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The Circular Economy and Cascading: Towards a Framework

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ABSTRACT

The principle of cascading, the sequential and consecutive use of resources, is a potential method to create added value in circular economy (CE) practices. Despite conceptual similarities, no research to date has explored how cascading has been operationalised and how to integrate it with CE R-imperatives (Reduce, Reuse etc.) to facilitate implementation practices. CE practices emphasise value creation and retention, yet, there has been little reflexive examination of explicit and intrinsic value considerations; namely, how allocation choices, i.e. the decision-making process, for resource utilization are made. This paper aims to (1) examine how cascading has been operationalised (empirically and theoretically) to understand its normative underpinnings and value considerations; and (2) integrate cascading with the CE practices in a manner that accounts for the complexities of material allocation choices. Through a literature review of 64 articles from three bodies of literature (CE, cascading and up/downcycling), plus additional material on sustainable development, we show the cascading concept is a suitable framework to direct material uses and provides an overarching concept to integrate with CE R-imperatives. From this, we propose a new theoretical framework that considers the socio-organisational necessities for a CE-cascading system, specifically by deconstructing the allocation choices and exchanges of product material combinations between actor groups. This considers a dual perspective of the physical aspects of materials and the social context in which material allocation is made. The framework transcends individual value chain actor configurations to propose an overarching steering/governance framework, based on the triple-P of sustainability (People, Planet, Prosperity), to examine and direct CE-cascading exchanges, between and above individual users/firms.

1. Introduction

In response to numerous interrelated socio-environmental challenges, the circular economy (CE) – while not completely new – is being embraced as a means of realising sustainable development (Geissdoerfer *et al.*, 2017). The concept has found its champions in governments, policymakers, scholars and businesses who call for a departure from the current linear-like economy, i.e. an economy where resources are extracted, processed and wasted, to a closed-loop system, which prioritises value retention and regenerative design (Blomsma and Brennan, 2017; Ellen MacArthur Foundation, 2013).

CE draws its influence from various disciplinary backgrounds, including industrial ecology (IE) (cf. Blomsma and Brennan, 2017), which has provided many theoretical and methodological tools used (Saavedra *et al.*, 2018). The underlying purpose of adopting CE practices is (presumed to) ultimately reduce virgin material consumption, eliminate waste and decouple growth from material use (Ghisellini *et al.*, 2016; Murray *et al.*, 2017). Notwithstanding the longer lineage of CE (Blomsma and Brennan, 2017), or its multiple definitions (Kirchherr *et al.*, 2017), the implementation of CE is being pursued through utilising the so-called R-imperatives or strategies. The number and sequence these R-imperatives is inconsistent and has evolved. A older framing presented the 3Rs (Reduce, Reuse and Recycle), whilst a recent synthesis outlined 10R-value retention options that can be initiated by consumers and businesses throughout the entire value chain of a product (Reike *et al.*, 2018).

In recent CE publications, the principle of cascading is mentioned as a method of retaining the ‘added value’ of materials as long as possible (Bezama, 2016; Mair and Stern, 2017; Gontard *et al.*, 2018; Lüdeke-Freund *et al.*, 2018). Cascading is understood as the sequential use of resources for different purposes, usually (or ideally) through multiple material (re)use phases before energy extraction/recovery operations,

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Abbreviations: CE, circular economy; IE, industrial ecology; B2B, business-to-business; B2C, Business-to-consumer; C2C, consumer-to-consumer; PMC, product/material combination

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and is most established within IE (Olsson *et al.*, 2018; Teuber *et al.*, 2016). Like CE, cascading is concerned with resource efficiency through promoting consecutive resource circulation; however, the concept is often conflated with recycling or downcycling (Blomsma and Brennan, 2017). Proponents of cascading contend it contributes to higher natural resource efficiency over the entire material lifecycle; from resource extraction, product consumption to disposal (Sirkin and ten Houten, 1994). In practice, cascading is predominantly studied within the lumber industry, concerning exchanges between lumber, paper and energy companies (cf. Korhonen and Niutanen, 2003; Sathre and Gustavsson, 2006; Mehr *et al.*, 2018; Jarre *et al.*, 2019). Research on cascading in the context of CE has focused on its possibility to use waste by-products (Venkata Mohan *et al.*, 2016; Egelyng *et al.*, 2018; Zabaniotou and Kamaterou, 2019), secondary textile use (Fischer and Pascucci, 2017) and wood (Bais-Moleman *et al.*, 2018; Husgafvel et al., 2018). Of these authors mentioned, most only tacitly reference cascading without thoroughly detailing how the cascading principle is operationalised in order to facilitate CE decision-making processes and activities.

