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A circular economy within the planetary boundaries: Towards a resource-based, systemic approach

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ABSTRACT

Circular Economy (CE) is the buzzword of today, promising an economy able to prosper on limited resources by closing material cycles. However, there is no guarantee that simple strategies of material cycling, as propagated by the various definitions of this concept, will indeed lead to an economy able to manage the world's resources, pollution and societal demand within environmentally sustainable levels. Based on the shortcomings of the present mainstream definitions of CE, this paper proposes an integrative, cascading, resource-based approach aimed at an environmentally sustainable and socially beneficial economy. The international community agrees on the necessity to maintain the current environmental equilibrium to ensure equity for future generations and to allow human well-being and dignity already in the present. Accordingly, physical and environmental limitations are identified, that are to be observed to make CE sustainable. This paper then suggests that a transition towards a sustainable resource-based CE goes hand in hand with a paradigm shift in the way environmental considerations are perceived by individuals, codified in different normative frameworks and dealt with by private companies. It therefore opens the discussion by underlying some challenges that could appear in the view of transitioning to CE.

1. Introduction

The concept of Circular Economy (CE) has recently gained broad diffusion and popularity, in particular in the policy and business circles in developed nations, promising an economy which can be both profitable and sustainable (Korhonen et al., 2018a; Lazarevic and Valve, 2017; Veleva and Bodkin, 2018). The growing amount of peer-reviewed articles on CE and various publications by major consulting firms are reflecting that CE is also becoming an important concept for science and business development (Kirchherr et al., 2017; Reike et al., 2017). As its name suggests, CE refers to a model of production and consumption that introduces a fundamentally different perspective from the dominant "linear economy" model (Sauvé et al., 2016); it is often presented as an alternative to the current "take-make-dispose" or "extract-produce-consume-trash" industrial model (among many others: Ellen MacArthur Foundation (2015); Ghisellini et al. (2016)). By conceiving end-of-life materials and products as resources rather than waste, it aims at closing the loops of materials, reducing the need for raw materials and waste disposal, following the example of ecosystems (Elia et al., 2017).

Despite its wide use, there is however no consent on what CE actually means and encompasses, not to speak of an agreed definition (Lieder and Rashid, 2016; Reike et al., 2017). The widespread acceptance of a somewhat not clearly defined concept, often presented as a solution for continuous economic growth and innovation without – or with minimal – damaging exploitation of the environment (e.g. Ellen MacArthur Foundation (2015); European Commission (2014)), can be explained through the benefits and interests of the actors driving the CE to actively support such a deliberately vague, but therefore uncontroversial approach (Lazarevic and Valve, 2017). The lack of conceptual clarity and an accepted definition represents a challenge for scholars to work on the topic given the abundance of CE conceptualizations, which has been described as "circular economy babble" by Kirchherr et al. (2017); it led Blomsma and Brennan (2017) to qualify CE as an "umbrella concept" and Korhonen et al. (2018b) as an essentially contested concept.

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This paper doesn't intend to offer another literature review of existing definitions, as this has already been done by different authors (see for an overview, e.g., Geissdoerfer et al. (2017); Ghisellini et al. (2016); Homrich et al. (2018); International Reference Centre for the Life Cycle of Products Processes and Services (CIRAIG), 2015; Kirchherr et al. (2017); Korhonen et al. (2018b); Lieder and Rashid (2016); Winans et al. (2017); Merli et al. (2018)). Based on an evaluation of these various reviews in section 2, it presents a conceptual framework that allows to integrate multiple CE strategies focusing on individual actors (micro-level) into a global and resourced-based approach. Building on a large consensus that an environment permitting a life of dignity and well-being should be ensured for current and future generations (section 3.3), it places environmental realities at the core of the here proposed approach (see section 3.4), which leads to the resource-based definition in section 3.5. Section 4 shortly addresses how the integration of these physical requirements into socio-economic activities represents a paradigm shift for all actors (e.g., consumers, institutions, private companies) and discusses some related challenges, with a particular focus on the legal system – illustrated in the Swiss context – and the economic actors.

2. Existing definitions and approaches of CE

As mentioned already above, there is no single definition of what CE means and encompasses. The most often cited and probably best known definition of CE of the Ellen MacArthur Foundation (see supporting information (SI) and Ellen MacArthur Foundation (2013)), which focuses on regenerative economy and new business models, has been adopted and modified many times (Kirchherr et al., 2017), also by political actors and for institutional positions (e.g., British Standard (2017); European Commission (2014); United Nations Environmental Program (2006), see also SI). Other definitions, mostly stemming from scientific literature, rather focus on material aspects (Bocken et al., 2017) or consolidate various definitions to be found in the recent literature into more comprehensive ones (e.g. Kirchherr et al. (2017); Korhonen et al. (2018a)).

The mentioned understandings of CE are mostly adopting a bottom-up approach, focusing on individual businesses and economic actors. They encourage them to improve their efficiency, reducing the (per-unit) resource input and minimizing final waste. These approaches are useful and necessary, as they provide tools for single actors to adapt their processes and help operationalizing theoretical principles; hence they certainly play an essential role in the transition towards CE. Such strategies can also be interesting from a pure business perspective, as they make companies less dependent on resource price fluctuations and strengthen customer loyalty thanks to new business models.

Despite its usefulness for direct application, such bottom-up approaches are not *per se* sufficient to reach sustainability. There is no proof that material-cycling strategies would be environmentally sustainable after all (Grosse, 2010, 2011; Zink and Geyer, 2017), as the idea of closing cycles alone does not touch the question on how large and fast such cycles can be (Cullen, 2017; Merli et al., 2018). Bottom-up approaches can lead to a confusion between different levels of analysis (micro, meso, macro)[1] and a lack of distinction between *relative* and *absolute* efficiency (Gregson et al., 2015; Hobson, 2016; Lazarevic and Valve, 2017). Indeed, most approaches focusing on production, production sites and techniques are aiming at improving per-unit efficiency but disregard a larger macroeconomic and macro-societal approach, which is necessary to build *"authentic"* circularity (Arnsperger and Bourg, 2017; Ferrari, 2017). By neglecting that CE can be conceived and implemented at different scales, they lack a systemic view on the global context of limited environmental resources (Korhonen et al., 2018a).

CE is often presented as a solution to overcome the tension between unlimited economic growth and finite planetary resources with no further explanation. It is implicitly assumed that improving the efficiency of businesses at the micro level will reduce the global environmental impact of businesses, neglecting the impact of continuous growth. Some authors refer to it as the "myth of decoupling" growth and resource consumption (Lazarevic and Valve, 2017). Grosse (2010) argues that in an economy where resource use is growing by more than 1 %, the positive effects of recycling on resource depletion are negligible. CE is seen as an enabler to economic growth (Ellen MacArthur Foundation, 2015), but in order to result in an absolute decoupling of resource use from GDP growth (Jackson, 2011), the growth would need to be linked to resource efficiency improvements (Kjaer et al., 2018). It is assumed that proposed strategies of material cycling will replace 1:1 primary production, which is a gross oversimplification. On the market, an increase in supply (initial primary production and recycled secondary production) usually leads to a decrease in price and, subsequently, to an increase in consumption (Zink and Geyer, 2017). This may in many cases lead to an increase of environmental impacts and create a "rebound effect" (Figge et al., 2014; Ghisellini et al., 2016). As mentioned, reducing the environmental impact per produced unit will not necessarily reduce the environmental impact of the economy as a whole, if the questions of the number of actors and the number of units produced per actor are neglected. The Institutional Resource Regime approach (Gerber et al., 2009; Knoepfel et al., 2007), the institutional economics approach of environmental policies (Bromley, 1991) or the Institutional Analysis and Development framework (Ostrom, 1990, 2009) have pointed out the theoretical limits and weaknesses of "classical" sectoral emission control-based environmental policy approaches when dealing with the issue of sustainable resource management.

Regarding material flows, it is commonly assumed that engineering materials can be cycled indefinitely in technical applications, disregarding irreversible effects, as well as technological and even physical limitations (Korhonen et al., 2018a; Winans et al., 2017). It is however inevitable that materials are irretrievably lost during the lifetime of technical products (Kral et al., 2013; Valero, 2006). Thus sustainable raw material extraction (Bocken et al., 2017) and safe disposal in final sinks (Kral et al., 2013) are necessary parts of a CE, yet they are rarely included in current approaches.

