

Circular economy: preserving materials or products? Introducing the Resource States framework.

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Abstract

This paper draws on material entropy and life cycle thinking to develop the Resource States framework. This framework clarifies and systematises the language around resources within the circular economy (CE) discourse, such that insights from different tools and approaches that investigate different aspects of CE can be aggregated and a more comprehensive picture of complex circular systems can be compiled. Currently, progress of the CE discourse is hampered by a lack of a clear and systematic approach to what we refer to as the *particles state* and the *products state*. That is: whether to approach resource circulation from the perspective of elements, molecules or materials; or whether to adopt the perspective of products or finished goods. As these two perspectives are often implicit in current contributions to CE, we first articulate both approaches, before assessing their respective contributions and limitations. Next, we draw on material entropy and life cycle thinking to integrate both perspectives and develop a more comprehensive way of conceptualising resource states, in the form of the Resource States framework. We furthermore present how this framework can be used A) to clearly distinguish between circular strategies, as well as between different implementation scenarios of the same circular strategy; B) to systematically explore and map synergies and trade-offs between combinations of circular strategies; and C) to link circular strategies with structural waste present in a given context. Lastly, we discuss the strengths and weaknesses of the framework and reflect on how it advances the CE field.

Keywords

Circular economy, resource states, closed-loop, resource productivity, circular configurations, circular strategies

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1. Introduction

The circular economy (CE) concept invites societies to rethink their relationship with waste and resources. The concept proposes the replacement of current ‘take-make-use-dispose’ systems, with systems that address structural waste - encompassing clearly visible, as well as hidden forms of waste (EMF, 2013). For instance, think of the possibility to recycle materials as opposed to landfilling or incinerating them, and using materials and products more intensively through cascading approaches, as well as sharing and access-over-ownership models. Instrumental in addressing structural waste is the application of a range of *circular strategies*, which improve resource efficiency and productivity, and reverse resource loss¹. The aim of this new way of conducting waste and resource management is to create more societal, environmental and economic value, whilst reducing, avoiding and negating value loss and destruction (EMF, 2013; Murray et al., 2015; Geissdoerfer et al., 2016).

To deploy circular strategies effectively it is essential that they can be linked to outcomes that address structural waste (EMF, 2013; Blomsma, 2018), and their contribution to value creation (EMF, 2013; Widmer et al., 2018), as well as that it is understood how associated business risks can best be managed (Linder and Williander 2017). Moreover, a range of technical requirements need to inform the feasibility and desirability of circular strategies, such as resource quality and conservation (Gregson and Crang, 2015; Golev and Corder, 2015), and energy investment (Cullen, 2017). In addition, the systemic impact needs to be understood, in particular the phenomenon of circular rebound (Zink and Geyer, 2017; Hollingsworth et al. 2019). Many tools and approaches for the development of circular strategies have been put forward to support these aspects, such as inspirational frameworks (EMF, 2013, 2015; Stahel 2006; Pauli 2010), business models (Bocken et al, 2019; Pieroni et al. 2019), product design (Bakker et al. 2014; Moreno et al. 2016), and (sustainability) metrics and assessment (Moraga et al. 2019; Saidani et al. 2019; Parchomenko et al, 2019).

These tools and approaches have their application areas in different stages of circular oriented innovation (COI) (Brown et al. 2019), and it is often challenging to use them alongside each other, to easily compare outcomes or to transfer learning across case studies. While these methods were developed for the purpose of managing resources and revalorising waste they were also developed by different people or groups having different worldviews and different perceived good outcomes. This has as a result that the language and conceptual tools available for examining circular strategies is varied and unsystematic. Think, for instance, of cycling operations that materials can undergo. These are referred to as ‘recycling,’ but by some also as ‘reuse’ (e.g. Krystofik et al., 2018; Lazarevica and Valvea 2017). Similarly, the cycling of products is also spoken of in terms of ‘reuse,’ and also in terms of ‘recycling’ (e.g. Corporate Citizenship, 2014). A result is that the different implementation scenarios of circular strategies are obscured, and opportunities for improvements and synergies overlooked.

In addition to this semantic confusion, the conceptualisation of circular strategies may be influenced by different underpinning ideas regarding what are - and what are not - feasible solutions. This can be observed when comparing the solution spaces put forward by circular strategy frameworks (Blomsma, 2018). Some frameworks, such as Cradle-to-Cradle™, emphasise the cycling of materials (Braungart and McDonough, 2002), whilst other frameworks, such as Material Efficiency, emphasise cycling of products (Allwood et al, 2011). On top of this, the same cycling strategy can have different meanings within these frameworks. In the Waste Hierarchy, for example, ‘recycling’ can also mean ‘downcycling’ - i.e. the use of a material in a manner that is considered lesser in some regard than its preceding use - and it is an acceptable strategy within this framework (EC, 2008). In contrast, within Cradle-to-Cradle™ downcycling is not acceptable, and true recycling should lead to the restoration of recyclate to a virgin-like state

However, what constitutes the most important type of waste may be context dependent, and a narrow view of the available solution space could prevent the appropriate type or types of structural waste from being identified and addressed. This furthermore ignores the potential contribution the combined application of circular strategies has to make. That different conceptualisations of solution spaces have a real-world impact and hampers transforming value chains, is shown by Lapko et al. (2018) and Machacek et al. (2018), who illustrate that it leads different actors to set different priorities and to pay heed to different success factors.

¹ We consider all strategies that address waste and promote more efficient and productive resource use as circular strategies. A such, we include resource efficiency, resource productivity as well as resource reintroduction strategies. Think of strategies such as but not exclusive to: lightweighting, ‘doing more with less,’ but also recycling, industrial symbiosis, remanufacturing, refurbishment, sharing, substance and product cascading, as well as re-mining and urban mining.

This lack of a clear language and conceptual understanding of circular strategies stands in the way of generating the deeper insights into circular strategies necessary to advance the CE discourse (Reike et al., 2018; Kirchherr et al., 2017; Blomsma and Brennan, 2017; Homrich et al., 2018), leaving barriers unarticulated and crucial success factors unidentified.

In this paper we therefore examine the source of these difficulties and explore how they can be resolved. This results in the creation of the Resource States framework, which can be used:

- A. to clearly distinguish between circular strategies, as well as between different implementation scenarios of the same circular strategy;
- B. to systematically explore and map synergies and trade-offs between combinations of circular strategies;
- C. to link circular strategies with structural waste present in a given context.

This paper is structured as follows. After explaining the rationale behind our approach, we continue with an examination of the key contributions and critique on the two perspectives or *resource states* that dominate the CE domain - the *particles and products states*, showing that both positions cannot be regarded as absolutes. Next, material entropy and life cycle thinking are drawn on as a means to develop a comprehensive approach and consolidating these two perspectives. This is used to construct and introduce the Resource States framework, and a discussion of its uses. We conclude with a summary and reflections with regards to how the Resource States framework advances the CE discourse.

2. Background – circulating particles and products

Next, we explain the key observation that prompted this work and justify our approach.

