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Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations

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ABSTRACT

So far, organizations had no authoritative guidance on circular economy (CE) principles, strategies, implementation, and monitoring. Consequentially, the British Standards Institution recently launched a new standard "BS 8001:2017 – Framework for implementing the principles of the circular economy in organizations".

BS 8001:2017 tries to reconcile the far-reaching ambitions of the CE with established business routines. The standard contains a comprehensive list of CE terms and definitions, a set of general CE principles, a flexible management framework for implementing CE strategies in organizations, and a detailed description of economic, environmental, design, marketing, and legal issues related to the CE.

The guidance on monitoring CE strategy implementation, however, remains vague. The standard stipulates that organizations are solely responsible for choosing appropriate CE indicators. Its authors do not elaborate on the links between CE strategy monitoring and the relevant and already standardized quantitative tools life cycle assessment (LCA) and material flow cost accounting (MFCA).

Here a general system definition for deriving CE indicators is proposed. Based on the system definition and the indicator literature a dashboard of new and established quantitative indicators for CE strategy assessment in organizations is then compiled. The dashboard indicators are mostly based on material flow analysis (MFA), MFCA, and LCA. Steel cycle data are used to illustrate potential core CE indicators, notably, the residence time of a material in the techno-sphere (currently 250–300 years for steel). Moreover, organizations need to monitor their contribution to in-use-stock growth, a central driver of resource depletion and hindrance to closing material cycles.

1. Introduction

Over the last decade, the circular economy (CE) concept has spurred a large movement towards the decoupling of economic development from natural resource use. Circular economy regulations at the national and international levels are now in place in China ("Circular Economy Law of the People's Republic of China," 2008; McDowall et al., 2017; Yuan et al., 2006; Zhijun and Nailing, 2007) and in the EU (European Commission, 2015). CE was acknowledged as a significant concept to facilitate the efficient and cyclical use of resources by the G7 Alliance (G7 Ministers, 2016). For the national, regional, and industrial park levels comprehensive sets of CE performance indicators exist (EASAC, 2016; Geng et al., 2012; Li et al., 2010; Su et al., 2013), though most of these indicators are actually resource efficiency metrics. So far, however, only some concrete (e.g., EMF, 2015a; Griffiths and Cayzer, 2016; Linder et al., 2017; Saidani et al.,2017) and no authoritative guidance on CE principles, strategies, implementation, and monitoring was given at the organizational and product system levels (EASAC, 2016; Ghisellini et al., 2016; Giurco et al., 2014; Saidani et al., 2017).[1] To fill that gap the British Standards Institution has developed and recently, in May 2017, launched a new standard "BS 8001:2017 – Framework for implementing the principles of the circular economy in organizations − Guide" (BSI, 2017a).

This work offers a critical appraisal of the BS 8001:2017 from the perspective of environmental systems analysis (Section 2), a dashboard of existing and new CE performance indicators at the organizational and product system levels (Section 3), quantitative examples of CE indicators and constraints for the bulk materials steel, cement, and aluminum (Section 4), and a few closing reflections (Section 5). For each of the subtopics the relevant literature is summarized separately. The remainder of Section 1 provides background information.

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[1] Organizations can be companies, corporations, authorities, charities, institutions, and more (BSI,2017).

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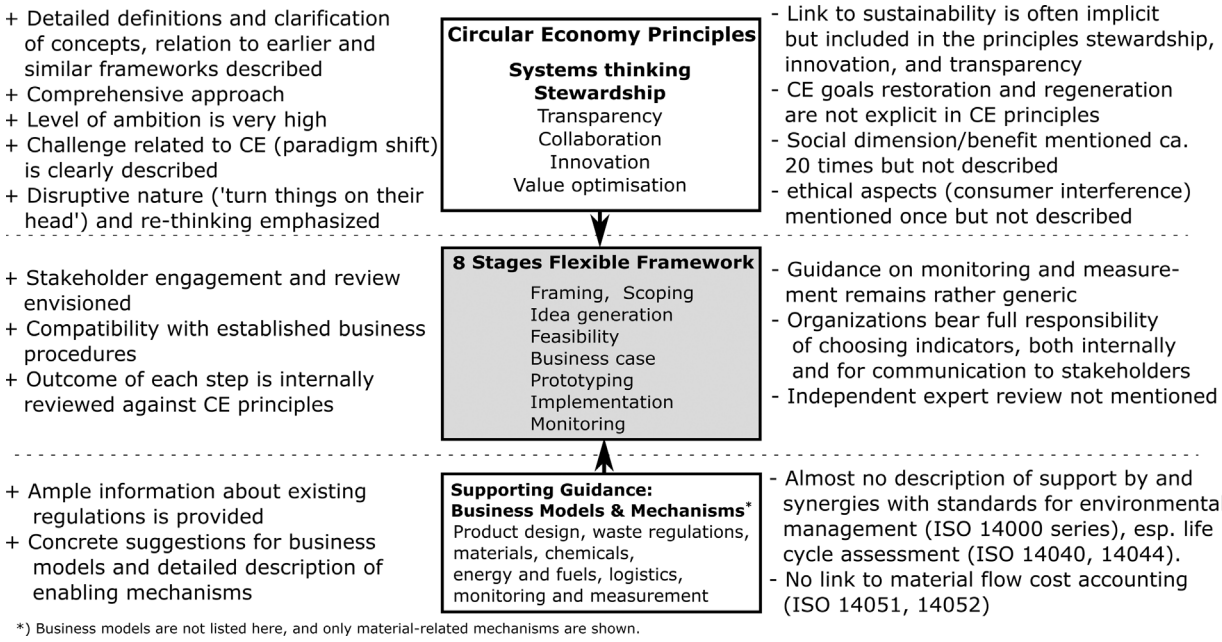

Fig. 1. Overview of the structure and the major categories used in the Circular Economy Standard BS 8001:2017 (middle), as well as a list of strengths (left) and weak points (right) of the standard in light of its overall ambition.

1.1. Circular economy, sustainable development, and the need for a standard

At the practical level, the CE framework is a combination and acceleration of strategies developed and tested under different existing systems approaches (EMF, 2015b). At the intellectual level, it can be seen as *umbrella concept* offering a new framing of existing strategies "by drawing attention to their capacity of prolonging resource use as well as to the relationship between these strategies" (Blomsma and Brennan, 2017). The exact relation between CE and sustainable development remains ambiguous (see Geissdoerfer et al. (2017) and Sauvé et al. (2016) for a detailed comparison of the two concepts) but there is a general understanding that both CE and sustainable business practice require a systems perspective on the role of businesses in the wider system of stakeholders and the environment (Murray et al., 2017). In China "circular economy (CE) has been chosen as a national policy for sustainable development" (Geng et al., 2012).