Even if there is no clear evidence of a single origin of the term (Murray et al., 2015; Winans et al., 2017), the paradigm of CE was surely rooted in a reflection around the concepts of environmental science and sustainable development (Ghisellini et al., 2016; Sauvé et al., 2016). Approaches like, e.g., industrial ecology (Ehrenfeld, 1997; Erkman, 1997), clean technology (Clift, 1995, 1997), cradle-to-cradle™ (Braungart et al., 2007), blue economy (Pauli, 2009), performance economy (Stahel and Reday-Mulvey, 1981) or biomimicry (Kennedy et al., 2015) share the idea of the systemic view on "spaceship earth" (Boulding, 1966) with limited resources. The development of different strategies to manage the resource flows in an essentially closed system was the result of the awareness that our planet is such a (almost) closed system.

Table 1 summarizes the main characteristics of the understandings of CE mentioned earlier, as well as compares them with some related schools of thought.

3. Cascading, resource-based framework and definition of CE

The concept of CE can, to some extent, be described through some of its components or strategies (like, e.g., reusing, recycling, eco-design and performance economy), but this is not sufficient to define it, if we aim for a socio-economic system that is sustainable from a resource-based point of view. To be complete, the components have to be seen as

[1] To add to the confusion, there is no accepted standard in the distinction between the different scales labelled as micro, meso and macro respectively (see e.g. (Ghisellini et al., 2016)).

Table 1
Summary of main approaches to CE and related schools of thought.

Approach	Core strategies	Focus / Aim
Practitioner's view on CE, e.g., Ellen MacArthur Foundation, 2013	Renewable energy No toxic elements No waste	Economic growth within a resource constrained world
CE with material focus, e.g., Bocken et al., 2017	Prolong service life Reduce resource intensity Closing resource loops	Keeping products, components and materials at a high value
CE consolidated from literature review, e.g., Kirchherr et al., 2017	Reducing Reusing Recycling Recovering Addressing different scales (micro, meso, macro)	Sustainable development to achieve environmental quality, economic prosperity and social wellbeing
Cradle-to-cradle (Braungart et al., 2007 Homrich et al., 2018 Netherlands Ministry of Infrastructure and Environment, 2011)	Replacing hazardous substances 100 % recyclable technical or biological nutrients	Creating a wholly beneficial industrial system Focus on chemical inputs
Industrial ecology (Erkman, 1997;Homrich et al., 2018)	System analysis Utilize by-products as inputs for other processes (symbiosis)	Designing mature industrial systems inspired by natural ecosystems as a subsystem of the biosphere
Performance economy (Stahel and Reday-Mulvey, 1981)	Selling performance instead of products (e.g., light as a service)	Economic growth within a resource constrained world

parts of the larger system, or "ecosystem" (Laurenti et al., 2018). Then so far, CE has not been systematically thought in a holistic and top-down manner, taking the planetary environmental constraints as the absolute limits of the system (Korhonen et al., 2018a). Our intent is therefore to develop a framework based on this understanding. The resulting global and systemic approach is a tribute to various authors and schools of thought (see Table 1) that have contributed to the emergence and development of the CE concept. This framework will allow to acknowledge the pragmatic utility of bottom-up and sectorial approaches, while overcoming the shortcomings of current definitions, as identified in section 2. After presenting the conceptual construction of the framework (section 3.1) and its epistemological status (section 3.2), we will develop the theoretical basis of the framework by first showing the development and foundations of the normative assumptions on which it is built (section 3.3) and then identifying the physical and environmental principles and limitations that have to be taken into account and how they translate to CE (section 3.4). This leads to the proposition of a resource-based definition (section 3.5).

To illustrate the theoretical concepts, we discuss the application of the findings and derive guidelines for practical consideration on a company or product level on the example of a washing machine. We will show qualitatively, how the different aspects can be considered in the design of the washing machine (section 3.4), its business model (section 4.3) and relate to the larger policy and societal frame (section 4.2). The example is based on the outputs of various discussions and workshops with a home appliance-company in Switzerland.

3.1. Conceptual construction of the framework

Our human societies are part of the Earth system; they are organized along normative principles, which can vary depending on cultures, religions and other moral considerations. Nowadays, there is however a global consensus on the fact that human dignity and well-being should be seen as an overall goal of any system developed by humans, while ensuring that the existence conditions of the system are not destroyed. We take this normative consensus as the basis of our CE framework and therefore aim for a CE that acknowledges the need of a sustainable resource management, in order to allow human dignity for current and further generations (see section 3.3).

The universe is organized along physical laws, which lead to the unique distribution of energy, and consequently matter, in space and time. These principles limit the possibilities for all natural, but also all technical processes. The Earth system provides vital ecosystem services to humanity, but has a limited resilience against anthropogenic stressors. These boundaries of the planet and the physical limits combined should be considered as the overall frame for human activity, in order not to trigger unintended anthropogenic changes in the Earth system. To design a sustainable CE, two fundamental engineering problems need to be addressed:

1 How to quantify the sustainable resource base and make sure that, despite all uncertainties, the Earth system can sustain the socio-economic metabolism in the long run?
2 How to utilize these limited resources best within the socio-economic system?

Finally, the economy is understood as a constellation of private and public actors and entities providing goods and services to society. The deductive approach implies that economic actors should operate within the environmental constraints, as well as comply to and participate in shaping the normative societal frame. In order to be most profitable, they strive to utilize the available resources most effectively.

In summary, our cascading approach for a circular economy (CE), shown in Fig. 1, is deducing a CE from the given environmental realities, which represent the frame for human activities.

3.2. Epistemological status and utility of our framework and definition

Our contribution relies on an inclusive and integrative approach, allowing to place the useful – but incomplete – individual perspectives into a larger frame. We conceived it as an "*ideal-type*" (see Weber, 1997 and SI), which represents a clear theoretical ideal version of a concept, a "north star" that helps orientation. In such an ideal–typical perspective, according to Weber, the conceptual challenge relies on identifying and caricaturing the significant and relevant (system of) features of the (social) phenomenon being studied (see SI). The methodological procedure then consists of confronting and measuring the divergence or, on the contrary, the congruence between the ideal-type or *Gedankenbild* (i.e. our systemic definition of CE) and the empirical cases studied (i.e. various CE situations or transition processes). Such an analytical construct can act as an ideal reference point for assessing progress and measuring efficiency of initiatives towards CE, allowing to analyze and qualify – and possibly even quantify – the degree of "circularity". Relevant normative principles for paving the transition process towards CE at different levels (company, sector, region, country, etc.) can be deduced from such an ideal-typical definition, as each of the elements

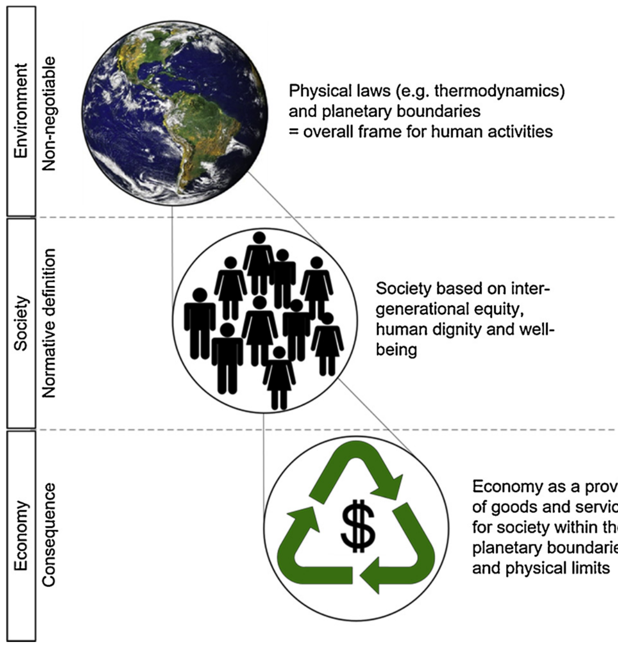

Fig. 1. Framework for holistic view on thecircular economy with a cascading top-down approach in 3 layers: The layer of the environment forms the overall frame for human activities. The latter can be described as the "society", which is part of the biosphere, as depicted in the second layer. To be sustainable in the long run, human activities should integrate the nature-given, non-negotiable, physical and environmental restrictions from the first layer. The society is organized along normative definitions. The economy as a third layer is understood as a constellation of actors and entities providing goods and services for the society. The deductive approach implies that economic actors have to operate within the environmental constraints.

composing it may be used as normative principles for such a transition process. Further research could then develop a more formalized step-by-step proceeding paving the way from linear economy towards the ideal-typical CE (for an example of such a normative use of an ideal typical definition, see Knoepfel et al. (2007)).