2.1. Starting point

The cause for the varied and unsystematic language and conceptual tools available for examining circular strategies can be understood as follows. First, the distinction between preserving *particles* (i.e. elements, substances, molecules or materials), or *products* (i.e. finished goods) is frequently either ambiguous or disregarded altogether. This affects situations where no specificity is offered whether the aim is to preserve particles or products. The semantic confusion affecting the term ‘recycling’ and ‘reuse’ discussed earlier is a result of this. However, the distinction between reuse and recycling matters greatly, as the processes aimed at preserving different resource states are different, with different conditions affecting their outcomes

Second, the unwarranted a-priori or context-less emphasis on particular solution spaces discussed earlier, can also be traced back to different attitudes towards *particles* and *products*. That is: a particular perspective is promoted at the expense of the other and either the renewal or preservation of either particles or products is promoted. The example of the Cradle-to-Cradle™ framework in the above is illustrative in this regard. What’s more: such stand-taking frequently involves downplaying strategies not prioritised. For example: Cradle-to-Cradle™ attaches less importance to efficiency and downplays the contribution of product reuse and longevity (Braungart and McDonough, 2002)². However, this framework is by no-means the only one affected in this manner: see, for example Allwood (2014), who uses the Material Efficiency framework to promote product longevity and is critical of recycling as a solution space.

Summarising, the CE discourse is hampered by a lack of a comprehensive approach to the *particles state* and the *products state*³. As these two perspectives are often implicit in current contributions to CE, we first clarify them, and then critically assess them. Through this, we develop insights beyond those a systematic review would provide (Boell and Cecez-Kecmanovic 2015).

2.2. Circulation of particles

This section explains the *particles state* in more detail, before identifying the potential contributions this perspective has to offer the CE discourse and discussing the main points of critique.

² In their more recent book *The Upcycle*, the authors moderate this view. However, as this work is not yet as widely cited at their original *Cradle-to-Cradle - Remaking The Way We Make Things*, it is worth highlighting here.

³ We realise that this positioning is, in some respects, a somewhat artificial dichotomy. However, for the sake of clarity of argument, we maintain it for now, and return to this constructed nature in the discussion.

2.2.1. *The particles state and its role in CE*

The *particles state* conceptualizes a resource as a collection of *particles-of-a-kind*: resources consist of a particular quantity of particles that share one or more properties. Different definitions of what defines such collections are in use. In Material Flow Analysis, for instance, it is common to consider chemical elements, such as iron (Fe) and nickel (Ni) (Brunner and Rechberger, 2005; Reck and Graedel, 2012). In contrast, a broader definition is used in material science: here uniformity is defined by means of chemical and mechanical bonding (Allwood and Cullen, 2012). Thus, polymers and alloys can also be considered as particles-of-a-kind, as are other composite materials, such as wood. This definition can even be extended to include mixed waste. That is: particles-of-a-kind are perceived as equivalent, whether they are interchangeable from a molecular perspective, or are inseparable for chemical or other reasons, such as technical capabilities or economic feasibility. Whether defined as *elements*, *molecules* or the more general term of *materials*, the particles state regards the possibilities for value extraction of particles-of-a-kind to be limited only by their inherent chemical and mechanical properties.

Viewing a resource's journey through the economy from the perspective of particles means that their extraction or production, their subsequent dispersion and what happens to them at the end-of-life become important focal points. Cycling, in the strict sense, implies that particles return to the state equivalent to when first extracted, produced or manufactured. The return to a virgin-like⁴ state requires operations to extract the particles from products and to 'renew' them if required. This may involve purification or other treatment that restores as much of the original properties as possible. An example of a circular strategy in line with the particles state is recycling, both the chemical and mechanical variants. If one also allows for biological processes to perform renewal, then composting in order to return organic nutrients to the soil also constitutes a form of cycling.

Deviating from the strict interpretation of cycling, are substance cascades. As part of this more broadly defined form of cycling, subsequent applications for particles are found that do not involve renewal. This can entail downcycling and involves finding applications that are less demanding with regards to technical or other properties. However, when followed by recycling or composting cascaded substances can also be renewed (Sirkin and Ten Houten, 1994).

Viewed from the particles state, products are merely temporary physical forms of enduring collections of particles. As such, the preservation of the physical form or shape those particles are given during this journey – the goods and products from which end-users extract value – is not an immediate priority when adopting this perspective.

The particles state is the dominant view in several of the CE frameworks that provide guidance with regards to how to operate in a CE on the macro level of industrial systems and economies (Blomsma, 2018). See, for example, the Blue Economy (Pauli, 2010), Cradle-to-Cradle™ (Braungart and McDonough, 2002), The Natural Step (Eriksson and Robèrt, 1991), Regenerative Design (Lyle, 1994) and Industrial Symbiosis (e.g. Lowe and Evans, 1995; Korhonen 2005).

2.2.2. *Contributions of the particles state*

The particles state is typically adopted when addressing questions relating to the preservation or depletion of material stock-levels (e.g. Lapko et al. 2018), environmental and human health, the facilitation of economic functions (e.g. Allwood and Cullen 2012⁵) and water-food-energy nexus interactions (e.g. Keairns et al. 2016). The primary use of this perspective lies in its capacity to generate insights into complex flows otherwise invisible due to the time and/or geographical scales involved, as well as due to their incorporation in products with complex formulation.

The World Economic Forum has referred to the particles state as “catalytic” in transitioning to a CE (WEF 2014:48). There are various reasons for this. For instance, the preservation of material quality and purity, the thinking goes, preserves the fundamental building blocks of society and therefore they remain accessible for future use and innovation, and future generations retain access to the full scope of material possibilities (Braungart and McDonough, 2002). Moreover, in relation to critical raw materials (CRMs), the particles state, according to Lapko et al. (2018), “underlines the urgency of the material perspective.” What is meant by this, is that due to their importance within economies, current recycling systems as well as product design practices for CRMs need to be improved if these materials are to continue to fulfil these functions (Hagelüken, 2014; Peck et al., 2015).

⁴ The term 'virgin-like' is used here in acknowledgement of the fact that it might not be technically feasible to reproduce the virgin state entirely.

⁵ See pages 52 and 53 where the end-use of steel and aluminium is depicted.

2.2.3. Critique on the particles state

Although adopting this perspective can bring valuable insights, an exclusive focus on promoting the circulation of particles has also been critiqued. Here, we summarise the key points of critique.

Quality and volume loss cannot be avoided

The quality and purity of any given collection of particles-of-a-kind will inevitably deteriorate: through wear-and-tear, contamination, etc. This can also be understood from the perspective of infrastructural and technical limitations to collect and 'renew' particles.

- *Recovery rates fall short of 100%*

Sirkin and Ten Houten (1994) already pointed out that recovery rates have to be unfeasibly high to maintain availability. For example: after 10 cycles, only recovery rates equal to or higher than 99% will maintain the availability of a resource at a comparatively high level (91%). In reality, however, recovery often falls short of these levels due to dissipative losses, and difficulties with collection: worldwide only 9% of end-of-life materials are recycled (Haas et al., 2015; Circle Economy, 2019). Even for materials with relatively high recycling rates, the current rates fall short of 99%: 67% for paper and paperboard, 34% for metals and 26% for glass (EPA, 2018: US figures for 2015). Although exceptions exist - such as lead-acid batteries, for which the recorded rate is 99% (ibid) - this means that the rate of loss of particles can only be slowed down, but not avoided. For non-renewable resources in particular this is an important consideration.