CE can be seen as part of a wider movement towards sustainable business practice (Kopnina and Blewitt, 2014). "The circular economy is not a new concept. It blends the principles of multiple schools of thought, some of which date back to the 1960s" (BSI, 2017a). The intellectual roots of CE include the 3R principle (reduce, reuse, recycle), regenerative design, performance economy, cradle-to-cradle, blue economy, green growth, natural capitalism, and biomimicry (BSI, 2017a; EMF, 2013; McDonough and Braungart, 2002) as well as the scientific fields industrial ecology, industrial symbiosis studies, and ecological and environmental economics (Andersen, 2007; Ghisellini et al., 2016). The evolution of the CE concept, its links to established research fields, and its current implementation in national policy in different countries have been described in detail (Banaité, 2016; BSI, 2017a; Cullen, 2017; Geissdoerfer et al., 2017; Ghisellini et al., 2016; McDowall et al., 2017; Murray et al., 2017; Su et al., 2013; Winans et al., 2017). The CE describes a theoretical optimum, similar to a 100% mass, energy, or exergy efficient system (Cullen, 2017). It is a counter-principle to the often prevailing disposal-after-use consumption pattern and to uncapped growth of in-use stocks. Our current socioeconomic metabolism is far away from a closed cycle: Globally, in 2005, about 62% of all raw materials processed by the global economy were throughput, and the complement, about 38%, were added to stock, but only about 6.5% of the materials processed stemmed from recycled waste or scrap (Haas et al., 2015). The eventual impact of the CE movement on closing material cycles is yet unknown. A recent assessment of CE strategies finds a positive but limited effect on raw material demand (Fellner et al., 2017), and another study demonstrates that the global implementation of core CE strategies can lead to savings of 6–11% of the energy used to support economic activity (Cooper et al., 2017). An estimate of the impact of material efficiency in the steel cycle on material flows and GHG emissions, which includes more ambitious changes than those investigated by Cooper et al., shows that, in case of a quick strategy roll-out, a 50% emissions cut could be possible (Milford et al., 2013). In that case no new blast furnace would need to be erected for the next 60 years. It was argued that rebound effects (Zink and Geyer, 2017) and demonstrated that labor taxes (Skelton and Allwood, 2013) may partly offset the theoretical gains of CE strategies.

To seize the resource and greenhouse gas (GHG) emissions savings potential of CE strategies their underlying principles must be integrated into both: national policy and legislation and business practice (Lieder and Rashid, 2016). Linking CE with business practice requires specific business models supported by a framework capturing the CE principles (Lieder and Rashid, 2016; Witjes and Lozano, 2016). Mendoza et al. (2017) assess four existing business frameworks (sustainable business model innovation, closed-loop systems, product-service systems (Tukker, 2015), and sustainable product design) against the CE goals formulated by the Ellen MacArthur Foundation (EMF) (EMF, 2015b). They find that no business model is compatible with or contains all CE goals and conclude that further framework development is needed.

Casting the CE framework into an international standard moves CE strategy development and implementation to a new level of relevance and bindingness as it provides an authoritative clarification of the scope, principles, and mechanisms of the CE. A CE standard will make the concept operable for organizations, which is needed as a complement to national policy and legislation (Lieder and Rashid, 2016). In 2017, the British Standards Institution has published the world's first CE standard "intended to help organizations and individuals consider and implement more circular and sustainable practices within their businesses, whether through improved ways of working, providing more circular products and services or redesigning their entire business model and value proposition" (BSI, 2017a, P1).

1.2. Development and function of BS 8001:2017

The circular economy standard BS 8001:2017 was developed during several stages (BSI, 2017b). Initial research, carried out by BSI in 2013, identified "more than 200 standards related to specific areas of waste prevention and resource management but no formal standards that defined or focused entirely on the circular economy" (BSI, 2017b). After a stakeholder forum held in 2014, BSI established an expert and stakeholder committee (SDS/1/10) responsible for standardization of sustainable resource management, which decided to develop a framework standard for implementing the principles of the CE in organizations (BSI, 2017b). In November 2015, a smaller drafting panel was formed to develop the actual standard within an 18-month period (BSI, 2017b). "A variety of businesses and organizations from differing sectors and sizes were consulted during this piloting phase, both within the UK and overseas, to ensure the standard met their needs for practical guidance and recommendations" (BSI, 2017b). The draft standard was also subject to public consultation. From the document and the working process description it becomes clear that a lot of effort has been put into this standard.

The standard is applicable to any organization, regardless of its location, size, sector and type (BSI, 2017b). It is a guide, meaning that it provides advice and recommendations, next to a set of definitions and clarifications. It does not contain requirements that must be met, which means that it is not possible to claim compliance to the standard or undertake some form of certification to it.

2. Critical appraisal of the circular economy standard for organizations BS 8001:2017

After a detailed introduction, in which the motivation for the CE, its mechanisms, and its relation to other concepts including resource efficiency and the bioeconomy are presented, the standard provides a comprehensive set of terms and definitions. In particular, the CE is defined as *"economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles"*, where 'restorative' refers to spent resources being fed back into new products and services, and 'regenerative' refers to the enabling of living systems to heal and renew the resources that are consumed (BSI,2017a, P10). Value is defined as "financial and/or non-financial gain" (BSI,2017a, P21).

The standard then lists the macro-level benefits of the CE, which are: improved resilience of economic systems (due to risk mitigation on raw material dependence), economic growth and employment (by decoupling employment from energy and material use), and preserved natural capital and climate change mitigation (by preservation and restoration of biological nutrients to rebuild natural capital and reducing negative externalities) (BSI, 2017a, P23).

Micro-level benefits include cost savings, new sources of innovation and revenue, improved customer relationships, and improved resilience for organizations (BSI, 2017a, P23f).

The standard establishes a minimal set of six CE principles that all organizations should refer to (Fig. 1, upper center). While the standard does not suggest any hierarchy among CE principles, it appears that *systems thinking* ("holistic approach to understand how individual decisions and activities interact within the wider systems they are part of" (BSI, 2017a, P28)) and *stewardship* ("an organization is responsible for the management of all facets of its decisions and activities, from inception through to fulfilment and end-of-life" (BSI,2017a, P29)) are two overarching principles that can, if consequently applied, have far-reaching consequences for decision-making within the organization.

An eight stage flexible framework guiding the practical implementation of CE principles in organizations is the core of the standard (Fig. 1, center). The framework is flexible, meaning that there is no predetermined starting point or order that has to be followed, so that organizations can adapt the framework to their level of 'circularity maturity' (BSI, 2017a, P33).

For each stage a detailed description of its purpose and the actions to be taken are provided. The outcome of each stage needs to be reviewed internally against the principles of the circular economy. The comprehensive guidance on business models, enabling mechanisms, and a total of 16 CE issues and considerations needs to be taken into account (BSI, 2017a). The latter include, among others, aspects of accounting, competition law, marketing, insurance, information management, next to seven issues that are directly related to material and energy flows (Fig. 1, lower center).