Developing a concept of CE that would allow, if completed, to stay within the bio-physical capacity of the planet is of great macro-societal importance. Keeping an eye on the global resource base is useful to ensure that initiatives towards CE do not turn out to be counter-productive from the environmental point of view (rebound effect) or phagocytosed by the current "linear" paradigm that CE expressly aims to overcome, by confusing the means (e.g., implementation of strategies improving eco-efficiency at the micro level) and the ends (staying within the planet's bio-physical capacity); such considerations can be useful for policy-makers and institutions to design environmentally effective strategies related to CE (top-down approach). On the individual and company level, an ideal-typical definition, and the normative criteria derived from it, can be used by businesses as a benchmark aiming at improving their environmental performance; by consumers to evaluate their choices (bottom-up approach). Moreover, the psychological aspect of presenting an ideal-typical vision should not be overlooked, as ideals and expectations do political work by bringing "*futures into being, while presenting pathways through which change is to be achieved*" (Lazarevic and Valve, 2017).

3.3. Normative basis of the framework: current international consensus

The willingness to maintain the environmental qualities of today's Earth intact is not an ideal goal pursued for its own sake. It is the result of an anthropogenic and utilitarian view (Sabag-Munoz and Gladek, 2017), which implicitly assumes that the focus should be on allowing humanity to survive and ideally to thrive further. The relationship between a healthy environment and human dignity and well-being of present generations is acknowledged in international agreements. The Principle I of the 1972 Stockholm Declaration, agreed at the United Nations (UN) Conference on the Human Environment, declared that:

> "Man has the fundamental right to freedom, equality and adequate conditions of life, in an environment of a quality that permits a life of dignity and well-being, and he bears a solemn responsibility to protect and improve the environment for present and future generations.(…)" (United Nations, 1972)

Even if it is not a legally binding instrument, its thinking is widely accepted, as shown by various subsequently adopted non-binding declarations (for a list see Hayward (2012)). Moreover, maintaining the environmental balance in control is necessary to ensure that future generations enjoy the same "playfield" than the present one. The will to ensure both *intra* and *inter-generational equity* lies at the core of reflexions on sustainability, as reflected in the famous definition of the notion of Sustainable Development which was defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987; Langhelle, 2000). It stems from the report of the World Commission on Environment and Development (WCED) "Our common future", which is advocating the growth of economies based on policies that do not harm and can even enhance the environment. In 1992, the UN "Earth Summit" in Rio de Janeiro confirmed that environmental questions should be seen as a major global preoccupation of the international community; the global character of problematics of ecosystem degradation and natural resource management was reaffirmed, which largely contributed to the emergence of international environmental law. Building upon a decade of major UN conferences and summits, in 2000, the Millennium Development Goals (MDGs) stated eight development goals for the year 2015 and reaffirmed the willingness to "ensure environmental sustainability"[2] . The Sustainable Development Goals (SDGs), which continue the MDG's and form the core of "Agenda 2030" again confirm the environmental concern and the need to act upon it (United Nations, 2018). CE is particularly relevant in relation to goal 12: "*Ensure sustainable consumption and production patterns*" and can be seen as a tool to achieve it. As the different SDG's are partly interdependent and CE touches on broad aspects pertaining to reducing environmental harm, it can moreover contribute to achieve others (e.g. direct links with goals 6, 7, 8 and 15 see (Schroeder et al., 2018)); actions towards achieving other goals can positively impact the transition towards CE (e.g. reversed links with goals 4, 9, 10, 13, 16, 17 see Schroeder et al., 2018).

The idea of Earth system limitations to human activities has led to the development of a multitude of approaches to describe the Earth system capacity in ecological terms (Sabag-Munoz and Gladek, 2017). Among the most frequently used are the planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) and the ecological footprint (Wackernagel et al., 1999). The basic idea behind such approaches is that all collective human activities need to be within the bio-physical capacity of our one and only planet in order to ensure its viability for humans in the long run. While the details of the calculation and of the scientific design of the approaches can be largely debated (Blomqvist et al., 2013a, b; Giampietro and Saltelli, 2014; Goldfinger et al., 2014; Montoya et al., 2018; Rees and Wackernagel, 2013; Running, 2012; van den Bergh and Grazi, 2015), the idea of assessing human impact in relation to the critical boundaries and the capacity of the Earth system has found wide international resonance (Sabag-Munoz and Gladek, 2017)[3] . Following this line of thought, we place the physical and environmental limitations of the planet at the core of our

[2] See https://www.un.org/millenniumgoals/bkgd.shtml

[3] For Switzerland specifically, see https://www.bfs.admin.ch/bfs/en/home/statistics/sustainable-development/ecological-footprint.html; and Dao et al. (2018).

CE definition.

3.4. Physical and environmental restrictions on resources

The physical and environmental constraints that have to be considered towards a transition to CE consist in identifying the sustainable resource base (see section 3.4.1) and determining how to best utilize it (see section 3.4.2).

3.4.1. Identification of a sustainable resource base

On a limited planet, the total amount of any resource is limited. Considering the vastness of the planet, human operation may appear insignificant compared with these absolute physical limits. For example, the Earth system receives a total energy flux from the sun of $\sim 10^{17}$W (Szargut, 2003), whereas primary energy demand of humans in 2015 is with $\sim 10^{13}$W (International Energy Agency, 2018) four orders of magnitude smaller. However, such an analysis is greatly misleading, as it disregards the resource requirements and emission-absorbing capacity of the Earth system (Desing et al., 2019). Thus it is necessary to have a sound understanding of the share of the Earth's physical resources which are sustainably available for human appropriation.

The scientific description of the Earth system is based on modelling, abstraction and empirical calibration, which creates uncertainties. With advances in science and modelling efforts, the uncertainties can be made smaller. Theoretically, the uncertainties will be zero when the models become as complex and complete as reality itself (Popper, 1968). Models are often used to describe and predicts a system's behavior, where the mean outcome (50 % probability) and the associated uncertainty range are of interest.

For management and design of technical and socio-economic systems, it is however important to make choices and decisions not based on mean values, but on those values which guarantee system functioning with a high confidence[4] (see Fig. 2). This logic is the underlying principle in engineering, i.e. designing systems with a very small probability of failure, despite uncertainties, simplifications and limitations in available models (e.g., Desing (2013); Heuler et al. (2010); Meyna and Pauli (2010); Molland (2008)).

From a legal point of view, this logic translates into the "precautionary principle"[5], which is a general rule that was developed by international case law in order to avoid potentially dramatic or irreversible hazards. According to this principle, the absence of absolute scientific certainty regarding the effects of an action cannot be used as an excuse to delay the adoption of effective measures for protecting the environment[6] . This principle is implicitly recognized in the Swiss legislation, where the State shall ensure that environmental damage or nuisance is avoided and take early preventive measures in order to limit effects which could become harmful or a nuisance[7] . The application of this principle is leading to determine and adopt a security margin, which is allowing to take the scientific uncertainties into account (Jungo, 2012).

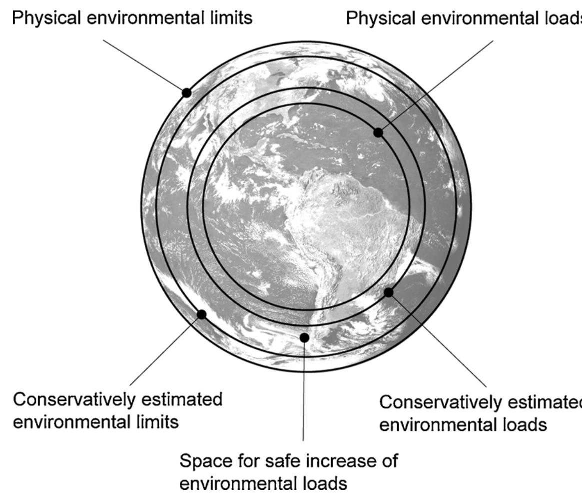

Fig. 2. Precautionary principle for estimating the carrying capacity (or planetary limits) and environmental loads from human activities: the carrying capacity needs to be underestimated and the environmental loads overestimated according to best scientific knowledge, in order not to risk any overshoot.

