Circularity Indicator (MCI) is perhaps the most ambitious attempt yet to develop a product-level circularity metric. The MCI consists of two factors, the linear flow index and the utility factor. The linear flow index factor can be viewed as a particular variant of MFA. One potential drawback of focusing on mass flow relates to the combination of different materials and components into a single number. This creates difficulties in incorporating different types of material recovery (e.g., remanufacturing) into the metric. The Ellen MacArthur Foundation suggests an efficiency index for recycling processes to resolve this issue. However, the efficiency index is unable to differentiate between different types of product constituents (e.g., a refurbished 500-kilogram [kg] engine and the equivalent 500-kg recycled materials). The so-called tightness of material cycles (e.g., reuse vs. remanufacturing vs. recycling) has potentially significant implications for the effectiveness of material cycling, a point often acknowledged by the Ellen MacArthur Foundation. Further, the utility factor is calculated based on estimated average product life spans. This constitutes a judgment call and invites optimistic circularity estimations that are inconsistent with unambiguous methodological principles.

Other attempts have been made to assess circularity at the product level. The Cradle-to-Cradle Products Innovation Institute has developed a C2C certification framework that has been used to evaluate 159 companies and around 2,500 products. The framework performs impact assessments of products and services based on five key principles. These include: material selection and reutilization; the use of renewable energy in the production system; water stewardship; and social fairness (C2C 2014). This broad focus jeopardizes the construct validity of the framework as a metric for circularity. The material reutilization part, which shows similarities with the principles of a circularity metric, does not account for different types of material cycles (reuse, remanufacturing, and recycling) and different materials and components.[2]

Also, at the product level, a tool entitled REPRO (Remanufacturing Product Profiles) performs statistical analyses of different end-of-life (EoL) product scenarios based on a set of 82 criteria. REPRO allows designers to compare their products with others that have been successfully remanufactured with a view to improve remanufacturing rates. The tool is, however, weakly implemented (Gehin et al. 2008) and has, with regard to circularity, low construct validity given that reuse and recycling are excluded. Moreover, the tool does not measure actual remanufacturing rates, focusing instead on criteria that are likely to improve remanufacturing rates.

Scheepens and colleagues (2016) created a circularity metric for products based on life cycle assessment (LCA) (LCA has also been applied to circular economy constructs such as IS; see Mattila et al. [2012]). The Eco-efficient Value Ratio model assesses sustainability through three dimensions: costs, market value, and "eco-costs" (i.e., externalities). A product or service is considered to be "clean" when eco-costs are below a certain threshold. This means that products and services can be improved by either lowering externalities or by increasing a product's market value to prevent rebound effects. Whereas increasing circularity may be a means to reduce externalities, this metric does not specifically address circularity and can thus be considered to have low construct validity. Moreover, a thorough LCA that follows strict guidelines (International Organization for Standardizayion [ISO] 14044) (ISO 2006) often requires a year to complete and is challenging when introducing new products.

The circular economy index (CEI), developed by Di Maio and Rem (2015), is a more applicable metric. CEI measures circularity in terms of the ratio of recycled material value from EoL products compared to total material value in recycling processes needed to produce new versions of the same product. By focusing on recycling process efficiency, other forms of recovering materials are excluded, and the metric can thus be considered to have low construct validity as a product circularity metric.

Metrics that specifically target circularity at product level are further described in table 1. The table shows that none of the existing metrics score highly across all criteria. Whereas both MFA and the MCI provide useful starting points, their operationalization appears to be problematic. In the next section, we outline the structure of an alternative circularity metric that aims to better fulfill corporate needs and stakeholder expectations.

Units

The units used to calculate circularity are a fundamental aspect of any circularity metric. As noted in the previous section, suggested units include mass, emergy, and time (duration in use). Each of these units creates challenges at the product level when seeking to distinguish between different types of materials and material cycles. In essence, the question is how to select units that allow for the aggregation of two or more materials and/or product components into a single value of circularity. To aggregate materials and parts in a theoretically robust manner, we need a source of information regarding the relative value (economic or otherwise) of circulating different product parts. Such information should preferably be consistent across time and context, to allow for comparisons of two similar products, different substitute products, and products that are produced or sold in different localities.