- *No technical capability to separate particles*

Mixing or bonding particles may be irreversible due to a lack of suitable technologies, such as for example with certain alloys and composites (Sirkin and Ten Houten, 1994; Reck and Graedel, 2012). Or, in other instances, large amounts of virgin materials are required to restore the properties of the cycled material to virgin-like levels, such as due to additives (Allwood et al., 2011; Allwood, 2014). Partly, this is the result of end-of-life systems that are relatively crude compared to manufacturing systems, and there is scope for improvement in this area (e.g. Garcia and Robertson, 2017; Hagelüken, 2012; Zhang and Xu, 2016). However, although it is necessary to consider material quality as a factor for cycling processes to be meaningful (Gregson and Crang, 2015), the loss of quality may have to be considered as the "necessary price to be paid for exploiting resources" (Giarini, 1980:10-25, in: Sirkin and Ten Houten, 1994).

- *Particle cycling degrades their characteristics*

Particularly in polymer and fibre recycling, the recycling process itself causes the resource to degrade, due to the mechanical stresses of the process (Allwood 2014).

Increased cycling, increased resource use overall

Because the quality of secondary resources is likely to be less than those of virgin resources, Zink and Geyer (2017) and Greson et al. (2015) point out that cycled particles may be produced in addition to, rather than instead of, virgin materials. In these instances virgin materials are not replaced, but new applications are sought for the secondary materials. This reduces the potential benefits of particle cycling.

Cycling of particles comes at a cost

Cycling of particles to a virgin-like state, particularly the recycling of materials within the technocycle, can demand such energy investments as to defy environmental or economic sense (O'Rourke et al., 1996; Frosch and Gallopoulos, 1989). From an energetic perspective, even virgin-to-virgin recycling can be regarded as a cascade (Sirkin and Ten Houten, 1994; Cullen 2017). With limited energetic resources available, therefore, quality and volume loss are inevitable.

Volume, location, timing and toxins matter for efficient and safe cycling

The cycling of particles may still not be desirable even when appropriate technology is readily available, recovery rates are high and the energetic costs per unit of recycled particles are relatively low. First of all, cycling large aggregate volumes of particles can still incur large energetic costs, and thus cause significant environmental problems (Sirkin and Ten Houten, 1994). Second, particle cycling cannot be viewed separate from the location where it happens: when composting materials the location has to have the capacity to absorb the excess nutrients, without this negatively affecting ecosystems (Reijnders, 2008). Neither can such cycling be viewed as detached from the time of year when it happens, as biochemical processes are influenced by seasonal cycles. Lastly, when materials contain toxins or need additional toxic additives to enable cycling, it can be questioned whether cycling is indeed the preferable option (Berndtsson et al, 2017).

The potential for cycling is limited whilst stocks in use are still expanding

While population and affluence levels are still rising, particles will be bound up in the material stock that is required to service the corresponding needs (Allwood et al., 2011; Allwood and Cullen, 2012; Stahel and Clift, 2015). During this time, only specific flows will be available at quantity for cycling.

Considering the above, the cycling of particles alone is unlikely to provide society with sustainable levels of material security.

2.3. Circulation of products

This section first explains the *product state* in more detail, before identifying the potential contributions this perspective has to offer the CE discourse and discussing the main points of critique on this perspective.

2.3.1. The product state and its role in CE

The *product state* conceptualises resources from the perspective of specific physical forms from which an end-user is able to extract value, or what is generally labelled as a 'good' or 'product'. The value extraction possibilities this perspective focuses on are defined within much more narrow boundaries compared to the particles state, as it is dictated by the specific form and features of the product.

Cycling as seen from the product state consists of those operations that prevent a product from losing its ability to deliver value, or operations that return it to a state of productivity after this ability was lost or compromised. That is: some limiting state has occurred that prevents it from functioning as desired, and through cycling operations the product undergoes renewal. This can be either physical renewal, through reconditioning in the form of maintenance, repair, refurbishment, remanufacture or upgrading; or renewal in relation to its use context, through co-use, sharing, redistribution, product cascading or use in alternate applications.

Viewing a resource's journey through the economy from this perspective inherently grounds it in the value that a particular physical form is able to deliver, as the physical form is inextricably linked with symbolic, or tangible and practical value it is designed to deliver. As such, this perspective directs attention to the use phase and use context, and towards situations where product functionality is compromised.

The product state is central to several of the CE frameworks that provide guidance with regards to operating a CE (Blomsma, 2018): for example, both the Performance Economy (Stahel, 2006) and Material Efficiency (Allwood et al., 2011) suggest applying such strategies as reuse, remanufacture, refurbishment and upgrading before any other strategies through which a product loses its structural integrity (e.g. recycling) are considered.

2.3.2. Contributions of the product state

The product state is typically used to look at improvement opportunities for product design and use and questions relating to the preservation of product stock levels, such as the possibility to perform repair by users or via professional channels. It therefore dominates in design studies (Chapman, 2005; Cooper, 2010), where reasons for product discard – e.g. damage to the product, changing needs or the product being superseded by superior technology (Solomon, 1994; Cooper, 2004) – have long since been studied. Another body of work that adopts this perspective studies user acceptance and behaviour, covering such issues as perceptions of ownership and its relationship with product care (Tukker, 2015; Sumter et al., 2018; Baxter et al., 2017).

Key to this perspective is preserving what Den Hollander and colleagues (2017) term "product integrity", which equates to the preservation of the resources that have been invested in creating them (materials, money, energy, time, labour), which would negate the need for replacement goods (e.g. Allwood et al., 2011; Stahel, 2006). Moreover, increased employment in the form of skilled jobs as a result of product renewal operations have been postulated, encouraged by such financial instruments as favourable VAT taxation (Stahel, 2006; EMF, 2013). This has led the European Commission to include financial measures to help ensure the extension of a products lifespan as part of the EU Action plan for the Circular Economy (EC, 2015).

2.3.3. Critique on the product state

Although adopting this perspective can provide valuable insights into product use and design, an exclusive focus on promoting the circulation of products has also been critiqued. Some key points are discussed next.

Increased product durability does not necessarily provide more opportunities for value creation

Preserving products does not always equate to preserving value. Products can become obsolete through factors other than breakdowns. For instance: technology changed in the case of typewriters, dedicated MP3 music players are superfluous due to the integration of this function in smartphones, and physical information carriers such as CDs and DVDs are now largely dematerialised through services like Spotify and Netflix. If the sole focus in such cases is on product longevity and no attention is given to recyclability, materials - e.g. particles - can be lost unnecessarily (Allwood and Cullen, 2012). Moreover, fashion and trends can cause preferences to change, causing users to discard their products for aesthetic reasons or simply because user practices have changed (Solomon, 1994; Linder and Williander, 2017). There may also be instances where product life extension will not be accepted by users and consumers. Think of, for instance, contexts where perceived 'contamination' may lead users to discard products that could technically still be reused (Baxter et al., 2017).

Extended product life vs consumables

Without considering a product's energy consumption during its lifetime, energy-in-use can become the primary impact compared to the product's other accumulated impacts during its lifetime (Bakker et al., 2014; EEA, 2017). More generally, if the impact of consumables exceeds the impact of discard and replacement with a new and more efficient solution, then preservation of the product no longer makes sense.

Cycling of products comes at a cost

As with cycling particles, the cycling of products also comes at a cost. Reverse logistics as well as additional parts and materials and other inputs (time, money, labour) may be required to extend product life. These additional resources may not always be readily available, nor can their environmental impact be ignored.

Product cycling can lead to an increase in consumption

Similar to the increased cycling of particles, the increased cycling of products could lead to increased product consumption overall (Gregson et al., 2015; Zink and Geyer, 2017). As convenience is increased, and less care is taken by consumers due to less affinity with the product such as in product/service systems (Tukker, 2015; Sumter et al., 2018), total product throughput may increase (Kjaer et al. 2018; Zink and Geyer 2017; Gregson and Crang, 2015).