The ultimate end of the framework activities is clearly stated: "When implementing the principles of the circular economy, the overarching goal for an organization is to create long-term business value by design through the sustainable management of resources in its products and services" (BSI, 2017a, P26). The standard also contains a clear warning against superficial adoption of CE principles: "Implementing any one business model does not necessarily equate to a shift to a more circular and sustainable mode of operation. More correctly, there are business models which have the potential to 'fit' within a circular economic system. Unless the wider systemic context is considered at the same time then they are simply new or reimagined business models operating within the prevailing linear economy." (BSI, 2017a, P43).

Using the flexible framework, the authors of the standard try to build a link between established business procedures and the far-reaching ambitions of the CE approach. As a consequence, the standard describes procedures at all stages of the framework whose purpose is to ensure that the actions taken by the organization are in line with CE principles and the CE vision of its stakeholders. These procedures include: a review of the outcome of each stage of the flexible framework against the principles of the circular economy, linking the CE principles to the organization's long-term success and resilience, gaining approval from top-level management, and taking into account the guidance on enabling mechanisms, business models, and circular economy issues and considerations provided by the standard.

The clarification of terms, the description of the profound changes needed, the formulation of CE principles and their integration into the business development process, and the detailed description of a number

of existing regulatory frameworks and mechanisms relevant for the CE are among the strengths of this standard (Fig. 1, left).

There is, however, some tension between the stated need for radical change necessary to establish a circular economy (organizations 'turning things on their head' (BSI, 2017a, P4)) and the main task of this standard, which is providing reliable and authoritative guidance on organizational processes. The transition to a circular economy happens in parallel to already ongoing efforts under the umbrella of sustainable development, including resource efficiency, supply chain management, critical raw material risk mitigation, and more. The BS 8001:2017 remains unspecific and often silent on the link between CE and these ongoing transformation processes and their regulatory, political, and scientific underpinning, (Fig. 1, right). No clarification of the link between the CE and sustainability or sustainable development is provided, which seems to be a widespread phenomenon (Geissdoerfer et al., 2017). Sustainability is often just mentioned in the description of some of the CE principles, as 'sustainable management of resources' and 'sustainable mode of operation' (BSI, 2017a). The social aspects, risks, and the ethical responsibilities attached to the different CE business models are mentioned but with the exception of recommending social life cycle assessment (S-LCA) as monitoring tool it is not described how these aspects should enter the flexible framework. The guidance given on monitoring and measurement within the flexible framework remains rather generic. The standard only stipulates that organizations should "map the system using relevant systems thinking tools and techniques, such as: system mapping for resource/material flows; value networks for stakeholder and relationship mapping; and existing life cycle assessment studies" (BSI, 2017a, P36).

According to the standard organizations bear the full responsibility of choosing CE performance indicators, both internally and for communication with stakeholders. At the same time, an independent expert review, as foreseen by the life cycle assessment (LCA) standard ISO 14040 (ISO, 2006a), for example, is not envisioned. The links between CE monitoring and ongoing accounting and assessment activities related to related organizational goals and standards, such as the mentioned LCA standards or the ISO 14045 on Eco-efficiency assessment of product systems (ISO, 2014), are not elaborated upon.

One reason for the lack of more specific guidance may lie in the early stage of CE strategy development and the resulting lack of relevant experience from the CE reality. Clarifying the linkages between CE, sustainability, social risks, and ethical responsibility will require a wider debate among stakeholders and onlookers. Developing more specific guidance for quantitative assessment of CE strategy performance should be in the focus of the future development of the CE concept and its standard. The different quantitative methods for assessing the biophysical flows in organizations and their environmental impacts, including material flow analysis (MFA) and life cycle assessment (LCA), are mature enough that specific suggestions can be given at this stage already, and a CE indicator dashboard proposal for organizations based on these methods is presented below. The dashboard proposal also addresses the rather loose connection between two of the ultimate goals of the CE, material restoration and nutrient regeneration, and the CE principles established by BS 8001:2017.

3. An indicator dashboard for assessing the circular economy in organizations

Quantitative indicators are essential to assessing how well an organization or product system performs in relation to the CE principles and to the wider national and international sustainability goals (Griffiths and Cayzer, 2016; Su et al., 2013 Su et al., 2013). Indicators need to be backed up by rigorous scientific accounting and assessment methods (Saidani et al., 2017).

3.1. Current circular economy and resource indicator systems

CE indicators are commonly grouped into micro-level (organizations, products, consumers), meso-level (symbiosis association, (eco)-industrial parks), and macro-level (city, province, region, or country) (Balanay and Halog, 2016; ; Geng et al., 2012; Geng and Doberstein, 2008; Mathews and Tan, 2016, 2011; Saidani et al., 2017; Su et al., 2013). Next to the economic and geographical scope, different layers (monetary, mass, energy, etc.) can be quantified (Hoekstra et al., 2015) and different variable types (flows, stocks, stock changes), or ratios thereof, can be used (Wisse, 2016).

The literature contains a plethora of indicators for environmental performance and resource efficiency, for example, at the EU level (Demurtas et al., 2014) and in Japan (Takiguchi and Takemoto, 2008). In its recent report on circular economy indicators, EASAC (2016) lists indicator sets developed by several global institutions with more than 300 (!) sustainable development, green growth, material flow analysis (MFA), CE, and resource efficiency indicators. Banaité (2016) reviewed studies proposing a total of 65 indicators and the micro level, 46 indicators at the meso level, and 153 indicators at the macro level. Geng et al. (2012) review a comprehensive list of CE indicators used in China at the macro- and meso-levels presented earlier by Li et al. (2010). For the EU and member state levels the development of a CE monitoring framework is currently under way (European Commission, 2017). An overview of the proposed CE indicators at all three levels is given in the supplementary Excel file SI2.

However, the existing environmental and resource efficiency indicators do not necessarily reflect the CE goals and principles well (Geng et al., 2013), and hence, specific CE indicators are taken from other dashboards or are newly developed (C2C, 2014; EASAC, 2016; EEA, 2016; EMF, 2015a; Franklin-Johnson et al., 2016; Geng et al., 2012; Huysman et al., 2017a; Linder et al., 2017; Magnier, 2017; Saidani et al., 2017).

A gap regarding CE indicators at the organizational and product system levels remains (EASAC, 2016; Elia et al., 2017; Ghisellini et al., 2016; Giurco et al., 2014; Moriguchi, 2007; Saidani et al., 2017), partly because indicators at this level are absent in the Chinese CE indicator system presented by Geng et al. (2012).