Considering the global scale of human operations, the Earth's resources and emission absorbing capacity can no longer be approximated as infinite. On the contrary, it is necessary to apply the precautionary principle when describing the planetary capacity and designing environmental loads. This is to ensure that, despite all uncertainties, there is a high probability that the ecosystem can sustain the socio-economic system for generations to come. Following this logic, planetary capacities need to be determined at the lower end of the uncertainty range, as it is done, e.g., in the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015), and environmental loads on the upper end of the uncertainty range, as it is done, e.g., in risk assessment of chemicals (Gottschalk and Nowack, 2013; Van Leewuen and Hermens, 1995).

The current state of the Earth system is the only one, where we know for certain, that it can support human societies (Steffen et al., 2015). Ecosystems, however, have a limited resilience against human influence and it is necessary to respect their resilience boundaries in order to maintain their functionality (Rockström et al., 2009). Biophysical boundaries have been observed for many variables on a regional (e.g., sustainable forestry (Thomas and Packham, 2007)) as well as global scale (e.g., biodiversity (Mace et al., 2014), net primary production (Running, 2012)). The planetary boundary approach (Rockström et al., 2009; Steffen et al., 2015) identified nine boundary categories, which are essential to Earth system integrity: Climate change, change of biosphere integrity, stratospheric ozone depletion, ocean acidification, bio-chemical flows, land-system change, freshwater use, atmospheric aerosol loading, and introduction of novel entities, respectively. None of the regional and global boundaries shall be transgressed, thus they are equally important. The actual values and categories can change with progress in Earth system understanding and

[4] E.g., an aircraft with a probability of arrival of only 50% (i.e. 50% probability of crash) would not be considered acceptable. That's why critical aircraft parts and systems are designed in a way that their actual lifetime reaches the expected lifetime with an probability of failure $< 10^{-7}$/h (Hupfer, 2011).

[5] The precautionary principle is often distinguished from the prevention principle. The latter applies in the case of recognized hazards and foresees the use of technical measures to reduce or suppress the risk. The prevention principle can be seen as a special case - where the uncertainty is identified and acknowledged - of the more general precautionary principle (Jungo, 2012; Largey, 2017); in the present article, we include the prevention principle into the precautionary principle.

[6] Principle 15 of the Declaration of Rio (1992 UN Convention on the environment and development); regarding case law see e.g., Southern Bluefin Tuna Cases [New-Zealand – Japan; Australia – Japan], List of cases: Nos. 3 and 4, Provisional measures order of 27 August 1999, § 77 ss; Gabcikovo-Nagymaros Project [Hungary-Slovakia], Judgment, I.C.J. Reports 1997, p. 77-78, in particular § 140. On the principle of prevention and precaution in international environmental law, see Dupuy/Viñuales, Environmental Law, p. 58-64.

[7] See art. 74 al. 2 of the Swiss Constitution: Federal Constitution of the Swiss Confederation of 18 April 1999, RS 101, status as of 1 January 2018; as well as art. 1 al. 2 and 11 al. 2 and 3 of the Federal Act on the Protection of the Environment [Environmental Protection Act, EPA]: Federal Act of 7 October 1983 on the Protection of the Environment, RS 814.01, status as of 1 January 2018. On the principle of prevention and precaution in Swiss law, see Jungo (2012); Marti (2011).

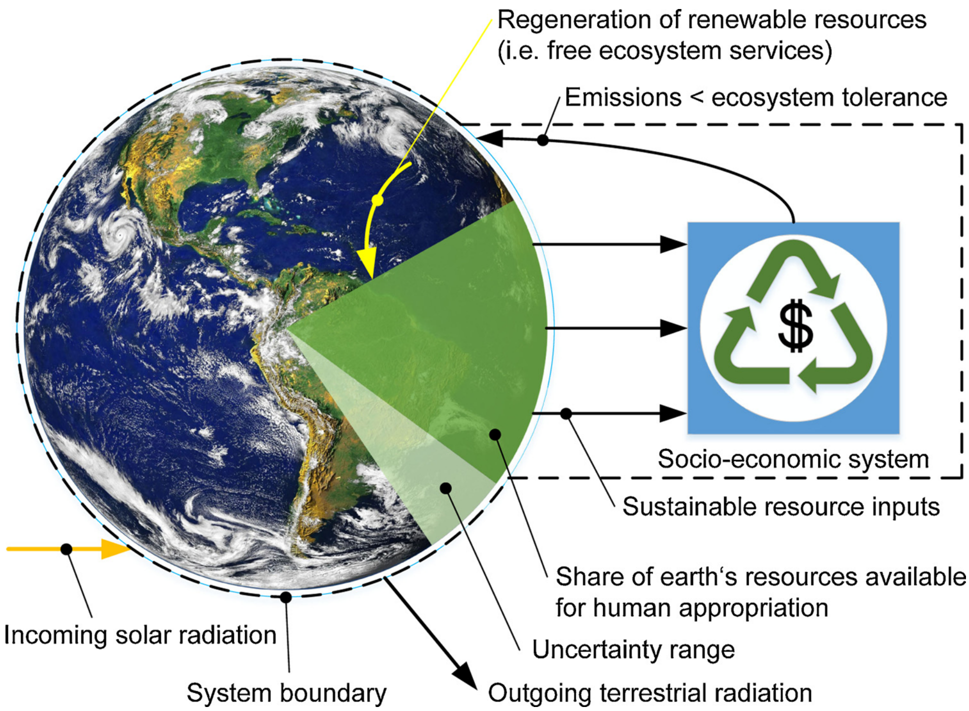

Fig. 3. The dark green slice schematically represents the sustainably available resources for the socio-economic metabolism. This slice may be in reality a little larger (light green slice), but the precautionary principle requires that the sustainable share is determined at the lower end of the uncertainty range. The rest of the resources are necessary for Earth system functioning, which includes the absorption and regeneration of emissions, providing free ecosystem services such as fresh water and air.

modelling as well as changes in the Earth system and are thus dynamic boundary conditions (Sabag-Munoz and Gladek, 2017).

Human activities need to be designed in a way that they do not compromise, ideally even advance Earth system functioning, also after intentional (e.g., abandoned building) or unintentional (e.g., dispersion (Geyer et al., 2017)) discharge of its material and energy flows. The appropriation and discharge of resources is thus limited by the biophysical capacity of the Earth system and have to be evaluated regarding the availability upstream and potential harm downstream (see Fig. 3). A CE can be considered sustainable, if it is built exclusively on the sustainably available resources, i.e. products and services utilize the ecologically available material and energy mix and a management system needs to ensure that globally resource needs don't exceed availability.

Let's consider our washing machine example. The outer panels can be made from different materials (e.g., plastics, coated steel sheet, stainless steel…). For a sustainable-circular washing machine, the materials would need to be chosen in regard to their global sustainable availability, considering resource utilization parameter like recyclability and lifetime of parts (which includes reuse, remanufacture and repair). Besides the comparison of different material alternatives, the absolute resource availability in relation to current global production indicates how much resource use needs to be reduced (or can be still increased) to become environmentally sustainable. Such targets can be considered in the design of product systems, such as a washing machine. It provides an indication on how much the resource intensity of the service "washing" would need to be reduced to become sustainable on a global scale, if the demand is assumed to be constant. It can also be used to set targets for industrial sectors and countries to reduce their absolute resource use, as it is attempted for CO_2 in the science based targets initiative (Pineda et al., 2015).

3.4.2. *Ensure an effective resource utilization*

CE is a system with restricted inputs and outputs. The highest standard of living can be achieved, when the inputs are used most effectively and outputs are reduced. There are, however, physical limitations to the utilization of resources.

Even though energy is conserved, only such energy conversions are possible where the entropy increases. Consequently, there are more or less useful forms of energy and its useful content can be described as exergy (Ayres et al., 1996; Connelly, 1997). Every conversion process decreases the exergy content, i.e. exergy is destroyed (Connelly, 1997; Shukuya, 2013). Entropy correlates to the probability of a system to appear in a particular state (Stephan et al., 2009). A high state of order (e.g., a crystal structure) is less likely than a low state of order (e.g., random distribution of molecules in gases). Thus the entropy is low, when the order is high and vice versa. It is possible to increase the order in a specific part of the system, such as in the refinement of iron ore to steel. However, this requires useful work (i.e. exergy) and in the overall system the orderliness decreases.

In a production process, raw material with high entropy is refined through the employment of exergy into a product with low entropy (i.e. high order). In the use phase of the product, the entropy increases and, to restore the initial order, it again requires exergy (see Fig. 4). Every change in the entropy level in a product leads to entropy production in the overall system and thus decreases the usefulness of its resources. Consequently, the first fundamental requirement for CE is:

The circular economy aims at minimizing entropy production.