In summary: the particles and products states cover important, albeit different aspects of the CE. Both perspectives furthermore exhibit important limitations. The difference between both perspectives can therefore not be ignored and neither can one perspective be said to be superior to the other. As such, there is a need for a comprehensive and integrative approach to both perspectives.

3. Framework development - foundations and synthesis

Next, we explain our approach to the development of the Resource States framework, and continue with assembling the framework.

3.1. 3.1 Approach to theoretical development

A clear basis for integrating the particles and product states is not readily available in the literature. If one examines circular strategies frameworks, for example, a range of organising principles are employed to explain how different (groups of) circular strategies relate to each other (Blomsma and Brennan 2017). Among these are: hierarchies of potential or expected impact (EC, 2008), capacity for handling resource quantities (Ricoh, 2018), preferred metabolisms determined by the nature of the material (Braungart and McDonough, 2002) or by ownership structures (Stahel, 2006). However, consensus on which principles to apply does not exist.

For this reason, we start from two basic concepts fundamental to CE: material entropy and life cycle thinking. Because CE is interested in material structures that are meaningful and useful to societies, a means is needed that allows for describing the degree to which materials are organised from this perspective. The concept of material entropy can be used for this. However, CE is not merely interested in one particular static state of matter, but in how they are used and transformed within economies, over time. This is where life cycle thinking adds the dynamism required for studying CE phenomena.

3.2. 3.2 Theoretical development

Material entropy is used here in the same sense as used by Boulding (1966) to describe the degree to which materials are distributed and diffuse, or are concentrated. The term is loosely based on the concept of thermodynamic entropy, where energy tends to equilibrate (or become 'disordered') in a system that is isolated from its environment (a "closed system"). Material entropy should be seen as an analogy that implies degrees of disorder in a material system, rather than a construct grounded in physics in the strict sense (Denbigh 1989; Khalil, 2004). A material in a low entropic state would be one that is more ordered, more concentrated or less diffuse; conversely a material in a high entropic state would be one that tends to equilibrium with its surroundings. In one sense, a fully-formed product would represent material in an ordered state; yet, the miniscule amounts of rare earths in mobile phones would be considered diffuse in the context of their ability to be effectively recycled, and thus in a relatively disordered state.

Applying the lens of material entropy, we can say that *resource states* have different degrees of order relative to one another and relative to their potential to become more ordered. Order is increased by the act of organizing - bringing matter from a lower state to one above it using, for example, technological or logistical means. On the other hand, order is decreased in products through everyday wear-and-tear, down-cycling and biological and chemical deconstruction.

To simplify and to operationalise this idea for the CE field and considering that CE focusses on material structures meaningful to societies, we map the previously discussed resources states onto a continuum where the products state is more ordered than the particles state. Doing so allows for the conceptualisation of a third intermediate state relevant for CE - the *parts state*, covering the level of parts, components, modules and (sub)assemblies. Here, entropy is neither particularly low nor particularly high compared to the other two states. That is: the value extraction possibilities of parts are defined within more narrow boundaries than is applicable to particles, but the parts do not yet allow end-users to extract value, as they first need to become part of the larger assembly to do so.

Together, the particles, parts and products states represent the three principal forms a resource can take in its journey through the economy⁶. Adding dynamism to these three states using the life cycle perspective, it becomes possible to conceptualise the industrial life cycle of resources as their movement within and between these three states. Consider a generic industrial life cycle from sourcing, through various stages of manufacture, use and eventual end-of-use and end-of-life, as is common in Life Cycle Assessment. In resource states terms, this involves the creation of a basic level of organisation through concentrating particles and giving them the required properties for further use. Next, particles are given an intermediate level of organisation in the form of parts. Finally, the resources reach their highest level of organisation through their assembly into products. At the end-of-use this process is partly reversed: products lose their form, through the temporary (partial) disassembly to allow for repair, upgrade or remake processes (refurbishment and remanufacturing) which negate a product's limiting state. Finally, when the product reaches its end-of-life it loses its high organisation level permanently: this is where it is either landfilled, or (taken apart and) (partly) recycled.

3.3. 3.3 Introducing the Resource States framework: a visual representation of complex value chains

Through drawing on material entropy and life cycle thinking, the Resource States framework depicted in Fig. 01 was created. The division lines separate the three resource states of particles, parts and products. Each resource state consists of a forward (pre-use) as well as a reverse part (post-use). The lines furthermore indicate where major resource transformations take place: this is where a resource transitions from one resource state to another. To indicate that these transitions are not binary but can entail a gradual process, a gradient is applied to the background of the figure.

⁶ Even higher levels of entropy, or lower level of order, could be conceived. For instance: a *raw materials state*, before materials are mined or concentrated. Similarly, even lower levels of entropy, or higher levels of order, could be conceived. Products are often used together with other products or are dependent on infrastructure for their use. It could be argued that this is an even lower level of entropy, a *product system state*. For reasons of simplicity, however, we limit ourselves to the three levels of immediate relevance to the CE discourse.