If MFA is the preferred approach, it may be possible to aggregate by allocating factor weights to different materials and components, such that 1 kg of iron is counted as less important than an equal mass of indium or reused touch screens. This could be done by compiling a material weights table with the help of an expert committee, based on each material's relative scarcity (or some other criterion). However, this particular approach is unlikely to be robust against the following challenges:

- The relative scarcity of materials often changes as more material becomes accessible, or if substitutes reduce the need for the material in question;
- There is no consensus on scarcity—different sets of practitioners demonstrate different levels of awareness regarding critical materials (Peck et al. 2015; Whalen and Peck 2014);

Table 1 Summary of reviewed product-level circularity metrics

Metric	*Construct validity*	*Reliability*	*Transparency*	*Generality*	*Aggregation principles*
Material Circularity Indicator (Ellen MacArthur Foundation and Granta 2015)	Medium Measures use of virgin material and resultant waste to landfill or energy recovery. Loop tightness not considered (though mentioned as potential future development).	Low Many data inputs required that might be uncertain or depend on several factors, such as ex ante assumptions regarding the destination of a product after use and the efficiency of recycling processes.	Low Required data (includes bill of materials of all components) normally considered confidential. Difficult to verify by a third party.	High Indicator can be applied to wide range of products.	Medium Circularity represented by a single value ranging between 0 and 1. Acknowledged difficulty weighing different types of cycles. Not applicable to every product, only for reference products that represent a group of similar products.
Eco-efficient Value Ratio (Scheepens et al. 2016)	Low Measures environmental impacts per euro spent, not necessarily focusing on closed material loops, but implicitly taking into account circular economy effects as sharing, reusing, and renewable energy.	Low Requires many data inputs for robust outputs. Environmental impacts during usage included, although uncertain: depends on the condition of use.	Medium Verifying eco-cost of a product might be difficult because of confidentiality. Content of product may be difficult to trace in upstream supply chain.	High Ratio can be applied to wide range of products.	High One easily understood value per product for specific use (functional unit).
Circular economy index (Di Maio and Rem 2015)	Low Measures recycling rates, excluding all other circular economy effects and loops.	High Detailed data on all products and components entering the recycling facility are required—information not commonly available. Index is computed per recycler, outputs can differ significantly depending on product assortment of recycler.	High If index is based on standards (e.g., material passports).	Low Only applicable to recyclers with same assortment.	N/A

(Continued)

Table 1 Continued

Metric	*Construct validity*	*Reliability*	*Transparency*	*Generality*	*Aggregation principles*
REPRO (e.g., Gehin et al. 2008)	Low Reuse and recycling are excluded	Low Dependent on ex ante assumptions regarding potential future remanufacturing.	Medium Requires detailed information about product parts, interfaces and processes.	Medium Applicable to many industries, but only remanufacturing loops.	Low Does not enable aggregation of different types of (non-reman.) cycles into a single value.
Material reutilization part - Cradle-to-cradle (C2C 2014)	Medium Loop tightness not integrated (though energy recovery considered special case).	Unknown We have not been able to find enough detail to properly assess this. Includes ex ante assumptions regarding recirculation.	Low Required data (include bill of materials of all components) normally considered confidential. Difficult to verify by a third party.	High Can be applied to wide range of products.	Low Does not allow for a fine-grained value summarizing degree of circularity (five ranks). No theoretical justification for weights for different combinations of cycles and materials

Note: REPRO = Remanufacturing Product Profiles; N/A = not applicable.

- New materials are continually invented and introduced; and
- At the component level, there are simply too many variations to tabulate and provide relative weights for. This is especially true for complex products where new components are created continually.

We argue that the economic value of recirculated elements is a reasonable unit upon which to base a robust and theoretically consistent aggregation principle. Through market interactions, aggregated relative demand and supply can be gleaned from the price system. This approach has the following benefits:

- Prices change as relative scarcity changes;
- New materials acquire prices as soon as they are utilized in products; and
- Although prices are not always available for proprietary components, there are reasonable ways to estimate the shadow price of components, assuming that firms are profit-seeking entities.