Small changes in entropy levels are preferable for a CE. The waste hierarchy, as it is often proposed in a CE context (e.g., European Union (2008)), can be derived from this requirement. Reuse of parts or products without any changes requires no change in the entropy level of the material, whereas refurbish and recycle result in increasing entropy changes. Production out of raw material and disposal in a landfill (i.e. "linear economy") results, in most cases, in the largest changes of entropy in the material and is thus the least preferable option. However, the principle of minimizing entropy is not limited to end-of-life strategies, but has to be applied to all lifecycle steps, e.g. material selection.

Coming back to the washing machine, every stage of the life cycle consumes exergy and produces entropy. For example, including the additional functionality of automatic dosing of detergent requires additional equipment but potentially reduces detergent consumption. The amount of exergy destruction for the alternatives with and without dosing system can be evaluated and the alternative with the lower value selected. Alternatively, the entropy production can be evaluated through either thermodynamic entropy (e.g., in energy dominated systems, like the heating system in a washing machine) or statistical

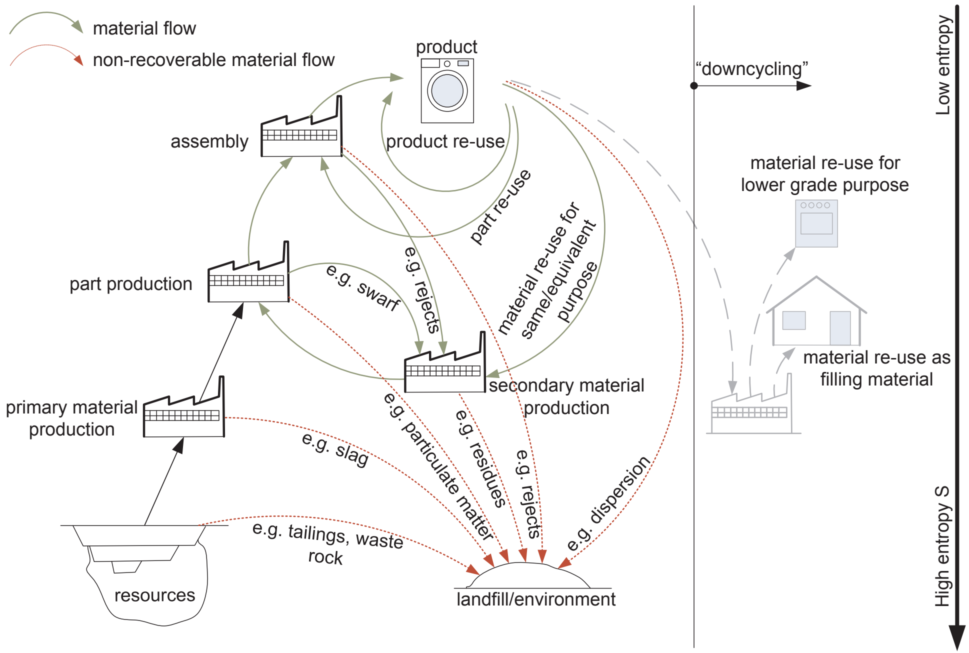

Fig. 4. Schematic representation of entropy changes in lifecycle steps (entropy axis on the right). Virgin resources (high entropy) are refined to products (low entropy). At the end of life, different strategies lead to different changes in the entropy level, where green arrows indicate recovered materials, and dashed-grey denotes downcycling, where the material cannot be used for the same purpose any longer. Every step in the life cycle leads to inevitable losses (dotted-red).

entropy (e.g., for concentration and dilution activities, like detergent production and waste water treatment, see Rechberger and Brunner, 2002).

Theoretically, materials can be cycled indefinitely as long as sufficient exergy is available (Ayres, 1999). Since available exergy is limited, materials need to be kept at a low level of entropy for as long as possible. However, many different mechanisms, such as dispersion, dilution, contamination, degradation and process losses, inevitably transform materials into a state of high entropy, where it is essentially lost for technical use and thus material cycles cannot be fully closed (see Fig. 4 and Table S1 in SI). For example, material can be dispersed as fine particles in the environment, with no practical means of recovery. Accumulation of impurities is another example for practically limiting factors to recycling (Lovik and Müller, 2014; Nakajima et al., 2009). In general, every process step and exposure to ambient conditions, eventually leads to a loss or degradation of the material. To utilize the materials as long as possible, it is essential to build "clean cycles" (Kral et al., 2013), minimize losses to the environment and design product cycles for longevity (Allwood et al., 2011). The faster a product needs to be replaced, the more often a cycle is needed to provide the same service again and the more material is lost per functional unit. As a second, general requirement for CE, we can thus derive that:

> Durability is key to preserve material value ("slow cycle").

The longer a material can be used for its beneficial and intended purpose, the less material per functional unit is lost. Even though material value is preserved, technological progress might make it beneficial to upgrade or replace the product prematurely due to increased energy efficiency in the use phase (Bakker et al., 2014a). This is however only relevant for technologies in early development stages and products causing high impacts in the use phase in comparison with other life-cycle phases and a technological upgrade may solve the problem (Telenko et al., 2016).

For example, once produced, the washing machine side panel doesn't cause any environmental impacts during its useful life and it is therefore beneficial to use it as long as possible. The washing machine, at the other hand, requires resources and causes environmental impacts during the use phase. The efficiency of the washing machine declines over time due to calcination, wear and material aging and a newer model may have increased efficiency, making it environmentally beneficial to replace the old machine at a certain point (i.e. ecologically optimal lifetime (Gensch and Blepp, 2015)). The side panel, as many other parts of the old washing machine, can be still used in its intended function in the new model, which however would require a standardization of these parts and a take back mechanism for old machines. The longer the use of its parts, the smaller the amount of resources required to fulfil the same functionality.

Materials and energy are available in limited quantities, especially those qualities, which can be technically made available for human use (Allwood et al., 2011; Ayres, 1999). To utilize both materials and energy as long as possible, they need to be applied as effective as possible. Efficiency is the third general requirement for CE:

> Optimizing output per unit input for all resources (i.e. efficiency) utilizes the sustainable resource base best.

For washing machines, energy efficiency had long been in the focus. However, this concept has to also be applied to resource in general, i.e. consumables in all life cycle stages (e.g., detergent, solvents) as well as materials in the machines itself. The efficiency can be increased at the level of processes (i.e. minimize process losses and manufacturing waste) or in the product. For example, light-weighting, functional integration and washing cycle optimization can reduce resource demand of a washing machine.

The strategies of material cycling of mainstream CE understanding, along with strategies from related schools of thought, are derived as a consequence of optimized resource use in a restricted socio-economic system. To select the optimal solution for a product, initiative or strategy, a thorough assessment against the general requirements and the sustainable resource base needs to be carried out. Again, such an assessment needs to follow the precautionary principle, that is to say, impacts need to be calculated as the upper limit of the uncertainty range.

3.5. Definition

Building on the findings of the previous sections, taking into account the limitations of current definitions, the idea of a normative status, but also the physical and ecological considerations, we propose to define CE as follows:

> The Circular Economy is a model adopting a resource-based and

systemic view, aiming at taking into account all the variables of the system Earth, in order to maintain its viability for human beings. It serves the society to achieve well-being within the physical limits and planetary boundaries. It achieves that through technology and business model innovation, which provide the goods and services required by society, leading to long term economic prosperity. These goods and services are powered by renewable energy and rely on materials which are either renewable through biological processes or can be safely kept in the technosphere, requiring minimum raw material extraction and ensuring safe disposal of inevitable waste and dispersion in the environment. CE builds on and manages the sustainably available resources and optimizes their utilization through minimizing entropy production, slow cycles and resource and energy efficiency.

Appropriate strategies within CE can then be, e.g., life time extensions, combination of functions, upgrade of old products to new technological standards, repair, reuse functions, reuse parts, recycle materials, etc., which have to be selected, case by case, considering minimum resource requirements and environmental impacts.