The Resource States framework

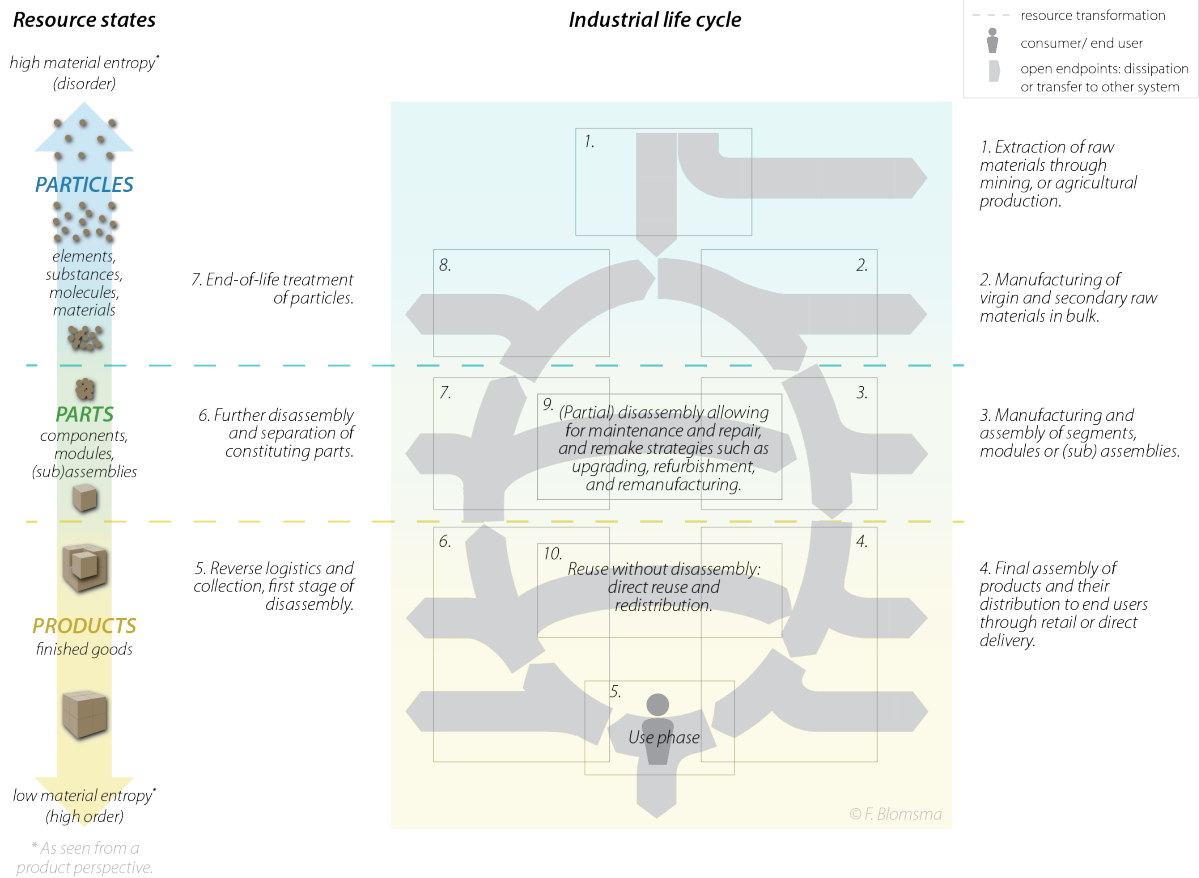


Fig. 01 Schematic depicting the Resource States framework, including a representation of the material entropy scale and the main industrial processes taking place in each entropic level, including important classes of circular strategies.

Next, we explain how the Resource States framework can be meaningfully applied to clarify how circular strategies can be understood from a systems or macro perspective.

4. Result - proposed uses of the Resource States framework

This section details how the Resource States framework imparts the CE domain with the ability to: A) clearly distinguish circular strategies from each other, as well as between different implementation scenarios of individual circular strategies; B) the competency to systematically explore and map synergies and trade-offs between combinations of circular strategies; and C) linking circular strategies with structural waste present in a given context.

4.1. Distinguishing circular strategies from each other & examining and comparing implementation scenarios

The Resource States framework visually links (groups of) circular strategies with a resource state. Thus, when discussing circular strategies it can be clarified what interventions in the industrial life cycle are within scope through indicating the *target state* or *target states*: which of the resource states are involved in the proposed process. In addition to this, it can be indicated if a circular strategy involves no, or one or more transformations across resource states. This we refer to as the different *modes* of cycling: *intra-state cycling* and *inter-state cycling*, respectively. Intra-state cycling taking place within the particle state, for example, are those recycling processes applied within the manufacturing of bulk materials, also referred to as industrial recycling (Roos, 2014), see also Fig. 02a. Likewise, intra-state cycling taking place within the product state refers to direct reuse through redistribution of a product to new use contexts (Fig.02b). Examples here are second hand sales that do not involve repair or refurbishment, whether informally organised such as with car-boot sales, or professionally such as through high-end second-hand fashion stores. Another example is peer-to-peer sharing platforms like Peerby.

Distinguishing between intra and inter-cycling modes

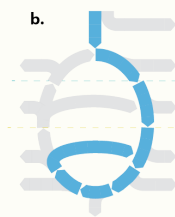
Intra-state cycling

Intra-state RECYCLING



a. Recycling - pre-consumer
Recycling applied within the manufacturing of bulk materials.

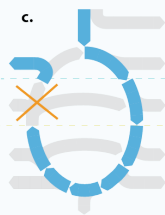
Intra-state REUSE



b. Reuse - direct or as-is reuse
Redistribution of a product to new use contexts.

Inter-state cycling

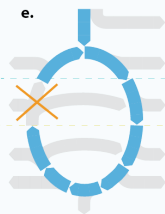
Inter-state RECYCLING



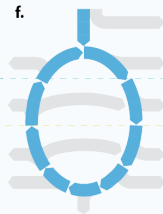
c. Recycling - post-market 01a, open loop
Product is collected, materials reclaimed by shredding the product and separating the resulting granulate for processing outside of the original system.



d. Recycling - post-market 02a, open loop
Product is collected, materials reclaimed by disassembly and separating the materials. Subsequent processing outside of the original system.

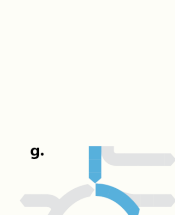


e. Recycling - post-market 01b, closed loop
Product is collected, materials reclaimed by shredding the product and separating the resulting granulate for processing within the original system.



f. Recycling - post-market 02b, closed loop
Product is collected, materials reclaimed by disassembly and separating the materials. Subsequent processing within the original system.

Inter-state REUSE



g. Reuse - involving remake
Product is collected, (partially) disassembled, remade, reassembled and returned to use.

Note: flow quantities disregarded, qualitative representation of flows only, and single cycle.

Fig. 02a-g Schematic of different modes of cycling, distinguishing between intra and inter-cycling for recycling and reuse, using the Resource States framework as a mapping tool.

Inter-state cycling, on the other hand, involves transitions from one resource state to another. For example, think of collecting a product and recycling its materials through shredding the product and (re)concentrating materials of interest through separating out recyclable fractions. In this example, the product is effectively considered a raw material at its end-of-life and transitions from being regarded as a product, to being regarded as a collection of particles to be purified. Collecting, shredding and recycling waste electronics with the aim to recover plastics, metals and rare earth elements is an example of this (WRAP 2016). This process can be executed as open-loop recycling or cycling within the same system (Fig.2c), or closed-loop recycling or cycling that involves transfer of the resource to another system (Fig. 2e).

However, this process can be expanded upon to include the separation of its materials through disassembly. In this scenario, the product travels from the products state, to the parts state, and eventually to the particles state. In the case of waste electronics, for instance, electronics could first be further disassembled, to not only be able to separate circuit boards, but to then also disassemble these into their constituent components (see for developments in this area e.g. Park et al., 2015; Palmieri et al., 2018). This process can likewise be executed in an open-loop mode (Fig.2d), or a closed-loop mode (Fig. 2f).

Consider also that a product can transition to the parts state and back to the products state: this involves (partial) disassembly and remake practices, such as through repair and maintenance, upgrading, refurbishment and remanufacturing (Fig. 02g), prolonging or restoring the product's productive lifetime. A well-known example in this area is Renault's remanufacturing plant, which takes in parts such as injection pumps, gearboxes, injectors and compressors from used cars and reconditions them to be used in other vehicles (EMF, 2012).

Although the parts state always operates 'in service' of either the products or particles state, its presence in the Resource States framework allows for distinguishing between differences in implementation scenarios of circular strategies in greater detail. Note, however, that the parts state does not need to be present in a given situation. An example of this in the reverse chain was already provided in the shredding waste electronics example above. This can also be used as a deliberate design strategy, by making a product from a single material, such that the quality of materials can be preserved when it is ground up, without requiring disassembly at the end-of-life. An example here is the Futurecraft Loop shoe by Adidas (Business Insider, 2019). The same is the case for the forward chain: through direct manufacturing (e.g. in-mould assembly) simple products can be manufactured without a distinct parts stage.

4.2 Systematically explore and map synergies and trade-offs between (combinations of) circular strategies

The Resource States framework furthermore allows for systematically probing and understanding situations where two or more circular strategies are combined for maximum resource productivity. Such situations - typically covering multiple resource states - are plentiful. Think, for instance, of cars, where repair, redistribution and recycling have been common practices for decades. However, new strategies continue to be added, such as car sharing services and refurbishing and remaking electronic parts (ABN and Circle Economy, 2016). Similarly, in fashion, new ways of providing services to customers such as through second hand sales or rental models, as well as material recycling are seen as part of an integral solution to improve resource productivity (Fischer and Pascucci, 2017). Such combinations of strategies can be facilitated by product/service systems, especially when they are combined with the upstreaming of performance agreements in the value chain (Blomsma et al., 2018).