Methods for designing organization- and product-level CE indicators are being developed (EMF, 2015a; Griffiths and Cayzer,2016). A report by the European Environment Agency lists 18 policy questions related to progress towards CE from a materials perspective (EEA, 2016). Some of them can be addressed at the organizational level, including the questions "Are products used more often or for longer periods of time?" and "Does the design take reuse and recycling into account?" Research by the Ellen MacArthur Foundation (EMF) identified four circularity assessment categories (EMF, 2015b): resource productivity, circular activities, waste generation, energy and GHG emissions. These categories apply to the organizational level as well. Many product and organizational level indicators follow the "fraction of maximum possible effect" principle by expressing the performance of a system, product, or process in percent of an ideal performance, which in case of the CE is described as a perfectly and indefinitely closed material loop (Cullen, 2017; EMF, 2015c; Huysman et al., 2017b; Pauliuk et al., 2017).

Exergy (Ayres, 2003; Ayres and Warr, 2005; Castro et al., 2007; Dewulf et al., 2007; Ignatenko et al., 2007; Romero and Linares, 2014) or emergy-based efficiency metrics[2] (Geng et al., 2013; Yang et al., 2010) have been proposed but there is no consensus regarding their usefulness for material cycles and other non-energy-related systems (Sciubba, 2010; Sciubba and Ulgiati, 2005).

[2] Emergy is the sum of all available energy inputs directly or indirectly required by a process to generate a product (Odum, 1988).

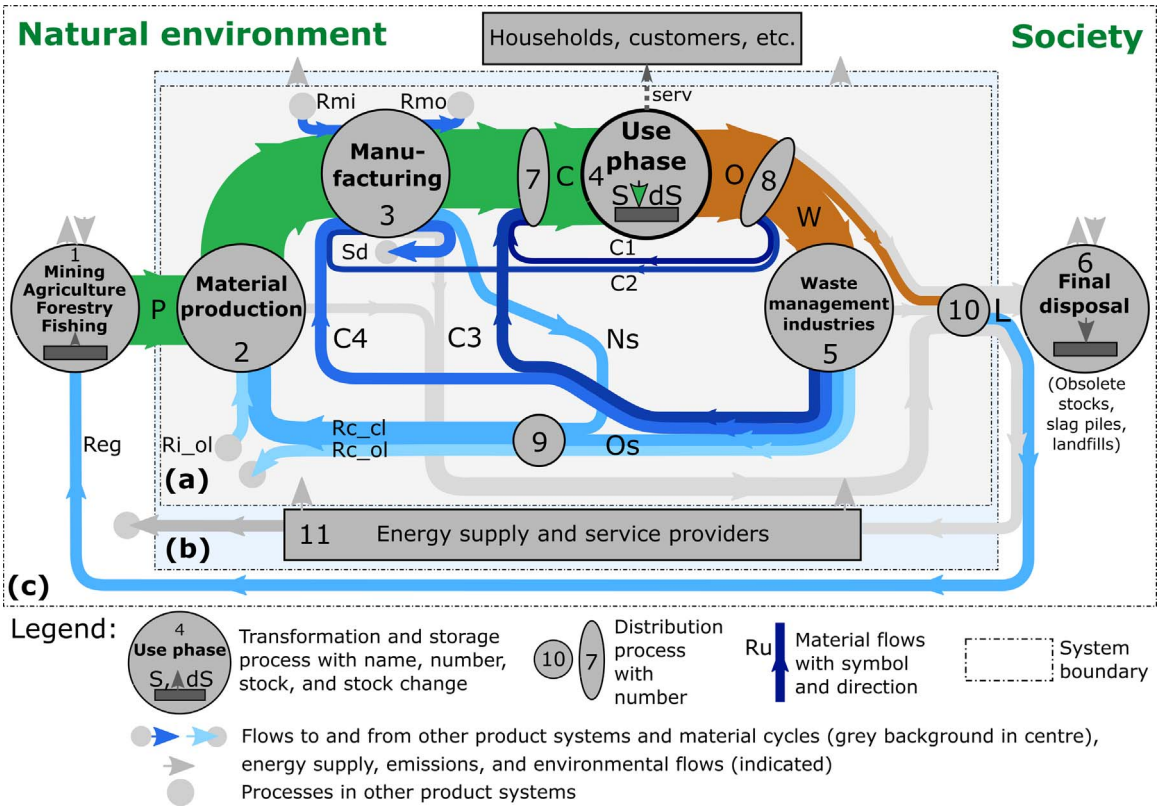

Fig. 2. Proposal for a general system definition of processes and material flows associated with circular economy strategies in a product life cycle or an organization. (a) Material flows and cycles and transformation and distribution processes directly relevant for the circular economy, (b) economic background system, (c) global socioecological system[3]. The services (serv) products in their use phase provide to people are indicated as dashed line. This system definition is based on the work by Graedel et al. (2011) and was extended by the recycling of biological nutrients, all major circular economy flows listed in BS 8001:2017, and the material efficiency strategies identified in the material efficiency literature, in particular, in Allwood et al. (2012). Flow color legend: green: From natural resources to the use phase ('upstream'), brown: from the use phase to waste management ('downstream'), blue: circular economy flows, grey: losses. Mass balances can directly be read from this figure, and indicators can be defined by pointing to individual flows and defining ratios of them. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. A system definition for circular economy assessments

An explicit system definition is the basis of systematic and transparent indicator development (Brunner and Rechberger, 2004). The system definition of the CE that is proposed and used here (Fig. 2)[3] is based on the earlier systematization effort by Graedel et al. (2011) and amended by the different circular economy flows listed in BS 8001:2017 and in the material efficiency literature, in particular, in Allwood et al. (2012). The CE processes, stocks, and flows are embedded into the wider global socioecological system, including the non-material part of the economy (energy supply and service providers, part (b)), and the natural environment and society, part (c). The system definition in Fig. 2 is the basis of a mass-balanced accounting framework for material flow analysis (Brunner and Rechberger, 2004) and material flow cost accounting (Guenther et al., 2012). It is not just another conceptualization of the CE, of which numerous examples already exist (Blomsma and Brennan, 2017). It also contains the flows listed by Potting et al. (2017), though with different connection to the system processes. The different process stages in Fig. 2 can be disaggregated to include more detail, for example, for the waste management industries (Haupt et al., 2016).

The explicit system definition in Fig. 2 facilitates the monitoring of the CE as it provides an accounting framework for tracing stocks and flows of materials and quantifying them in physical and monetary units. CE performance indicators can then be derived from those measurements. The system definition can be replicated at the organizational, regional, sectoral, national, etc. levels to set up a multi-scale framework (Geng et al., 2012), in line with the rationale behind the MuSIASEM method[4] (Giampietro et al., 2009). It supports the suggested use of material flow analysis (MFA) for CE assessments (BSI, 2017a; Geng et al., 2012) by embedding CE strategy assessment into the MFA framework and by coupling the latter to decision making (Brunner, 2002) and management practice (Binder, 2007). Integrating the costs associated with material flows into MFA accounts leads to the standardized method material flow cost accounting, MFCA (Guenther et al., 2012; ISO, 2017, 2011; Schmidt, 2014). In combination with supply-chain indicators for individual material and energy flows, derived from environmental or social life cycle assessment (LCA) (Benoît et al., 2010), a rich set of biophysical and social indicators can be derived from the CE system definition.