Two key articles have begun examining the interconnection between cascading and CE. Olsson *et al.* (2018) provide a historical review and critical examination of 'imposed' material hierarchies for cascading wood use over energy recovery. They argue that prescribing static hierarchies creates the high risk of unwarranted consequences; instead, cascading processes should emerge bottom-up, with cascading "treated as a guiding principle or tool – not an end in itself" (Olsson *et al.*, 2018, p. 8). Moreover, Mair and Stern (2017, p. 291) reviewed the conceptual interlinkages between cascading and CE. They concluded that the former "perfectly" fits into the latter, but the lack of integration between them is likely due to divergent research communities. Thus, Mair and Stern (2017) recommend actively integrating cascading with CE, potentially as a communication tool to describe specific CE processes. Nevertheless, despite these reviews, there is a lack of knowledge that illustrates the practical interlinkages between cascading and CE practices. No author, to our knowledge, has integrated cascading with the CE R-imperatives. Furthermore, little is known about how cascading can be operationalised for practitioners and connected to value creation and retention in a CE.

This suggests the need to connect CE and cascading in a manner that can analyse and facilitate CE decision-making and implementation processes. CE has a long-established theoretical lineage (cf. Ghisellini *et al.*, 2016; Saavedra *et al.*, 2018). In light of this, there is a precedent to thoroughly examine the existing knowledge base to provide greater insight and support for the present and future CE-cascading developments. Therefore, this article aims to review the existing literature on CE and cascading. The purpose is to examine how cascading has been operationalised in a theoretical and empirical sense to understand its normative underpinnings and value considerations including higher use options (up/downcycling). Based on this review, we propose a new framework that integrates cascading with the CE R-imperatives whilst accounting for the social complexities of decision-making processes.

This paper is structured as follows. Section 2 describes the methodology. Section 3 provides an overview of CE practices and cascading, including historical origins, frameworks and empirical case studies, illustrating how it has been operationalised (empirically and theoretically). Section 4 deconstructs the value assumptions within CE and cascading processes, reflecting on the terms upcycling and downcycling to understand how these practices determine the innate value of material exchanges. Section 5, for the first time, integrates cascading with CE R-imperatives in a new framework. Section 6 discusses and concludes illustrating the applicability for the proposed framework for CE decision-makers.

2. Methodological approach

To explore the gaps outlined in Section 1, this paper conducted a critical review of three bodies of literature: CE, cascading and up/downcycling. There are various types of literature reviews, each with their own attributes and limitations (see Grant and Booth, 2009). A critical review goes beyond a mere topic description and is useful to identify significant items in a field, synthesise knowledge and derive new theories or models (Grant and Booth, 2009). This review was comprised of two layers of analysis and four distinct steps (labelled a, b, c and d), each step developing insights for the subsequent analysis. Layer one consists of an overview and description of the key concepts: CE, cascading (step a and b, Section 3) and up/downcycling (step c, Section 4). Layer two consists of a critical interpretation and synthesis of these bodies of literature, to integrate CE and cascading (step d, Section 5). For this final step we also incorporated insights from the sustainable development literature. All of the selected literature for this study are listed in the Supplementary Materials.

2.1. Layer one: descriptive overview

The first step (a) consisted of an overview of recent CE literature. Many in-depth reviews have been written on this exact topic, outlining its history, contestations and theoretical diversity. As a short-cut and to avoid repetition of those studies, we searched for key reviews since 2015, which address conceptual diversity and operationalisation of the CE. Of 400 potential articles in Scopus, most are not in-depth reviews. Thus, we chose eight key articles (Supplementary Materials), with high citation counts and in-depth conceptualisation of the concept of CE, implementation practices and operationalisation. These articles were analysed to provide a brief description of the operationalisation of CE R-imperatives (Section 3.1). For these reviews, we adopted the 10R framing of CE as outlined by Reike *et al.* (2018).

Following this overview, we initiated (step b) string searches (see Supplementary Materials) for articles on cascading and its connection to CE. We set our timeframe from the 1990s, as that is the commonly accepted date for when the term CE first appeared (Blomsma and Brennan, 2017). Little has been written on the connection between these two bodies of literature (Fig. 1), giving further credence for our study. We selected 30 of 188 articles, by scanning abstracts and keywords for their relation to historical overview, conceptualisation, links to CE, operationalisation and detailed case studies. Four articles were added by searching through the references of selected articles. Two additional articles (Mantau, 2012; Vis *et al.*, 2016) were recommended during the review process, which we added.