With the Resource States framework it becomes possible to systematically explore where particular circular strategies can be applied in a manner that is sensitive to the context. Consider Fig. 03, for example. This hypothetical configuration contains three strategies that cycle resources within the same product system (in orange). At the end-of-use, direct or as-is reuse is applied first: this is reuse that involves no other processes than redistribution to a new use context (number #1 in Fig. 03). In the next use cycle, this can be followed by remake processes, such as repair or refurbishment (number #2). In the end-of-life stage this can be followed by closed-loop recycling, where the materials of the product are used to make new products of a similar type (number #3).

Fig. 03 furthermore indicates where resource exchanges with other industrial or product systems could take place⁷. For example: by-products can be exchanged between manufacturing facilities, such as in industrial symbiosis, leading to the extension of resource life within the particles state (number #4). Think of the material, energy and water exchanges taking

⁷ Of course, such exchanges can also involve dissipative losses of resources into the environment. For reasons of clarity and brevity, we do not expand on this here.

place in eco-industrial parks in Kalundborg and other places around the world (Zaoual and Lecocq, 2018). Likewise, product life can be extended through giving products alternative uses, serving different users in different environments (number #5). For instance, think of glass food packaging that can be reused as tableware (WAPF, 2017). Also, parts can be taken from end-of-life products and used in other product systems (number #6). For example, using used car batteries in the electricity grid (Heymans et al., 2014).

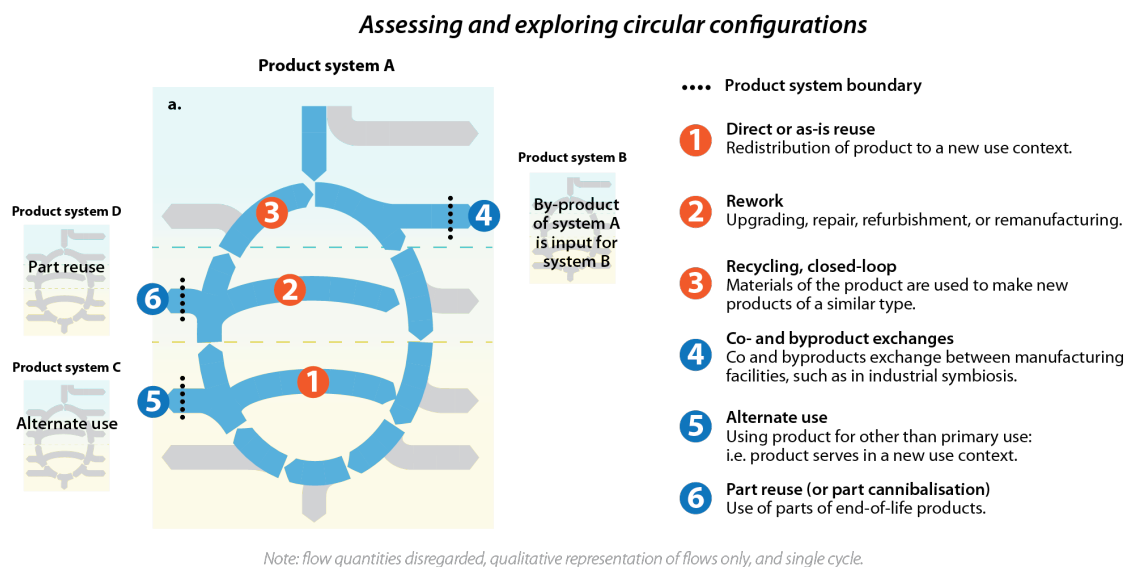


Fig. 03 Schematic of a hypothetical circular configuration with six different circular strategies.

As well as identifying where opportunities for cycling are present, the Resource States framework allows for identifying the influence of circular strategies on each other through dependencies and interactions that influence their combined impact on flow magnitude and frequency. For example: an increased focus on end-of-use strategies (#1 and #2), will delay the possibilities for recycling (#3). Likewise, increased alternate use (#5) reduces the possibilities for as-is reuse (#1), reuse through remake (#2), recycling (#3) and part reuse (#6). The Resource States framework can be used as a boundary object in such discussions, identifying areas where interactions need to be more closely examined and quantified through such methods as Material Flow Analysis (MFA).

4.3 Linking circular strategies with structural waste present in a given context

For linking circular strategies with structural waste, we draw on the *Waste and Resources Grid* described in Blomsma (2018). This typology considers the two main types of resources - particles and products; and two types of waste - a lack of resource renewal and a lack of resource consumption. Here, we expanded on this in two ways. First, by adding efficiency and preventative strategies. Second, we derived questions for each quadrant to guide the assessment with regards to what the most important structural wastes are in any given context. This results in the 'Big Five' Structural Wastes, see Fig. 04 (top).

As the 'Big Five' provides additional guidance with regards to what circular strategies are relevant for addressing specific types of structural waste, an analysis can be made of the current situation. Once the most important type or types of structural waste have been identified, one or more circular strategies can be identified as the core strategies. In addition to this, supporting circular strategies can be applied to further increase the resource efficiency and productivity of the new solution.

Use of the 'Big Five' furthermore allows for assigning labels to circular strategies clarifying what type of waste they address, and thus implementation scenarios of circular strategies can be better understood. For example: open-loop cycling can take two forms. In Fig. 4b, particles are returned to a virgin-like state - the retention of quality implies that this can be considered a *closing loop strategy*, although it is used in another system. Whereas cycling particles in such a way that the capacity of particles to generate value is further utilised without this involving their renewal (e.g. a cascade), this can be considered an *extending loops strategy*, as is depicted in Fig. 4c.

Likewise, when products are renewed through remake strategies such as repair or upgrading, and returned to the same user this can be classified as a *long life loop* strategy, see Fig. 4d. However, remake strategies are combined with redistribution to a new user, because, for example, the previous user no longer requires the product but in its current state it is not suitable for or acceptable to a new user for aesthetic or technical reasons, then both *long life* and *intensifying loop* strategies are applied together. See also Fig. 4e.

In both these reuse and recycling examples, different (combinations of) structural wastes can be identified. Linking these circular strategies to the structural waste that they address, as in Fig. 4b-e, means that the role of the circular strategies can be better understood. This, then, also offers a means to assess what strategies are appropriate in what circumstances.