3.3. A dashboard of system indicators for the circular economy for organizations and product systems

To reduce the ambiguity of terms for flows and stocks and subsequent incompatible and confusing measurements all indicator components need to be located in an explicit system definition wherever

[3] The flow symbols are: P: production, C: consumption, O: outflow from use phase, W: waste flows, L: losses, C1: Direct re-use of end-of-life (EoL) products, C2: re-filling or refurbishing of EoL products, C3: re-distribution of EoL products, C4: re-manufacturing of EoL products, Rc_ol: open loop recycling, Rc_cl: closed-loop recycling, Ns: new (fabrication) scrap, Os: old (post-consumer) scrap, Sd: fabrication scrap diversion, Rmi: input of remanufactured goods from other product systems, Rmo: output of remanufactured goods to other product systems, S: in-use-stock, dS: change of in-use-stock.

[4] MuSIASEM: Multi-scale integrated analysis of societal and ecosystem metabolism (Giampietro et al., 2009).

Table 1
Dashboard for selecting core indicators for the quantitative assessment of circular economy strategies for organizations and product systems. See supplementary material SI2 for a description of each indicator.

Category	Goal	Possible indicators (variables from Fig. 2 in italic)	Method	Reference
Circular Economy (BS 8001:2017)	Restore	Total restored products, *C1 + C2 + C3 + C4*, or parts thereof, and ratios based thereon	MFA	Fig. 2
		Total restored (*Os + Ns*) or total recycled (*Rc_cl + Ri_ol*) material, and ratios derived such as recycled content (RC)	MFA	Fig. 2, Graedel et al. (2011)
		Recovery rates *Os/O, C1/O, C2d/O, C3/O, C4/O,* (for scrap, remanufacturing, …)	MFA	Fig. 2, Graedel et al. (2011)
		Lifetime of material in the anthroposphere	MFA	Fig. 4, several[a]
	Regenerate	*Reg*, supply chain footprint of regenerative flows	MFA, LCA	Fig. 2
	Maintain utility	Quantity of material restored and its quality: Contamination, Tramp element content	MFA, SFA	several[b]
		Material circularity indicator CIRC (actual cumulative service in percent of maximal service)	MFA	Pauliuk et al. (2017)
	Maintain financial value	Circular economy index (CEI): material value (recycling) in percent of material value (new product)	MFCA	Di Maio and Rem (2015)
		Ratio of recirculated economic value from EoL components over total product value	MFCA, LCC	Linder et al. (2017)
	Maintain nonfinancial value	Material Circularity Indicator (MCI), or anthropogenic lifetime of material in product	MFA	Fig. 4, EMF (2015b)
–				
Life cycle resource efficiency	Increase service per material stock	Material stock per service (service generated by material in the use phase, MSPS = *S/serv*)	MFA	Figs. 2 and 3
	Increase service per material consumption	Service generated by material consumption, *serv/C*, or Material input per service (MIPS)	MFA	Fig. 2, Ritthoff et al. (2003)
	More value added per resource input	Value-based resource efficiency (VRE) (value added divided by energy and material costs)	MFCA	Di Maio et al. (2017)
	Waste reduction	*L, W,* or *ΔL, ΔW* (comparison to alternative life cycles), and ratios based thereon	MFA	Fig. 2
	Reduce, reuse, recycle	*C, C1, C2, C3, C4, Rc_cl, Rc_ol, O,* and ratios based thereon	MFA	Fig. 2, Graedel et al. (2011)
	Increase recycled content	*(Ri_ol + Rc_cl)/(P + Ri_ol + Rc_cl)* for product or organization	MFA	Fig. 2, Graedel et al. (2011)
	Natural resource conservation	What and how much primary resource does the circular economy activity replace?	MFA, LCA	Fig. 2, Geyer et al. (2016)
		P, or resource footprint, or mineral depletion indicator	MFA, LCA	Fig. 2, ISO (2006a,b)
Climate, energy & other	Reduce greenhouse gases	Life cycle greenhouse gas emissions and changes thereof	LCA	ISO (2006a,b), Fig. 3
	Reduce energy demand	Cumulative energy demand (CED), or cumulative exergy demand	LCA, EFA	several[c]
	Reduce water, land, and material use	Water, land, material footprints, or a combination thereof (footprint dashboard)	LCA	ISO (2006a,b), ISO 14046
	Reduce exposure to critical materials	Vulnerability to supply restriction and supply risk	MFA, LCA	Graedel et al. (2012), Graedel and Reck (2016)
	Address social indicators	Social life cycle indicators: Employment, work safety, transparency, supplier relations, etc.	SLCA	Benoît et al. (2010)
	Reduce cross-impacts	Which CE strategies have the highest impact reduction potential in the relevant categories?	LCA	Geyer et al. (2016)
		Eco-cost value ratio (EVR). Costs of reducing environmental damage over product price	LCA, LCC	Scheepens et al. (2016)
–				
Stocks and sufficiency	Curb stock and stock growth	*S, dS*, ratio of stock growth over consumption: *dS/C*	MFA	Figs. 2 and 5, Eq. (1)
		Per capita stock expansion: *dS*/capita	MFA	Fig. 6
	Reduce primary production	Primary production P, ratio of stock growth over primary production: *dS/P*	MFA	Fig. 5, Eq. (2)

MFA: material flow analysis; MFCA: material flow cost accounting; SFA: Substance flow analysis; EFA: energy flow analysis
LCA: life cycle assessment; SLCA: Social LCA; LCC: life cycle costing; CE: Circular economy; EoL: End-of-life

[a] Yamada et al. (2006), Matsuno et al. (2007), Eckelman and Daigo (2008), Eckelman et al. (2012), Franklin-Johnson et al. (2016).
[b] Baxter et al. (2017), Daehn et al. (2017), Ohno et al. (2014), Reuter et al. (2006).
[c] Dewulf et al. (2007), Huijbregts et al. (2010), Castro et al. (2007), Ignatenko et al. (2007).