4. Discussion

Except for the assumed normative position to ensure inter-generational equity and the acknowledged willingness to serve human well-being and prosperity (see section 3.2), our abstract and systemic definition of CE intently disregards the content of normative considerations, as they are, per definition, subject to change. From a theoretical perspective, the organization of the society and the contours of – and how we actually define – human well-being and economic prosperity are the result of normative and political choices that therefore do not have to be further defined in the view of an ideal-typical definition as developed above. Different social organization forms and political systems could certainly be fit to stay within this frame and achieve a non-wasteful use of resources, given that they respect a resource based-approach. Moreover, different forms of CE can be imagined and could coexist (Hobson and Nicolas, 2016). In an attempt to nevertheless give hints and avenues for reflection and to embed the natural science and engineering considerations developed in section 3.4 into a larger context, we suggest that following general considerations may be discussed, if the goal is to implement a CE concept that is systemic and resource-based by definition. In section 4.1 we raise some important governance questions and show in section 4.2 possible pathways towards an integration of Earth system capacity into resource governance. Section 4.3 discusses the role of business in this approach and will highlight some possible challenges and consequences deriving and whenever useful, applied to the example of a sustainable-circular washing machine.

4.1. *Resource management and governance questions*

A resource-based approach implies to quantify the resources available and then to agree on repartition mechanisms. A big task ahead will consist in developing mechanisms to ensure the allocation of the available resource base, as different allocation principles can be imagined (e.g., egalitarian, based on economic throughput or capacity, using historical approaches like the grandfathering principle, etc. (Sabag-Munoz and Gladek, 2017)). In this regard, some of the questions which need to be addressed in a political discourse – and more importantly agreed on and implemented – are:

- How to globally agree on a method or standard to quantify the available resource base, as different methods can be challenged and all integrate necessary approximations and assumptions?
- How to divide and allocate this available resource base then among nations, regions, economic sectors, companies and individuals? By whom should the allocation be calculated and by using which criteria?
- How to ensure that the planetary limits are respected everywhere and at all times? What kind of (world-wide) monitoring system could help achieve such a goal?
- What are the more efficient and politically acceptable policy instruments? Should we favour top-down regulations, with quotas, legal interdictions, obligations and penalties over "political incentives" and self-regulation ("budgeting" and/or "targeting")?
- Under what conditions could we rely on existing market-based mechanisms for a sustainable resource allocation? In other words, could the weight of negative externalities be integrated into and reflected by price mechanisms?
- How to achieve coherence in the governance of natural resources, especially with regard to the current spatial mismatch between sovereign institutional territories and global resource flows?

4.2. *Towards a systematic socio-economic integration of Earth capacity*

Ehrenfeld (1997), building on intuitionalist models of organized social behaviour, describes "*the dominant social paradigm*" (DSP) as the paradigmatic foundation in which dominant beliefs and social norms are contained: specific forms of social structures result from the diffusion of "*the culturally foundational notions into more explicit organizational (or paradigmatic) forms -government, church, family, corporate, etc.- and the shape of missions, tools, and authoritative relationships that characterize them"*. The author states that the natural world has been disconnected from social thinking and action in the paradigmatic base of western modernity; therefore implementing our ideal-typical CE within the current DSP represents an (impossible) challenge. Indeed, most of our current institutional structures are being rooted in a "linear" world view and the transition towards a more "systemic" one imply deep changes. Environmental law for example, as credibly shown by DeLucia (2013), historically, is infused with particular epistemological assumptions and cultural values, which reflect a worldview developed "*under the influence of the prevailing Cartesian legal ontology*". The current position of environmental law internationally is therefore really delicate, as its role is to address multiple ecological crises, while "*structurally and conceptually being rooted in a broader legal tradition thoroughly implicated in the domination and 'othering' of nature*", hand in hand with science ("*the scientific-legal complex*") (DeLucia, 2013).

With regard to a systemic and resource based CE, it appears that the integration of the natural world and the Earth capacity into socio-economic thinking requires a shift in the paradigmatic base, as it implies a change in the way all social actors, be it individuals, businesses or governments consume and produce, and more generally, on how they see the world. It may require to question and adapt our world-views on different subjects (e.g., relationship between humans and nature, patterns of politics, methods of scientific inquiry) (Ehrenfeld, 1997; Wallace et al., 1996). As stated by the World Business Council for Sustainable Development (2017), *"transitioning to the circular economy will catalyse the most transformational economic, social and environmental changes since the First Industrial Revolution*". As an illustration, in the following lines, some institutional consequences of a model being deeply rooted in a linear world view and how systemic thinking might affect them, are briefly discussed.

4.2.1. *From compartmentalization towards integration*

According to a strong compartmentalization logic, environmental considerations are treated as separate and distinct from social and economic considerations. For example, "e*nvironmental sustainability"* was only one out of 8 MDGs and the environment is considered in only 3 out of 17 SDGs. A similar logic is often present in national regulations, where environmental law is approached as a specific domain instead of being embedded into other regulatory fields. The interests of the environment are weighted as separate parameters to be balanced with other considerations, implicitly occulting the link between the economic and social impacts of the environmental and resource crisis. This reductionist understanding is particularly visible in the weak understanding of sustainable development[8], which is aiming at balancing environmental, economic and social considerations, while accepting that a decrease of environmental capital can be compensated by the increase of economic or social capital. The original conception of sustainability, as presented in the Brundtland (1987) report, imposed to preserve natural systems and resources in order to maintain the global integrity of the Earth system, is more in line with a systems perspective; there was no possible trade that would allow to compensate irreversible environmental losses through an increase in economic or social capital (Flückiger, 2006). For approaching our ideal-typical definition of CE, the physical limits and environmental boundaries, derived according to the precautionary principle, can be seen as the frame within all activities need to take place. Hence, to reach a socio-economic system that is sustainable in the long run – at least from an environmental perspective – it should be ensured that the principles of CE, as defined in section 3.5, are respected on a global scale and every socio-economic activity takes place within these boundaries. As a consequence, when it comes to regulating the social organisation (and the economy, which is part of the society), decisions that are not allowing to stay within the safe operating space for humanity (Dearing et al., 2014; Raworth, 2013) should be dismissed. Considerations about the sustainably available resource base are therefore to be integrated into every sector and activity. An example of this understanding is the "wedding cake" representation of the SDG's developed by the Stockholm Resilience Centre, which acknowledges that economies and societies are embedded in the biosphere and that different SDG's directly or indirectly rely on a sound resource base and food system[9] . Also, the idea of integration has already found its way into the policies of the EU: making sure that environmental concerns are fully considered in the decisions and activities of other sectors is a requirement under the EC Treaty since 1997[10] . To put this requirement into practice, the European Council launched the "Cardiff process" in 1998, which was designed to introduce a horizontal approach to environment policy by incorporating it into all Community policies[11] . The importance of environmental integration was reaffirmed in the 6th Environment Action Programme[12] .

4.2.2. From short-sighted and free market coordination towards prioritization of long-term sound management of resource base

Given the combination between the free market as the primary coordination institution (Ehrenfeld, 1997) and a short time-horizon for decision making and profit earning, environmental regulations are generally perceived as barriers to the exercise of individual and economic freedom[13] . The subsidiary importance of environmental protection acts and its potential opposition with individual and economic freedom can be observed in the international context[14] . Environmental law is sometimes presented as a "mitigating" or "containment" instrument aiming at reducing the ecological problems created by economic and industrial activities "to the extent possible" (DeLucia, 2013). The same phenomenon is to be found at the national level: in Switzerland for example, some dispositions of the Environmental Protection Act (EPA)[15] are weakened by typical reservations expressed as "wherever possible" (e.g., art. 30 al. 1 et 2 EPA) or "provided that this is economically acceptable" (e.g., art. 30d al. a EPA, see also art. 11 al. 2 EPA). Swiss case law also explicitly addresses the relationship between environmental protection and economy as a "tension field" (ATF 131 II 431 ss, ground 4.1)[16] . According to art. 36 of the Swiss Constitution (Cst.)[17] restrictions to fundamental rights can be admitted, if the restrictions are necessary and proportionated to guarantee a higher public interest (health, political stability, etc.). In some cases, restrictions to economic freedom (which is a fundamental right, see art. 27 Cst.) were justified by the protection of the environment (ATF 140 I 218 ss, ground 8.8; Supreme Court 2C_ 136/2018, September 24, 2018, ground 6.1). From a systems perspective this makes a lot of sense, a stable environment is a precondition for the economy and society to function. As already identified by the Commission of the European communities in 1998, "*the current pattern of economic development too often entails conflicts between development and environment; this cannot be permitted to continue. Policies that result in environmental degradation and depletion of natural resources are unlikely to be a sound basis for sustainable economic development*" (COM/98/0333)[18] . Regulations, their application – and therefore mentalities – need to adapt in order to overcome this constructed and unsystematic tension field that lies in the way of a transition towards a CE. With a change of perspective, environmental regulations and restrictions could even be perceived as a positive enabler to allow well-being (including economic wealth) and long-term survival (and profit), rather than a barrier to the exercise of their rights and freedom[19] ; hence, instead of thriving to balance supposedly conflicting interests, measures towards a sound resource management would be prioritized in order to ensure other interest (like economic and

[8] For the distinction between strong and weak sustainability and different understandings of the notion, see e.g. (Flückiger, 2006; Reiser and Pforr, 2018)

[9] See https://www.stockholmresilience.org/research/research-news/2016-06-14-how-food-connects-all-the-sdgs.html, consulted on June 17, 2019.