The idea of prices as information carriers is not new and has repeatedly been expressed in several schools of economic thought, including Austrian economics (Von Hayek 1945[3]; Menger et al. 1963); neo-classical economics (e.g., Mankiw 2015; Cowen and Tabarrok 2010); and financial economics (Fama 1970). Similar ideas appeared in John Stuart Mill's work (Mill 1848) and the concept of natural prices featured in Adam Smith's Wealth of Nations (1776).

Although serving as an excellent source of information, it is important to remember that prices will never convey *perfect* information regarding economic value as well as uses for and the scarcity of goods. Prices can only convey the best information available to any collection of market actors (Von Hayek 1945). In other words, prices cannot provide information that is currently unknown by any part of the market. Further, prices only carry information regarding exchange value, which is only one aspect of economic value. Value-in-use is another form of economic value (e.g., Smith 1776). In the cases where market failures occur, these will also distort the information conveyed by prices. The notion that fully perfect information is conveyed in market prices under competition is inconsistent with the concept of market equilibrium (Grossman and Stiglitz 1980). Finally, for market prices to convey much information regarding demand and scarcity, there must exist a (thick) market for the good. Such markets may not always exist for recirculated product components or for recycled materials.

Hence, in order to make an economic value-based circularity metric applicable in practice, we must satisfice with approximations of economic value. In the next section, we show how a cost-based estimation of economic value can be implemented as the basic unit used for aggregation.

A New, Product-Level Circularity Metric

In the sections above, we argued for the use of economic value as the basic unit for aggregating product parts in a product-level circularity metric, where circularity is defined as *the fraction of a product that comes from used products*. Reasoning from this, we outline a metric based on the ratio between recirculated and total economic product value. The circularity metric ranges between 0 and 1 (or 0% to 100% recirculated parts). This is expressed in equation (1), where *c* denotes product-level circularity:

$$c = \frac{economic\ value\ of\ recirculated\ parts}{economic\ value\ of\ all\ parts} \qquad (1)$$

There are several ways to estimate economic value. A common approach is to use market prices. Although prices only capture the exchange value aspect of economic value, and fail to account for externalized costs and benefits, they are, in practice, often the best available signal of the relative scarcity of, and demand for, many goods. However, there may not exist an active market and consequent market prices for many product parts that can potentially be recirculated. In the interest of making estimations that are practically feasible, we propose the use of a cost-based estimation of economic value.[4] By "costs," we refer to the cost to the vendor of a product for which circularity is calculated. Cost-based estimations are likely to correspond roughly to (counterfactual) prices if the firm is profit-seeking or trying to survive under competition. This is based on the assumption that a firm would likely try to procure a part externally if their judgment of market prices indicated that the latter would be significantly lower than their own costs of producing the part. Given that costs are used for both the numerator and denominator, the estimation is neutral to differences in product margins achieved by different vendors. A cost-based approach will also simplify comparisons of in-house and outsourced collection, inspection, and cleaning activities.

Circularity can be calculated by the iterative application of rules for each combination of product parts and work applied to product parts in the value chain. These rules are expressed in equations (2) and (3). A side effect of this approach is that circularity can be calculated for all vendors in the value chain, including component suppliers, original equipment manufacturers, and retailers. Hence, downstream actors must know the circularity values of upstream actors in order to calculate the circularity of their own product. That is, there is no incentive to calculate circularity for only a small and optimized part of the value chain. The iterative application of equations (2) and (3) for all sequential combinations of product parts will garner the same results as the direct application of equation (1). However, equations (2) and (3) are likely to be more feasible in practice and serve to highlight the specifics of how to attribute value and circularity to a product part from different types of processes. They also allow value chain actors to share circularity data without sharing strategically sensitive marginal data. Note that in each combinatory step, both circularity (c) and value (v) are updated. These updated values are then used in the next application of equations (2) and (3), when the previously combined product parts are combined with a third product part, and so on.