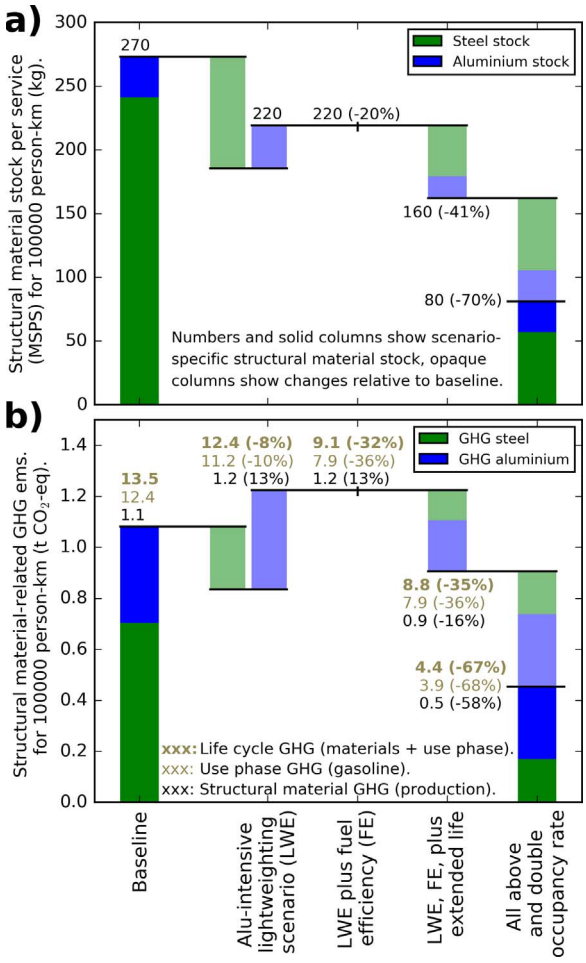

Fig. 3. Material stock per service (MSPS) (a) and greenhouse gas (GHG) emissions for the production of steel and aluminum (b) for the reference flow of 100,000 person-km provided by a gasoline-driven passenger car under different light-weighting and efficiency scenarios. The life cycle carbon footprint decreases from left to right. Data and scenario assumptions were extracted from Modaresi et al. (2014) and are described in the SI, the doubling of the occupancy rate in the rightmost scenario is an assumption.

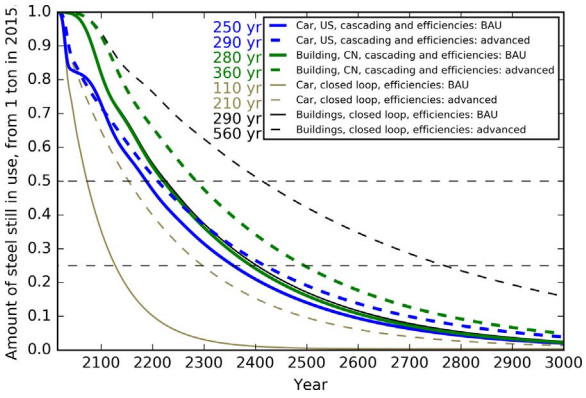

Fig. 4. Long-term extrapolation of the share of steel remaining in useful applications after an original amount of 1 ton primary steel was consumed in 2015. Data and scenario assumptions were extracted from Pauliuk et al. (2017) and are described in the SI. The numbers left of the legend box indicate the average lifetime of the material in the anthroposphere, which corresponds to the area under the curves shown.

possible. Based on the system in Fig. 2, Table 1 contains a list of potential core CE indicators, grouped by the five CE goals and the wider focus areas resource efficiency, climate, energy, and sufficiency. The indicators proposed in the dashboard can be defined and derived directly from Fig. 2, from mainstream LCA tools, and from the literature sources provided in Table 1. The setup of the table was inspired by the taxonomy for CE indicators proposed by Elia et al. (2017).

The dashboard proposal includes indicators from a wide range of literature sources, next to the ones that can be directly derived from Fig. 2. A brief explanation for each proposed indicator is given in the supplementary material SI2.

The first indicator group contains measures of progress towards the CE goals as defined by the standard BS 8001:2017. For example, any of the blue flows leaving processes 5 and 8 (Fig. 2) contribute to the CE and can thus enter indicators for material restoration. Recovery of materials with sufficiently high quality is crucial to reach polity targets for higher recovery rates of materials from end-of-life products (Fellner et al., 2017). Tracing material quality at all cycle stages is therefore an essential aspect of circularity assessment, and quality assessments must include knowledge about the content of alloying elements (Løvik et al., 2014; Ohno et al., 2015), tramp elements (Daehn et al., 2017; Ohno et al., 2014; Reuter et al., 2006), and other contaminants (Baxter et al., 2017).

The physical circularity indicators are complemented by monetary or monetary-to-physical indices. Linder et al. (2017) present a financial circularity index: the ratio of recirculated economic value from EoL components over total product value. Di Maio and Rem (2015) propose the circular economy index (CEI) as material value (recycling) in percent of material value (new product). Scheepens et al. (2016) propose an indicator that relates the costs of reducing environmental pollution from economic activities to the market value of the products and services supplied.

With a material life cycle model it is possible to calculate the average residence time of a material in the anthroposphere, a crucial indicator for CE assessment (cf. also Fig. 4) (Daigo et al., 2005; Eckelman et al., 2012; Eckelman and Daigo, 2008; Franklin-Johnson et al., 2016; Matsuno et al., 2007; Yamada et al., 2006). The dashboard includes established direct and indirect resource efficiency indicators such as material and waste intensity and footprints (Ritthoff et al., 2003) and new indicators that better fit the CE rationale, such as the value-based resource efficiency (VRE) indicator (Di Maio et al., 2017). Direct and indirect use of water, materials, and land as well as greenhouse gas emissions were earlier identified as important complements to the core CE loop indicators (EMF, 2015b). They provide crucial information for quantifying tradeoffs between CE goals and other sustainable development goals such as climate change mitigation, cf. Fig. 3 for an example. Information about the exposure of organizations to critical raw materials and material criticality can be included as well (Graedel et al., 2012; Graedel and Reck, 2015).

Additional modelling may be needed to divide nutrient emissions from product systems into those that contribute to a regeneration of ecosystems and those that represent a pollution. Such a division is needed to evaluate the 'regeneration' goal of the CE, for example, in the case of emissions of reactive nitrogen, a major pollutant (Battye et al., 2017).

Indirect material and energy flows (those that are not contained in part (a) of Fig. 2) and their environmental impacts are best quantified with life cycle assessment (LCA), for which a standard is already in place (ISO, 2006a). Life cycle energy demand is routinely quantified with the cumulative energy demand (CED) method of LCA (Huijbregts et al., 2010), and other energy and exergy metrics are also available (Castro et al., 2007; Dewulf et al., 2007; Ignatenko et al., 2007).

Murray et al. (2017) and Moreau et al. (2017) point out the absence of the social dimension in CE concept, but in contrast to that finding, the Authors of the Ellen MacArthur Foundation list 30 social indicators to complement the material circularity index (MCI) proposed (EMF, 2015c). In the dashboard social life cycle indicators (Benoît et al., 2010) are listed as general category, and it is acknowledged that choosing appropriate social indicators and integrating them into the flexible framework of BS 8001 requires additional research and guidance.