[10] Article 6 of the Treaty establishing the European Community (Consolidated version 2002), OJ C 325, 24.12.2002, p. 33–184 (ES, DA, DE, EL, EN, FR, IT, NL, PT, FI, SV), Document 12002E/TXT, http://data.europa.eu/eli/treaty/tec_2002/oj: "environmental protection requirements must be integrated into the definition and implementation of the Community policies [.] in particular with a view to promoting sustainable development".

[11] More information related to the Cardiff Process see https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:l28075 and Communication from the Commission to the European Council - Partnership for integration - A strategy for Integrating Environment into EU Policies - Cardiff - June 1998 /* COM/98/0333 final */ (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:51998DC0333&from=EN)-

[12] Pertaining to art. 1 al. 1 of Decision No 1600/2002/EC of the European Parliament and of the Council of 22 July 2002 laying down the Sixth Community Environment Action Programme, "[t]he Programme should promote the integration of environmental concerns in all Community policies (…)" (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32002D1600&from=EN).

[13] For an example: the main argument for rejecting the interdiction of single-use plastic bags in Switzerland was that it could be considered as a disproportionate limitation of economic freedom, see (Epiney and Hehemann, 2015)

[14] See e.g. in the field of biodiversity protection art. 2 al. 3 of the Convention on Wetlands of Importance especially as Waterfowl Habitat (or Ramsar Convention): "the inclusion of a wetland in the List does not prejudice the exclusive sovereign rights of the Contracting Party in whose territory the wetland is situated", https://www.ramsar.org/sites/default/files/documents/library/scan_certified_e.pdf; RS 0.451.45 or art. 22 of the Convention on biological diversity (CBD) "The provisions of this Convention shall not affect the rights and obligations of any Contracting Party deriving from any existing international agreement, except where the exercise of those rights and obligations would cause a serious damage or threat to bio-logical diversity", https://www.cbd.int/convention/text/.; RS 0.451.43.

[15] Federal Act of 7 October 1983 on the Protection of the Environment, Systematic Register for Swiss Federal Legislation ("SR") 814.01, status as of 1 January 2018; it is among other intending at preserving "the natural foundations of life sustainably" (see art. 1 al. 1 EPA).

[16] ATF stands for "arrêt du Tribunal federal", which means Decision of the Swiss Federal Supreme Court; on this question see Felix Uhlmann, Grundprinzipien der schweizerischen Umweltverfassung aus der Sicht des Wirtschaftrechts, in URP 2007 p. 706.

[17] Federal Constitution of 18 April 1999 of the Swiss Confederation, SR 101.

[18] See footnote 13.

[19] Regarding frameworks aiming to elaborate an ecological philosophy of law, see (Tallacchini, 2000)

individual freedom).

4.2.3. From end-of-life towards life-cycle thinking

The evolution of environmental law shows that often, major regulations were adopted after main environmental catastrophes, namely to mitigate contaminations, when they became a visible nuisance (see e.g., Knoepfel, 2019). Waste law is being rooted in an end-of-life approach, where the goal is to better manage waste and the contamination of the environment. It is focusing on improving collection and recycling. A lot of progress has been made over the years (from landfill to incineration, better recovery rates and recycling techniques, etc.). However, such an end of pipe approach, focusing on reducing the symptoms and trying to mitigate the negative impacts of production and consumption, rather than examining the global picture, does not cover all aspects of a CE and is therefore insufficient. A conceptual shift towards life-cycle thinking which could be recognized as a formal environmental principle (De Römph, 2018) would be beneficial. It reflects a perception of environmental problems that puts the product at the centre, through its entire life phases and associated impacts (Bugge et al., 2018). Product design and the policy framework impacting design "*assume a central role, guiding the flows of materials in and out of the environment, and, at the same time, reflecting their social, economic importance. Looking at products, rather than processes, shifts the policy-maker's focus from the end of the process pipe to the center stage of the market and the market's social importance as a means to satisfy the collective demands of a policy*" (Ehrenfeld, 1997). Legislation doesn't expressly addresses or define life-cycle thinking yet, but the EU environmental policies, namely in the light of the CE Package[20] and the Green Paper on Integrated Product Policy[21] consider it as an important "policy principle" (De Römph, 2018). The cascading waste hierarchy, which establishes a priority order from prevention, preparation for reuse, recycling and energy recovery through to final disposal, such as landfilling, is a principle that aims to encourage the options that deliver the best overall environmental outcome (see COM/2015/0614 fin. l cited in footnote 24; in Switzerland, see art. 30 EPA), which is also reflecting a step in direction of life-cycle thinking approach. Going a step further could consist in recognizing the existence of "(EU) materials law" (De Römph, 2018) or to shift from waste to product law (Backes, 2017).

In relation to the illustrating example of the circular washing-machine, the integration principle could lead to take into account a sound allocation of resource scarcity and budgets in public policies or legislation: that could for example be formalized through importation taxes or directives regarding the choice of materials and product design (e.g., prohibition to use scarce materials if an alternative is available); prioritizing environmental impact rather than free market as a coordination mechanism could for example lead in extended interdictions of toxic substances and materials, changes in accounting rules and standards, taxing "entropy production" rather than "value creation", which should all be designed in a way to make a circular washing-machine more attractive over its life-cycle. Finally, shifting to a life-cycle approach could, for example, be reflected with further implementation of the Extended Producer Responsibility, extension of guarantees, obligations to provide spare parts, higher taxes on primary resources and lower taxes on labour, which are all possible actions that incentivize a better conception of the product with a long-term perspective in mind and an extended usage, through maintenance, repair and refurbishment.

4.3. Business as a driving force of the transition?

Implementing sustainable CE imposes new boundary conditions for the economic system and also requires a paradigm shift in corporate understanding. As argued in section 3.4.1, resources are available in finite quantities. Hence, either there will be regulations that oblige companies to internalize their resource budgets or companies will voluntarily internalize it. In the second case, companies will benefit from the saleable first mover advantage, reduced dependence on resource price fluctuations and positive benefits of social welfare. Either way, this inclusion of resource finiteness would be the starting point for companies to change the current inside-out perspective in the business-as-usual paradigm and shift the perspective to outside-in. Analogous to the considerations of Dyllick and Muff (2016) thoughts to "Truly Sustainable Business", this means that companies need to integrate environmental and social factors into their business management strategies and in their business models. The typological increase (Business Sustainability 1.0, 2.0 and 3.0) used by Dyllick and Muff (2016) starts with companies that pay attention to sustainability due to external pressure or market factors without changing the current business premises up to companies that convert sustainability challenges into business opportunities and give business sense to social or environmental issues. The voluntary inclusion of such resource budgets as a self-restricting instrument raises companies in this typology high upwards.

The pragmatic application of this outside-in approach can be found in the innovation from traditional to more sustainable (e.g., Baden-Fuller (1995); Joyce and Paquin (2016); Lüdeke-Freund et al. (2018)) or in our case cycle-oriented business models (e.g., Bocken et al. (2014)). The change of perspective through the outside-in approach can also lead to more integral and sustainable management practice as called for, e.g., by Stead and Stead (2008). Especially the voluntary restriction to sustainable resource budgets and optimizing its use through company management may stimulate activity in the market economy as well as in social and political structures and provide important impulses for the introduction of state-coordinated regulations towards sustainable resource allocations. The paradigm shift lies in the fact that the inclusion of a finite availability of resources becomes a key factor in strategic decisions and thus actively flows into the corporate calculation.