The circularity of a combination of two product parts is calculated using equation (2). We use the index number (1, 2) to denote product parts; c to denote the circularity of each part; and v the value of each part. We explain the estimation of c and v for newly introduced product parts after introducing equations (2) and (3).

$$c_{1\&2} = c_1 \times \frac{v_1}{v_1 + v_2} + c_2 \times \frac{v_2}{v_1 + v_2} \tag{2}$$

Equation (3) is used to calculate the value of a combination of two product parts:

$$v_{1\&2} = v_1 + v_2 \tag{3}$$

Both equations are applied from the bottom up, combining ever-refined product parts one after another. Thus, values (c, v) for one part (here assumed to be c_1 and v_1) will usually follow from earlier applications of equations (2) and (3). The question that remains is how to estimate c and v for newly introduced product parts. The respective values for newly added product parts (here assumed to be c_2 and v_2) and ultimately for c_I and v_I must be estimated from first principles. When no circularity values are available, c for a product part can be calculated using the principles expressed in equation (1). "Parts" in equation (1) then refers to parts of the relevant product part (i.e., parts of product part i, not all parts of the product). In equation (4), this is expressed in a format that is easier to operationalize. r_i denotes the economic value of recirculated parts of the new product part, and n_i denotes the economic value of nonrecirculated parts (i.e., virgin materials for the relevant product part i):

$$c_i = \frac{r_i}{r_i + n_i} \tag{4}$$

The economic value (r) of recirculated parts sourced by the firm is calculated using equation (5):

$$\begin{aligned} \mathrm{r} = \max[&\text{cost of parts including handling costs such as} \\ &\text{procurement and logistics costs; sum of market prices for} \\ &\text{virgin materials contained in the product; secondhand} \\ &\text{market price for used material or component}] \end{aligned} \tag{5}$$

The value of virgin parts (n) sourced by the firm is calculated using equation (6):

$$n \;=\; \mathit{costs\ of\ non-circulated\ parts} \tag{6}$$

The value (v) of a newly introduced product part is therefore the sum of the values of the recirculated part and the virgin part of the introduced product part. This is expressed in equation (7):

$$v_i = r_i + n_i \tag{7}$$

For activities that do not involve any material except the original product part, only the value of the combination of activity and component changes, not the circularity. Examples of activities that only include work include some types of inspection, assembly, and sales. This distinction is important given that it makes the circularity metric neutral to in-house and outsourced value adding activities, such as cleaning, inspection, and collection.

When work is done on a product part, its circularity (c) stays the same whereas its value (v) increases. This can be shown using equations (2) and (3) and by treating the work done on a product part as a combination of the product part and a second product part that constitutes work done. For the work part, we define c_2 as per equation (8) and v_2 as the cost of the activity (equation 9):

$$\mathrm{c}_2 = \mathrm{c}_1 \tag{8}$$

$$v_2 = \; \mathit{cost\ of\ the\ activity} \tag{9}$$

Most value-adding activities include material and work elements. To calculate the resulting c and v for a combined product part after such an activity, we divide the activity into two steps: a material part and a nonmaterial part (work). The material part is always applied first and the work part second, because the order influences the resultant circularity value.

Simple Example

A firm wants to calculate the circularity of a plastic toy product. They purchase recycled plastic for €1,000. The recycled plastic cost is similar to virgin plastic of the same type.

Given that no circularity value was provided with the purchase of the recycled plastic, the firm calculates it using equation (4) and needs to provide values for r and n. From equations (5), (6), and (7), they calculate $r = €1{,}000$ and $n = €0$. This gives $c_I = 1$ and $v_I = €1{,}000$.

Remolding plastic into toys and transporting toys to retailers consumes some material, in this case packaging for transport. It also adds value to the plastic. The combined material cost of transport is $v_2 = €50$ and work an additional $v_3 = €2{,}000$. The material used has a circularity value of zero, given that nonrecycled material is used for packaging.