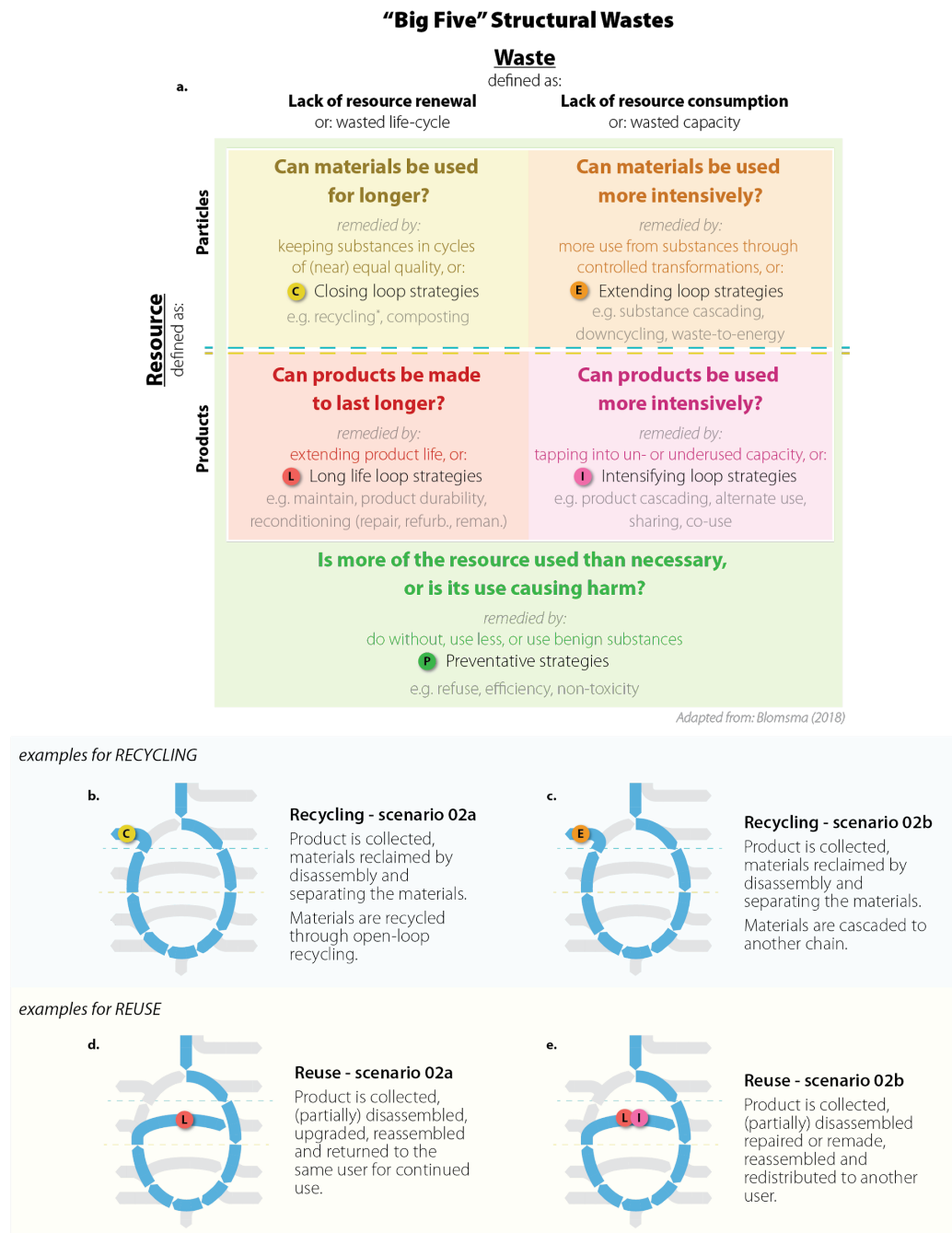


Fig. 04 Representation of the ‘Big Five’ Structural Wastes framework (adapted from Blomsma (2018)) (top) and its application together with the Resource States framework.

4.4 Empirical case mapping - current situation and design for a new circular system

Fig. 05 depicts an empirical case that was mapped using the Resource States framework. Although the mappings were created as part of analysing the case study and not as part of the innovation project, the mappings illustrate how circular innovation cases can be investigated and how insights can be generated from these mappings. The case depicts an electronic product that was analysed and subsequently redesigned as the result of an InnovateUK CE themed feasibility study during the period 2013-2016 (InnovateUK, 2012). Fig. 5a. depicts the structural wastes as perceived by the company; Fig. 5b. depicts the various circular strategies that were devised to address these wastes.

The analysis of this case started with the observation that the product was frequently discarded by users with household waste as opposed to via the designated WEEE channels, leading to the loss of the metals and rare earths contained in this product in landfill (a lack of closing loop strategies). Aggravating this, was the fact that recycling systems were poorly equipped to deal with this waste stream. Due to a lack of incentives for specialised treatment - e.g. the presence of low quantities of highly concentrated materials, this frequently led to subsequent use of the materials in the form of downcycling. In this case, this subsequent use was not perceived as a positive aspect, as it involved the loss of critical raw materials for applications essential for the functioning of modern economies. As such, extending loop strategies were not the preferred outcome. In addition to this, energy efficiency gains due to the future technological development could not be capitalised on because of the longevity of the product. Here, product longevity leads to a lack of preventative strategies in the form of energy efficiency.

This systemic outlook on all key structural wastes led to the proposal of a product/service system that involved the particles, parts and products state. For one, the new system would allow for remanufacturing the product, enabled by a new modular design - a parts state intervention. Quick and easy change of key parts would take place, either when a breakage occurs or when the technology has advanced sufficiently to warrant replacement. The latter would lead to a preventative strategy in the form of increased energy efficiency during the use phase - a product state outcome. In this manner, not only could the lifetime of the remainder of the product be extended through multiple cycles - a second product state outcome, but a pure recycling stream of the discarded parts could be created, providing input for further recycling - a particles state outcome. Although relatively small in quantity, this would enable recapturing critical raw materials for future use. Due to the exact knowledge of its constitution and the increased quantity and concentration of this stream, high quality recycling outcomes can be achieved. When this case study was concluded, further commercialisation was being pursued by the company.

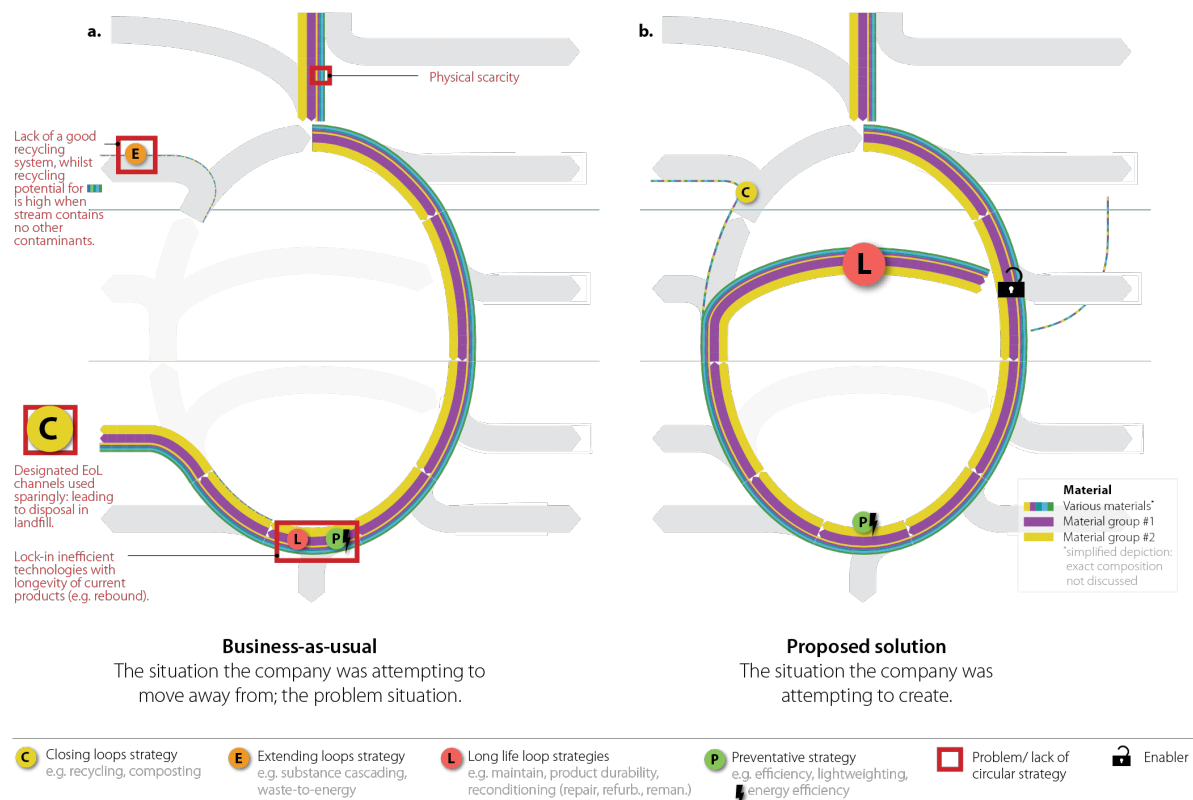


Fig. 05a-b Mapping of an empirical case on the Resource States framework. The case depicts the simplified mapping of an electronic product and its modular redesign. See more detailed mapping and data collection method Blomsma (2016).