The paradigm shift can also be seen in a further pragmatic step as the effort of companies to innovate their business models as a result of the (exogenous) resource budget constraints. This is due to the fact that innovative business models (e.g., "light as a service" (Philips Lighting, 2018)) can drastically reduce the resource requirement and thus can be of significant competitive advantage. And business models determine the profound purpose and activities of a company as well as the logic of how value is delivered to the consumer as a holistic description (Chesbrough, 2010; Chesbrough and Rosenbloom, 2002; Teece, 2010; Zott and Amit, 2010). The growing business model literature deals with the in-depth redesign of business models and demands an easier integration of sustainability into the business of companies (Bocken et al., 2014; Boons et al., 2013; Joyce and Paquin, 2016; Schaltegger and Wagner, 2011; Stubbs and Cocklin, 2008; Yunus et al., 2010). In this context, various authors speak of "circular business models" (Bakker et al., 2014b; Geissdoerfer et al., 2018; Urbinati et al., 2017). It is important to note that the idea of "one" business model on its own can achieve CE seems rather illusory – in view of all the business activities that have to be undertaken to create a CE. The "circular" says more about the "cycle applicability" than about a self-contained circular business model. It is therefore helpful to place the innovation of

[20] More information on the Final CE Package for Circular Economy see http://ec.europa.eu/environment/circular-economy/index_en.htm; regarding the adoption of an Action Plan towards CE, see COM/2015/0614 final: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Closing the loop - An EU action plan for the Circular Economy, 2.12.2015: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

[21] COM/2001/68 ; see also Commission Communication on Integrated Product Policy Building on Environmental Life-Cycle Thinking, COM/2003/302 final, p. 10.

"circular" business models in the larger context and to see it as a bundle of business models along the closed-loop supply chain which enable a CE (Guide and Van Wassenhove, 2006, 2009; Lüdeke-Freund et al., 2019). It is important, consequently, that the considerations of the boundary conditions are carried out over the entire closed-loop supply chain.

The practical example of the washing machine from section 3 with the changes in design, selection of materials and the adapted possibilities of usage show how challenging the design of new, cycle-oriented business models can be. A critical and complicating issue, which is typical for the linear economy, is the fact that products are classically sold to the consumers. The resulting loss of customer relationship and control over the product itself while it is used – due to the change in ownership – makes lifetime-extending repairs, maintenance or concrete refurbishment measures difficult (Bocken et al., 2016; Moreno et al., 2016; Ritala et al., 2018). In order to increase the profitability of such circular changes, incentives can be internalized via new revenue models, which no longer require a change of ownership and expand the corporate customer relationship (Bocken et al., 2014; Moreno et al., 2016). For practical illustration, two suitable revenue models – as an important part of a cycle-oriented business model – are presented in more detail: performance-based contracting or pay-per-use (Bocken et al., 2016; Ellen MacArthur, 2013; Gassmann et al., 2014). The first one enables companies to deliver a comprehensive service promise (which includes maintenance, upgrading, etc.) to their customers which aims to provide a desired outcome (e.g., clean garments) instead of the purchase of the washing machine. Due to the new contractual situation, the company generates income during the entire lifetime of the washing machine, and no longer only by selling it once. Also with the second revenue model the washing machine remains in the ownership of the manufacturer and the customer pays simply per wash, i.e. pay-per-wash. In addition, this increases the incentive for consumers to limit their consumption to what is necessary and to price it more precisely. Studies in the corporate context show that the implementation of cycle-oriented business models or patterns is complex and subject to a wide variety of interlinked dimensions of politics, market, society and technology (de Jesus and Mendonça, 2018; Kirchherr et al., 2017; Ormazabal et al., 2017). All these studies show barriers towards the implementation of CE and demonstrate at the same time the key role of companies in the centre of all these interconnections and interdependencies as effective implementing bodies of CE. The analysis of the barriers identified (often divided into cultural, technical, market and regulatory barriers) indirectly reveal the enormous inherent potential that can be found in solutions to overcome them. Kirchherr et al. (2017) show how the different barriers are connected and that the interrelatedness of these can lead to chain reactions towards the implementation failure or success of CE. In this way, market-relevant factors can prevent political and thus legal changes, which in turn prevent market efforts towards new and innovative cycle-oriented business model innovations and in the end hinder change in consumer behaviour. For example, a lack of demand for resource-saving and cycle-oriented products can lead to a restrained supply of such products on the market and limited funding related business models, which in turn reduces the signal for politicians to elaborate incentive systems for companies who want to produce cycle-oriented products. The described interdependence does not only move in one direction but can also be seen as one with reciprocal potential.

This is a clear statement for the voluntary participation of companies in the integration of the above-mentioned resource budgets and thus taking up the role as exemplary signal carriers in the market. Companies can therefore not only benefit from the predicted financial long-term potential of CE and innovative cycle-oriented business models (Ellen MacArthur Foundation, 2015; World Business Counsil for Sustainable Development and Boston Consulting Group, 2018), but also redefine its corporate sense of purpose. They can directly or indirectly as a by-product of their traditional corporate activities play this important role in the transition towards CE. The corporate opportunities resulting from new cycle-oriented business models can thus be transferred on the one hand to secure corporate prosperity and long-term survival and on the other hand, trigger important impulses beyond the actual corporate sphere of activity. In order to bring CE forward, there is a need to critically evaluate the risk that either companies or governments use CE as pure symbolic signalling effect (Baker, 2007; Matten, 2003). Otherwise, CE as a concept becomes meaningless and degenerates into a simple marketing medium.

5. Conclusions

This paper presents a systematic top-down approach to CE, which describes an ideal, or reference, and aims at connecting global sustainability criteria with initiatives at company level. The normative assumption behind this ideal is based on the global consensus that humanity thrives for well-being and survival for present and further generations. In order to connect environmental boundary conditions with individual decision making, we identified a need to translate ecosystem boundaries into resource budgets. These serve two purposes: the comparison of material alternatives to aid the selection of materials based on easy-to-handle environmental criteria, as well as the quantification of the absolute resource intensity reduction required to reach environmental sustainability on a global scale. A CE strives to utilize these limited resource most effectively and we have identified three general engineering guidelines to achieve this:

- Minimize entropy production: selecting circular strategies (e.g., reuse, refurbishment) according to the entropy production over the whole life-cycle.
- Slow cycles: prolonging the service life of parts (e.g., to be used in refurbished products) or the whole product (e.g., reuse).
- Resource efficiency: reducing process losses (e.g., off-cuts) and material demand for functional equivalence (e.g. light-weighting).

The implementation of a CE could be eased by the adoption of punctual new regulations and incentives, such as for example interdiction of mixed-materials, higher tax on raw material and lower tax on labor, etc. More importantly, transitioning towards a sustainable CE is tightly linked with a shift in the way we look at the world, which in turn impacts how we conceive, systematize and apply our regulatory and institutional systems. Namely, from a policy perspective, we suggest that a CE could benefit from and lead towards higher integration of environmental concerns into every other field, a clear prioritization of maintaining a sustainable resource-base over other short-term interests – in order to safeguard these interests in the long-run – and finally a life-cycle-thinking approach. At the company level, this raises the question of how business models can be innovated along closed-loop supply chains in such a way that they can jointly satisfy customer needs within the resource budgets. This involves the shaping of customer relationships, entrepreneurial cooperation in value networks along the closed-loop supply chain and the shaping of suitable revenue models as well as product take-back procedures.

To support business model and technical innovations, guidelines and indicators need to be developed to enable and ensure an effective implementation of CE. These guidelines can influence the design of a product system starting with the conception phase, when the environmental impacts are essentially determined. Before a product enters the market, a life cycle assessment (LCA) (Pennington et al., 2004; Rebitzer et al., 2004) study can show how effective the design process had implemented the sustainability requirements of CE. Further, material flow analysis (MFA) (Brunner and Rechberger, 2016) on sector, country and global scales need to keep track of the material flows and monitor the actual utilization of the sustainable resource base and its associated environmental impacts of socio-economic activities. The business motive will drive innovation to utilize the restricted resources best. This will, we believe, trigger research and development of truly "circular" products, following the general guidelines outlined in this paper.

As a next step, there is a need to develop possible pathways to initiate a transition process towards such a CE. It is necessary to develop a methodology to estimate and calculate global sustainable resource budgets. Based on this, concrete product design guidelines can be formulated and tested in case studies together with companies. Business model innovation goes hand in hand with the product design, in order to achieve the resource intensity reductions in the product or service required to reach environmental sustainability globally. From an implementation perspective, the allocation of resource budgets requires the creation of new institutional structures or a political agreement within the current ones; however, voluntary bottom-up initiatives from companies, sectors, countries, can lead to self-orientation towards the respect of planetary boundaries.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary data

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