The firm adds the material part first, using equation (2). This results in $c_{1\&2} = 1 \times 1{,}000/(1{,}000+50) + 0 \times 50/(1{,}000+50) \approx 0.95$, and equation (3) results in $v_{1\&2} = v_I + €50 = €1{,}050$. This is interpreted as follows: 95% of the material used to provide molded plastic toys to retailers is recirculated.

When the firm applies the work part of the activity, the circularity remains unchanged, but the value (v) of the product increases (attributed to having given shape to recirculated materials and by redistribution) to $v_{..\&3} = v_{I\&2} + €2{,}000 = €3{,}050$. At this point, the increased value ($v_{..\&3}$) only matters for circularity calculations at a later stage ($c_{\&..i}$), in cases where more material is consumed before a purchase is completed (as per equation 2).

Advanced Example

Another firm collects and remanufactures used starter engines. They receive used engines for free as part of a deal with authorized service centers. Before selling them, two processes are completed: washing and inspection (to retain high-quality starter engines) and remanufacturing (some drilling, replacing a few bolts). All materials except used starter engines are of virgin type.

The used starter engines have a circularity of 100%, $c_1 = 1$. We use equation (5) to estimate their value. With regard to sourcing costs for the starter engines, the (virgin) market price of raw materials contained in starter engines, or the market price of the used engines, selecting the maximum (according to equation 5) unfortunately involves a judgment call. Costs include logistics costs (which should be added as an activity using equation 2) and arguably some sort of discount or service provided at service centers in exchange for the starter engines. If there is a secondhand market for used starter engines, the firm could use that to estimate the market value of a used starter engine and add the logistics activity to this value (using equation 2). Whereas it is likely that secondhand market exists, let us assume that this is not the case to make matters more complicated. The firm decides to set the value of recirculated starter engines using raw material prices. The virgin price of the material is $v_1 = €8$ (€4 per starter engine) for steel and some copper. Logistics costs include €1 for packaging and €5 for work done per starter engine. We add the packaging (material) using equations (2) and (3), for $c_{1\&2} = 0.8$ and $v_{1\&2} = €10$ (€5 per starter engine). We add the admin and logistics (work) using equations (8) (or equation 2) and (9), resulting in $c_{..\&3} = c_{1\&2} = 0.8$ and $v_{..\&3} = €20$ (€10 per starter engine).

Disassembly and inspection uses a significant amount of work (€10 per successfully remanufactured starter engine). During this process, it is uncovered that some used starter engines are not reusable and will be recycled; for simplicity, we assume 50%. The value of reusable starter engines includes therefore the value of two used starter engines and the amount of work for disassembly and inspection. Because no direct material, except for the used starter engines, is used in this process, the circularity $c_{..\&4} = 0.80$ stays the same following equation (8). The value is increased to €30 ($v_{..\&4} = 30$).

For the remanufacturing element, there is considerable work done ($c =$ n/a, $\Delta v = €30$) and some amount of added virgin material in the shape of bolts ($c = 0$, $\Delta v = €1$). Adding the material first, equation (2) gives $c_{..\&5} = 0.8{\times}30/(30{+}1) + 0{\times}1/(30{+}1) \approx 0.77$ and $v_{..\&5} = €31$. Adding work done, equation (2) gives $c_{..\&6} = 0.77{\times}31/(31{+}30) + 0.77{\times}30/(31{+}30) \approx 0.77$, and $v_{..\&6} = €61$. Each subsequent step in the above calculations is summarized in table 2 below.

If the firm were to have valued (or procured) used starter engines at the secondhand market price of €30 per unit ($v_1 = 2{\times}€30 = €60$), the result after remanufacturing would have been $c_{..\&6} \approx 0.96$ and $v_{..\&6} = €113$. This is significantly higher than the circularity value that results from the raw virgin material value estimation. For remanufactured starter engines, we suspect that this higher value is likely to be more correct in the sense that it is more consistent with the rules we proposed in equation (5).