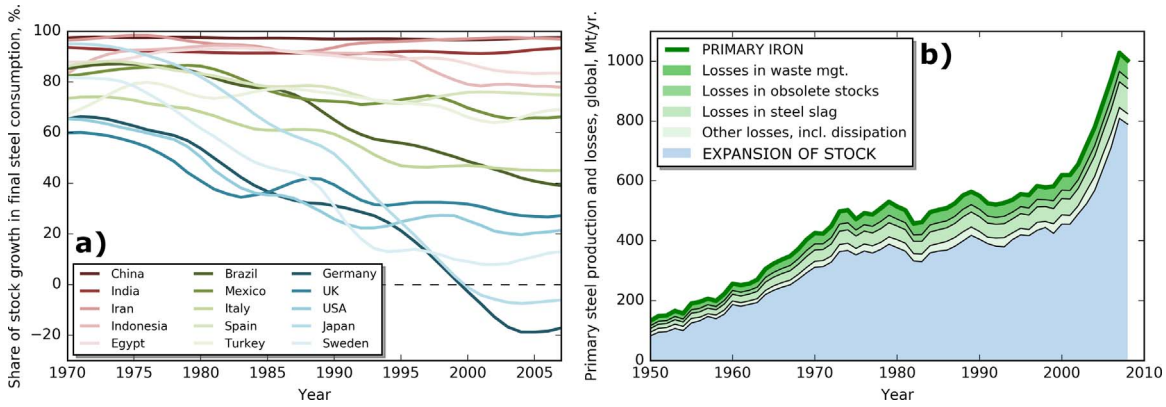

Fig. 5. Share of final steel consumption that expands the in-use stock of steel for selected countries, five year moving average (a), and a decomposition of global primary iron production into different loss categories and expansion of stock (b). Data were extracted from Pauliuk et al. (2013).

In-use stocks of products and materials, both within organizations and in the product systems under their stewardship, provide service to end users and their growth determines the amount of additional raw materials needed (Krausmann et al., 2017; Müller, 2006; Müller et al., 2006; Pauliuk and Müller, 2014). Monitoring and managing the development of in-use stock is thus central to the transition to a more circular socioeconomic metabolism, which is why a separate stock category is part of the dashboard. Ultimately, the CE requires in-use stocks to be constant or declining, as stock growth is a central hindrance to establishing a circular economy (cf. also Fig. 5). There is a possible sufficiency threshold for stocks at least for some materials (Müller et al., 2011), (Fig. 6), which means that the link between sufficiency and stocks should be included in circular economy monitoring.

3.4. Beyond the indicator dashboard

Systems indicators like those listed in Table 1 need to be combined with other relevant CE information like the presence of take-back schemes and bills of materials for products (Griffiths and Cayzer, 2016) to provide comprehensive information to the management processes under the flexible framework.

Research on supply chain integration, business model design, and other CE aspects is ongoing and produces insights and indicators that can help both organizations and policy makers to design new CE strategies and policies. Dunant et al. (2017), for example, analyze barriers to reuse of construction steel and suggest a better integration of the actors along the chain from old to new buildings, a process that requires trust and better communication between the actors involved. Prosman et al. (2017) study the role of internal and external coordination to facilitate industrial symbiosis. Bocken et al. (2016) and den Hollander et al. (2017) present a list of product design and business model strategies to facilitate the transition to a circular economy. Processes to integrate the end-of-life stage into product design are available, for example, for remanufacturing (Gehin et al., 2008). Indicator development should be part of such research activities in cases where there existing performance measures do not reflect the CE principles well enough.

4. Illustrating the systems context of the circular economy indicators for organizations

Systems thinking is a core CE principle (BSI, 2017a), and many of the indicators in Table 1 can help organizations map their system linkages over space and across industries (supply chains) and over time (subsequent material life cycles). Some important examples of CE system linkages are presented here to underline the importance of choosing a sufficiently broad set of organizational CE indicators. The importance of coupling CE assessment with life cycle thinking is illustrated (4.1), the technical residence time of materials as important CE indicator is recapitulated (4.2), the relationship between material consumption and in-use stock growth is quantified for steel (4.3), and a possible sufficiency threshold for material stocks is demonstrated for cement and steel (4.4).

4.1. Trade-off between life cycle benefits and CE goals

While material efficiency (Allwood et al., 2012, 2011) is a core strategy in the CE, the motivation for material substitution (Allwood et al., 2010; Graedel et al., 2013) is often derived from external goals, such as the desire to reduce life cycle greenhouse gas (GHG) emissions.

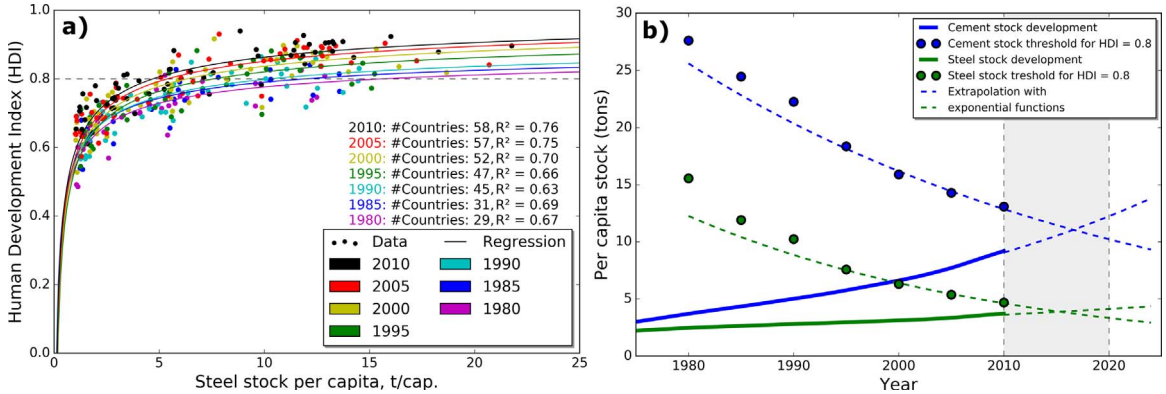

Fig. 6. Regression analysis of the relation between the Human Development Index (HDI) and the per capita steel stock (a) and plot and extrapolation of the global sufficiency thresholds (HDI 0.8) for steel stocks derived from plot (a) along with the actual global stock development (b). The method is an exact replication of the analysis of Steinberger and Roberts (2010) for steel and cement stocks. The steel data were taken from Pauliuk et al. (2013), the cement data from Müller et al. (2013). The method and the results for cement can be found in the SI.

Fig. 3 shows the material stock per service (MSPS), also described as 'materials intensity per service unit' (Müller, 2006), and the GHG emissions for different scenarios of material substitution and subsequent light-weighting and emissions savings of a passenger car for a functional unit of 100.000 passenger-km.

While the MSPS declines with life cycle GHG emissions, there is a shift from steel to aluminum stocks (Fig. 3a), which could, if implemented at large scale, triple the amount of aluminum consumed for new passenger vehicles globally (Modaresi et al., 2014).