This short case study exemplifies how the understanding of structural waste and its presence in different resource states can provide insight into the manner in which multiple circular strategies can be synergistically combined in circular configurations. It furthermore shows how the Resource States framework – in combination with the Big Five Structural Wastes – can make circular oriented innovation projects accessible by providing a means to analyse and understand them. Through conducting the analysis of both the current and future situation in this holistic manner circular strategy configurations can be developed that are fit for purpose, and that truly address structural waste. What's more, critical assumptions and knowledge gaps can more easily be identified, and relevant information sought, when different areas of the framework are linked to tools and approaches that provide more in-depth insight into specific aspects such as business models, product design and (sustainability) metrics and assessment.

5. Discussion

The Resource States framework put forward in this paper addresses the root cause of the varied and unsystematic language and conceptual tools available for examining circular strategies, by providing a comprehensive and integrative approach to the particle and product states. That these two perspectives should not be perceived as diametrically opposed but can be fruitfully applied together, was already illustrated by, for example, Sirkin and Ten houten (1994). These authors pose that the consequences of some of the methods of achieving product durability can result in greater efforts for salvaging particles at the end of the product's life-cycle. This implies that both perspectives need to be considered as part of a single holistic approach, where multiple considerations have to be weighed against each other. Likewise, Bakker et al. (2014) point to the importance of considering a product's 'optimal life span:' the time when the technological improvement of products in terms of energy consumption justify their replacement, considering the impact of material extraction of the replacement products and the recycling of the old product. Similarly, Kjaer et al. (2018), extend life cycle assessment (LCA) methodologies, which traditionally rely heavily on the attribution of impacts to material extraction and processing in the beginning and end-of-life phases, by taking into consideration user behaviour and displacement effects that could occur when users interact with circular product systems, such as those that provide access-over-ownership models. Hollingsworth et al. (2019) illustrate this line of thinking with the recent example of dockless e-scooters, by showing that the sustainability impact is dependent on the total sum of user practices, operating procedures and material inputs. In this sense, the Resource States framework consolidates and systematises this thinking.

Moreover, the addition of a third and intermediate state - the parts state - is in line with recent contributions to the field of CE. A range of authors, such as e.g. Romero and Molina (2013), Fischer and Pascucci (2017), Mendoza et al. (2017), Zink and Geyer (2017), Govindan and Hasanagic (2018), Hahladakis and Iacovidou (2018), Hopkinson et al. (2018), and Hahladakis and Iacovidou (2018), already include the perspective that resources also constitute components, segments, modules or (sub)assemblies.

Through applying the Resource States framework as described in section 4, it becomes possible to clearly identify and systematically explore the impact of different system interventions in terms of *where* cycling is needed, of *what* type it should be, *how* it should be implemented, and *whether* down- or upstream effects can be anticipated. In particular, when comparing cases and analysing barriers and enablers, the Resource States framework can be used to provide insight into what circumstances cases share, and in what ways they differ from each other. Larger data sets can be compiled using this approach, generating more in-depth insights into what circular approaches work or do not work, and why.

Although this type of analysis shares characteristics with existing approaches like MFA or Sankey diagramming, it has two distinct benefits. One, it offers a single template that can be used to describe different scenarios, functioning as a boundary object (Star and Griesemer, 1989) among those involved in the analysis. Through including the whole industrial life cycle, it provides a much-needed means to clarify and bring together different perspectives on a given context (Lapko et al., 2018; Machacek et al., 2017). Second, the framework offers a means to provide a conceptual and high-level exploration of systems, without the need to engage in intensive data collection. In this sense, it should not be seen as a replacement of the MFA or Sankey, but rather as an addition to the toolkit that can aid in identifying where more information is needed.

A key limitation that should be kept in mind when applying the framework, is that the resource states are defined as relative to each other: they do not indicate an absolute measure of order. As such, it cannot be taken as a measure of organisation that can be used across products or product groups, rather the possible degrees of order and disorder related

to a product-part-particle system. Further work on the Resource States framework could be done both in the theoretical as well as the application domain. With regards to the former: further work can add additional detail with regards to the strategies present within each resource state, on how to appropriately demark the boundaries of systems analysed with it, and on linking it with business processes, as well as sustainability assessment (economic, environmental and social aspects) that are the most salient to the different resource states. It could furthermore be investigated how to include temporal interactions in this approach.

With regards to its use by practitioners, further work should be directed at understanding how the framework can be used in CE oriented innovation processes by businesses and policy makers. Think, for example, of developing the accompanying step-by-step methodology for describing both the current situation in systems and its use in generating alternative circular configurations, for use in workshop settings. That is: how can the framework best be used to answer questions such as whether proposed circular configurations optimise resource productivity and in line with the concerns that they aim to address? Further work should also be directed at understanding how the framework can be used to improve the feasibility of proposed CE systems, such as through using it in answering questions related to whether the relevant resource transitions are taken into account, whether barriers and enablers are appropriately addressed or wielded, and whether proposed interventions take into account the role and sphere of influence of relevant stakeholders.

6. Summary and conclusion

This paper has drawn on material entropy and life cycle thinking to develop the Resource States framework, with the aim to clarify and systematise the language around resources with the CE discourse. We answer the question “Circular economy, preserving materials or products?” with: both perspectives are needed to create holistic circular approaches. It was shown that the proposed framework – which links and integrates the two perspectives through the addition of the *parts state* - allows those active in the CE domain:

- A. to clearly distinguish between circular strategies, as well as between different implementation scenarios of the same circular strategy;
- B. to systematically explore and map synergies and trade-offs between combinations of circular strategies;
- C. to link circular strategies with structural waste present in a given context.

These abilities provide an analytical framework through which the scope of research as well as practical initiatives can be understood. For example, it allows for a clear articulation of which intra or inter-state processes are studied and thus which parts of the CE body of knowledge a study contributes to, or where a tool or approach can provide insights. This allows for finding, classifying and integrating related knowledge, as well as tools and approaches supporting circular oriented innovation. In turn, this provides a basis for building a more coherent body of knowledge on the CE. Practitioners in business and policy can use the framework to perform a system level analysis of the contexts they operate in. Moreover, when knowledge, tools and approaches are organised in a way that it can easily be found, it helps practitioners find the information they need to inform decision making more easily. With this, we have contributed to additional theorising needed to advance the CE field (Reike et al., 2018; Kirchherr et al., 2017; Blomsma and Brennan, 2017; Homrich et al., 2018).

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