Discussion

In the section above, we sought to outline a scientifically robust circularity metric for products with a high level of construct validity, reliability, transparency, and generality, taking special note of the principles for aggregating different cycles for different product parts into a single value. The metric focuses exclusively on circularity vis-à-vis products' composition in terms of virgin and recirculated materials and the activities required to recirculate materials. By excluding other criteria such as environmental impact, the proposed metric achieves good construct validity for product circularity. By utilizing a cost-based approach, the metric allows for different actors to calculate circularity that reliable and robust against market dynamics and innovation. The metric can be applied across different product categories and has a high degree of generality. It is formulated in a manner that allows for the aggregation of value chain recirculation activities across firm boundaries without sharing sensitive data.

The metric has other potential benefits. It may be used as a product label to inform consumer choices, and it may be utilized as a criterion for procurement activities between companies or within the public sector. To this end, the metric can potentially function as a springboard for a transition to a circular economy in that it can allow customers to elicit demands for products with a higher degree of circularity and encourage manufacturers to

Table 2 Summary of the circularity calculations in example 2 where *c* denotes the circularity and *v* the value of the part

Prev. c	*Prev. v*	*Added part c*	*Added part v*	*Updated c*	*Updated v*	*Added part or activity*
—	—	1.00	8	$c_1 = 1.00$	$v_1 = 8$	Two used starter engines
1.00	8	0.00	2	$c_{1\&2} = 0.80$	$v_{1\&2} = 10$	Packaging needed in return transport
0.80	10	0.80	10	$c_{..\&3} = 0.80$	$v_{..\&3} = 20$	Admin and logistics work
0.80	20	0.80	10	$c_{..\&4} = 0.80$	$v_{..\&4} = 30$	Disassembly and inspection
0.80	30	0.00	1	$c_{..\&5} = 0.77$	$v_{..\&5} = 31$	Bolts
0.77	31	0.77	30	$c_{..\&6} = 0.77$	$v_{..\&6} = 61$	Remanufacturing work

engage in material recirculation activities. The metric also has potential utility as a key performance indicator that may be used to benchmark and compare companies and industries. To this end, a range of business stakeholders can leverage different types of resources with the aim of promoting circularity within the private sector (Geng et al. 2012). Here, we assume that the metric can gain traction as an international standard and thus be taken up within different industries as part of their corporate reporting activities.

Limitations

Our proposed metric does not contain information regarding issues that are linked to the circular economy, including toxicity, job creation, environmental impacts, and the way products are sold (e.g., product-service systems). The narrow focus of our metric may be viewed as a weakness or as a strength (in terms of specificity). In practice, however, the specificity of our proposed metric means that other indicators and metrics must be used to gauge other aspects of product quality (e.g., LCA to quantify environmental impacts). This was our aim at the outset. That is, the circularity metric was designed to have a high level of construct validity. Given the plethora of extant indicators and product labels that can be used to assess other aspects of product quality, we do not foresee this level of specificity as a problematic.

It is challenging to estimate the total cost of a product part relative to other product parts in situations where manufacturers procure components in a way that implies ongoing costs (e.g., an automaker that leases batteries from a supplier). The reason is that the economic value parameter (v) of the leased product part is dependent on lease duration and is therefore potentially initially unknown. To correct this issue, it may be possible to estimate the life span of a product or leased component similar to the MCI approach. However, this would sometimes introduce the same weakness to the metric as those inherent to approaches that estimate life spans on an ex ante basis: It would necessitate a judgment call regarding life spans or lease durations unless these are specified in the agreement. This may allow for opportunistic behavior, jeopardizing the reliability, transparency, and generality of the metric. Note that these problems pertain only to cases where a producer leases parts of a product, not to when a final product is leased by the end customer. One possible solution to the producer-leases-a-product-part situation that does not require judgment calls is to supply two circularity values, one for the main product and one for the leased part.

The metric is currently limited to measure the degree of recirculated direct material in the product weighted by direct costs, including material and labor costs. Indirect resources used in the production process, such as equipment, tools, water, chemicals, energy, etc., are not included. In theory, the circularity of indirect resources could be calculated and added, which will provide a more complete and comprehensive picture of the product's circularity. Determining circularity of resources is, however, not straightforward and questions arise, like what is circular energy (solar, nuclear, etc.) and how far back should the metric go (energy used to produce the solar panels?). Including these aspects will complicate the tool and increases the computational effort significantly. Our goal of the metric is, however, to provide an accurate, yet easy to implement, metric. Ancillary costs are implicitly included when the product is bought by the downstream partner. The value attributed to the bought part equals the sales price (see equation 5), which generally includes depreciation of equipment, indirect costs, and added value.