At the same time, due to the higher specific GHG intensity of aluminum, the GHG emissions of vehicle manufacturing would increase to enable life cycle savings in future years (Fig. 3b). To anticipate and avoid ill-posed incentives to organizations both CE and sustainability indicators, such as life cycle GHG emissions, should be quantified in conjunction.

4.2. Residence time of materials in the technosphere

In a perfect CE the residence time of a unit of material in the technosphere would be indefinite. This goal is as unattainable as the theoretical efficiency limit of heat engine, for the same thermodynamic reasons (Cullen, 2017). Quantifying the expected residence time of a material unit consumed by an organization or manufactured into the organization's products gives an indication of both the degree of circularity of the respective product system and of the cumulative service that can be provided to end users with that material. The current residence time in the technosphere was estimated for steel (Daigo et al., 2005; Matsuno et al., 2007), copper (Eckelman and Daigo, 2008), and nickel (Eckelman et al., 2012), and Fig. 4 gives an update for steel based on recent scenario work (Pauliuk et al., 2017).

With current steel cycle process parameters a hypothetical closed-loop recycling system for passenger cars would show an average steel lifetime of 110 years only, which is less than eight full use cycles of 15 years. In reality, secondary steel from cars is cascaded ('down-cycled') mostly into buildings, which have a longer lifetime, leading to a steel residence time of 250–290 years under business as usual assumptions. With prolonged product lifetime and highly efficient recovery and re-melting the average residence time of construction steel could reach up to 560 years. A longer residence time requires advanced CE strategies, in particular, the re-use of construction steel (Dunant et al., 2017) and the reduction of quality loss due to tramp elements like copper and tin (Baxter et al., 2017; Daehn et al., 2017; Hatayama et al., 2014). When using the technical lifetime of a metal as CE indicator it is important to include material lifetime extensions as a result of open-loop recycling, as closed-loop systems are not per se environmentally more beneficial than open-loop systems (Geyer et al., 2016).

Given the large contribution of the steel industry to global GHG emissions (IEA, 2015) current technical metal lifetimes of 250–300 years and less than 150 years for a hypothetical high-quality closed loop system for vehicles are too short and also far away from the CE vision. Lifetime extension, improvements in all stages of the recycling loop, and a shift towards more remanufacturing and reuse (Allwood et al., 2012), now often labelled as CE strategies, are clearly needed. Bold roll-out of these strategies will determine the success of CE beyond raising awareness and shape the CE's eventual contribution to sustainable development. Material cycle modelling helps identify those life cycle stages and parameters that are the biggest hindrance to longer material service lifetimes.

4.3. Stock growth and sufficiency

A core question for organizations in the CE is whether their products contribute to stock growth or replace or maintain existing stocks, as in the case of stock growth primary production must be attributed to that product, nullifying the CE intention. If stocks continue to grow a circular system remains an illusion (Cao et al., 2017; Chen and Graedel, 2015; Cullen, 2017; Fellner et al., 2017; Haas et al., 2015; Pauliuk et al., 2012). From Fig. 2 one can see that material consumption C always has two components: replacement of outflow O and stock expansion dS (mass balance of the use phase).

$$C = dS + O \quad (1)$$

Developing countries need to build up stocks, and for steel the ratio of stock growth to consumption (dS/C) lies almost at 100% (Fig. 5a), rendering the CE into a vision for the future and not into something that could be implemented in the present system (cf. also Figs. S1–S3 in the Supplementary material). More developed countries use a higher share of their steel consumption for stock maintenance and thus dS/C attains values below 30% for the richest countries and even negative values for countries where stocks were found to be shrinking (Fig. 5a).

In cases where there are no links between the foreground system and other product systems, or at the global scale, the entire material foreground system (part (a) in Fig. 2) has the following mass balance, which also applies to material flow accounting (Fischer-Kowalski et al., 2011):

$$P = dS + L \quad (2)$$

Primary production P is either replacing system-wide losses L or contributing to stock expansion dS. A plot of this relation for the global steel cycle (Fig. 5b) shows that the share of stock expansion in total primary production has not changed substantially in the last 60 years, it has even gradually increased from 60 to 70% in the 50ies to 73–79% in the period 1998–2008.

Ever-growing material stocks drive resource depletion and production-related GHG emissions. Although individual product systems within an expanding material economy can show high degrees of circularity, the overall system cannot if stocks continue to grow. The CE principles systems thinking and stewardship entail that organizations monitor the contribution of their products and services to stock development to understand how their decisions impact the material cycles at the large scale.

A sufficiency threshold analysis (Steinberger and Roberts, 2010) was performed, using steel and cement stocks as examples, to illustrate relative decoupling of human development from in-use stocks of materials. It appears that the global economy is slowly becoming more in-use-stock-efficient, meaning that a certain development level, here quantified with the Human Development Index HDI, can be achieved with ever-decreasing stock levels (Fig. 6a). A comparison of the sufficiency thresholds for an HDI of 0.8 with actual stocks shows that the global average sufficiency thresholds for steel and cement needed for an average HDI of 0.8 are likely to be reached during the current decade (Fig. 6b).

Organizations can use the material sufficiency levels such as the ones shown in Fig. 6b to decide how the issue of stock growth should enter their decision making: the smaller the stocks in the region of the customer base compared to the sufficiency level the easier it is to justify stock growth from a sufficiency perspective. In (mostly rich) countries with stocks larger than the sufficiency threshold products and services that lead to a dematerialization may be preferable from a global sufficiency perspective.

5. Conclusion

A closer link between the circular economy standard BS 8001:2017 for organizations and the established accounting and assessment tools for material flows and their environmental and social impacts is needed. The bigger picture obtained by looking at material cycles needs to be taken into account. From a material cycle perspective it becomes clear that natural resource depletion, in-use stock growth, and the useful service lifetime of materials should enter the group of core circular economy indicators. If circular economy strategies are not monitored from a systems perspective there is a danger that a pool of

incoherent circular economy indicators will evolve and organizations, left without specific guidance on monitoring and assessment, cherry-pick results that fit their corporate message but not necessarily contribute to the wider circular economy and sustainability goals. Organizations can use the available methods material flow analysis and its organizational offspring, material flow cost accounting (ISO, 2017, 2011) to trace the material resources that pass through and accumulate in their area of responsibility. They can apply the standards for life cycle assessment (ISO, 2006a,b) to quantify the environmental and life cycle impacts of the products and services they deliver to their customers. Both methods can be applied already during design to evaluate different possible product designs and circular economy business models as listed in the BSI circular economy standard.

From the demonstration of the systems context of the circular economy in Section 4 it becomes evident that it is unlikely that organizations alone can capture the full circular economy potential identified. Additional policy interventions to support material efficiency and other circular economy strategies are likely to be required. To become successful circular economy strategies and business models must therefore be better linked to ongoing processes in policy making, in particular, the sustainable development goals (UN, 2017) and the climate targets.

Conflict of interest

The author declares no conflict of interest.

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Appendix Supplementary material and data

Supplementary material and data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.10.019.

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