Further, our proposed metric requires significant cooperation across the value chain. Whereas the metric is specifically designed to avoid situations where value chain actors share confidential data, it still requires upstream actors to provide circularity values for products used downstream (or at least the information required to calculate it). Achieving such collaboration may constitute a barrier to introducing the metric in certain firms, particularly for system integrators.

One other weakness of the metric is that it treats two products with different life spans as equals. That is, regardless of whether two products within the same product category have different life spans, the metric would calculate their circularity as equal if they are produced from the same fraction of recirculated material (assuming all ancillary costs are equal). This is problematic given that product life extension has been billed as fundamental to the realization of a more circular economy (Bakker et al. 2014) given the need for material recirculation to proceed as part of a moderately slow cycle (Webster 2013). Again, one may correct this issue by estimating product life spans for all products and including a weighting factor within the metric to give products with longer life spans a higher degree of circularity. However, the same risks for opportunistic behavior as those noted above would weaken the metric. Another solution is to let circularity denote only the fraction of recirculated product parts and accept the need for complementary indicators. These may include indicators that measure environmental impacts or the degree to which product circularity influences the transition toward a circular economy.

The cost-based approach to estimating economic value is susceptible to biased estimations given that external costs for certain activities or use of materials sometimes exist. Although it may take considerable time and innovation before all such externalities are allocated proper valuations, there are no principal barriers to include such external costs as costs of parts in the metric. However, until such valuations are readily available, we caution that the arbitrary inclusion of external costs may reduce the reliability and legitimacy of the metric. In other words, the accounting cost approach used here may be imperfect with regard to externalities, but consistency and reliability may trump accuracy in terms of usefulness of the metric. Further, as markets or taxes are introduced for previously externalized costs, accurate costs will be automatically included in accounting costs.

Finally, prices (and therefore costs) often fluctuate rapidly. If product circularity is to be used for procurement or policy decisions, there are benefits of a more stable metric. A possible solution to this may be found in some sort of averaging of the estimations of economic value, for instance, by a rolling average approach. However, the specific details of such a solution are yet to be determined.

Research Opportunities

The metric proposed within this article has a high degree of construct validity (i.e., it focuses solely on product-level circularity) and is based on economic value. The pursuit of a metric that is formulated this way creates opportunities for future research. First, the metric was developed with regard for five criteria (construct validity, reliability, transparency, generality, and aggregation principles) that are critical for scientific robustness. The further development of the metric must, however, aim to fulfill other criteria. One important criterion is *legitimacy* among key stakeholders, which, in this case, includes the private sector, governmental organizations, standards agencies, public procurement professionals, and environmental agencies. Private sector stakeholders are particularly important in that the metric must be further developed in collaboration with manufacturing companies from different industries and at different positions in the value chain. One avenue for future research is to examine how collaborative research can contribute to the further development, testing, implementation, and standardization of a robust and legitimate circularity metric. Another is to explore the possibility of cheaper and more *lightweight approximations* of circularity in various industries. For instance, the share of total procurement costs attributed to recycled materials might be highly correlated to product circularity in some industries. Such a shortcut to estimating circularity could greatly facilitate the adoption of the metric and can gain significant legitimacy if tested initially against the more complete circularity metric. Related, validated approximations and heuristics to handle situations when circularity values are not available from upstream suppliers would further reduce barriers to implementation.

A fully functioning metric can be used to *examine the relationship between product circularity and other variables*. The shift to circular principles has been billed as a potential source for cost savings (Webster 2013; Stahel 2006; Heese et al. 2005; Giuntini and Gaudette 2003). Future research should examine the relationship between *production costs* and circularity. If, for instance, the labor costs linked to remanufacturing are significantly higher than those linked to other material recirculation strategies (or the use of virgin materials), a strong case can be made for policy interventions that create incentives for remanufacturing. These may take the form of economic instruments (e.g., subsidies) or fiscal reforms. The latter have been billed as an important stimulus for the transition to a circular economy, particularly as regards reduced labor taxes and higher taxation for the use of raw materials (Stahel 2006, 2013).

The circular economy has been framed as a source of local/regional job creation (Stahel 2006, 2013; Webster 2013). Studies that investigate the relationship between a high level of product circularity and *employment* would elucidate key findings on this hypothesis and also generate knowledge that is of interest to both governments and industrial stakeholders.

A further claim is that an increased degree of circularity is a means to make *environmental improvements* (Kama 2015; Webster 2013; Stahel 2006, 2013) and boost resource productivity (Webster 2013). The metric could again form the basis of research that examines this relationship through other well-established metrics such as LCA.

The metric could be used to examine *willingness to pay* for and perceived *attractiveness of products* with a high degree of circularity among different types of customer segments. This relationship has been documented for remanufactured goods within certain product categories (Michaud and Llerena 2011; Camacho-Cuena et al. 2004), but not across industries and for other material recirculation strategies. An improved understanding of customer preferences would be of benefit to product developers, corporate strategists, marketing professionals, and even for policy makers that are interested in promoting "circular" consumption.

The metric proposed here could be used to examine *different types of business models*. The metric in its current formulation pays no attention to the way products are sold, despite the fact that business models are widely seen as important for the transition to a circular economy (Tukker 2015). Hence, a further line of investigation would be to examine associations between business model characteristics and circularity.

One may also examine ways to include *product life extension* within a metric without compromising on construct validity, reliability, transparency, and generality. Here, it may be possible to develop two connected indicators—the current formulation, which functions on a post hoc basis using actual product data; and a complementary metric that functions on an ex ante basis based on future projections of product longevity (a similar approach could be used to reward longevity in servitized business models).

Finally, researchers could examine ways to aggregate the proposed metric proposed to *gauge the circularity of entire industries*. To this end, it may be necessary to combine our metric with other measures of circularity that are applicable to other aspects of circularity and spatial scales (e.g., MFA analyses of IS). By combining metrics in this way, it may be possible to measure circularity at meso and macro levels in a more nuanced manner that is useful for policy makers and governing bodies that have a mandate to govern at national and regional levels.

Conclusion

We began this article by noting that there is an urgent need for metrics that quantify product-level circularity both to critically evaluate and to facilitate a transition toward a more circular economy. We evaluated existing circularity metrics based on five dimensions: construct validity; reliability; transparency; generality; and the principles used for aggregating different cycles for different product parts into a single circularity value. We found several limitations in extant circularity metrics, particularly with regard to the principles for weighting and aggregating differing product parts into a single circularity value. We proposed a novel circularity metric based on the use of product parts' economic value as a basis for aggregating recirculated and nonrecirculated elements into a combined measure of product circularity. This is calculated by iteratively adding the economic values and circularity of product parts and value chain activities. The metric can enable customers and producers to contribute systematically to an increased degree of material recirculation. It can serve as a solid foundation for further research such as the association between circularity and other important variables, including job creation, competitive advantage, and environmental sustainability.

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Notes

1. See EU action plan for circular economy (EC 2015a) and also the Resource Efficiency and Raw Material Scoreboard: http://ec.europa.eu/environment/resource_efficiency/documents/re_scoreboard_2014.pdf.
2. Except for a special rule regarding energy recovery, which is not counted as material reutilization if the firm aims for certain C2C ranks (i.e., gold, platinum).
3. An indication of the mainstream acceptance of this idea is given by the article's (Von Hayek 1945) selection as one of the top 20 articles from the first 100 years in American Economic Review (Arrow et al. 2011).
4. This approach has some similarities with Marx's value theory (Marx 1894, Capital, vol 3, part 7, ch 48). An interesting avenue for future research is to examine which of the limitations of that value theory might create limitations in the interpretation of the circularity metric proposed here.

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