To analyse the literature concerned only with cascading we constructed an overview of the history and development of the concept (Section 3.2), including the environmental and material benefits and

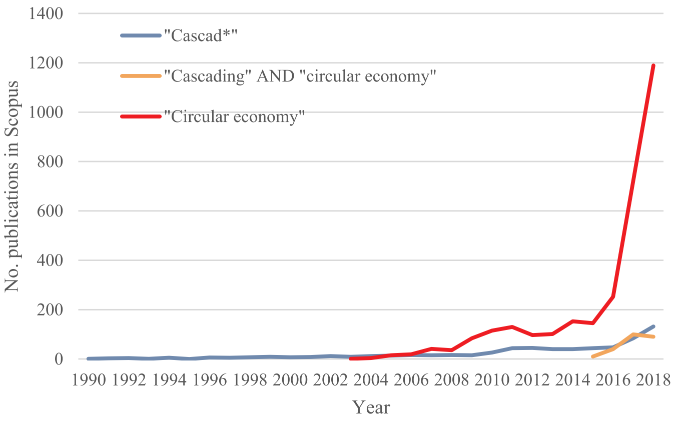

Fig. 1. Total scientific publications in Scopus that cite cascading and circular economy, 1990 – 2018 (for relative numbers see Supplementary materials). "Cascading AND circular economy" numbers (orange) are multiplied by a factor of 10 for readability

Table 1
R0 → R9 Hierarchy of CE options (Reike, Vermeulen and Witjes, 2018)

R-imperative	Description
R0 Refuse	For consumers to buy less. Also for producers who can refuse to use specific materials or designs.
R1 Reduce	Linked to producers, stressing the importance of concept and design cycle, e.g. less material per unit of production (dematerialisation).
R2 Resell, reuse	Second consumer of a product that hardly needs any adaptation and works as good as new.
R3 Repair	Bringing back into working order, by replacing items after minor defects. This can be done peer-to-peer or people in the vicinity.
R4 Refurbish	Referring to large multi-component product remains intact while components are replaced, resulting in an overall upgrade of the product.
R5 Remanufacture	The full structure of a multi-component product is disassembled, checked, cleaned and when necessary replaced or repaired in an industrial process.
R6 Re-purpose	Popular in industrial design and artistic communities. By reusing discarded goods or components adapted for another function, the material gets a new life.
R7 Recycling	Processing of mixed streams of post-consumer products or post-consumer waste streams, including shredding, melting and other processes to capture (nearly) pure materials. Materials do not maintain any of their product structure and can be re-applied anywhere. Primary recycling occurs B2B, whereas secondary recycling takes place post municipal collection.
R8 Recovery (energy)	Capturing energy embodied in waste, linking it to incineration in combination with producing energy.
R9 Re-mine	Landfill re-mining.

complexities of implementing it (Section 3.2.1) and its connection to CE (Section 3.2.2). Next, we described the operational and theoretical frameworks for implementing cascading that already exist (Section 3.3). A key question of this research concerned the empirical operationalisation of cascading systems. Cases found during this search were coded according to key attributes observed in the CE literature. This included coding *which* products/materials were cascaded, the number of cascades in the process, the operational scale and exchanges between the actors. The operational scale of cascading activities concerns either the micro, meso and macro (see Ghisellini *et al.*, 2016). Exchanges were divided to describe the specific sectors involved, whether they (material and energy) took place between different sectors or within the same sector, and the type of exchanges, e.g. business-to-business (B2B), business-to-consumer (B2C) or consumer-to-consumer (C2C), an important feature as outlined by Reike *et al.*, (2018). We further classified these cascading chains according to the CE value retentions options based on the framework of Reike *et al.*, (2018) (see Table 1). We excluded examples that deal solely with energy and water cascading (eco-industrial parks), instead, focusing on studies that included product and material cascading.

A key issue that derived from this initial analysis was the contextual application and allocation, i.e. the decision-making process regarding materials and the perceived value of it. The terms up/downcycling were closely tied to this process. Thus, we initiated (step c) more string searches for these two terms (Supplementary Materials) and selected 15 of 256 potential articles. The selection criteria consisted of choosing examples where the above terms were used to describe a specific material use and justification for doing so. Articles were analysed for the context in which they were used and justification, in terms of value, for doing so (see Section 4). In all topics, we deemed we had reached saturation when we encountered similar perspectives within the text.

2.2. *Layer two: critical synthesis*

The second layer of analysis consisted of a critical interpretation of all three bodies of literature (CE, cascading and up/downcycling), to ultimately integrate CE and cascading into one framework (Section 5). For this step, we reengaged with the broader literature on sustainability (step d) to provide insights for broader social and contextual ambitions; concerns that emerged during the initial analysis, which are not generally explored in CE (Kirchherr *et al.* 2017). In total, 64 articles were reviewed and analysed for this study. This analysis is based on a critical interpretation of the literature, to outline research issues and develop new theoretical insights. The emphasis is on a conceptual contribution. Whilst this is an interpretivist approach, the outcome is the starting point for future exploration. We acknowledge the subjectivity on the choice over which articles were included and which were not. However, the sparse number of articles on this subject and inter-author agreement on the selection gives us confidence in the thoroughness of our sample.

A figure of the research process can be found in the Supplementary Materials.

3. Circular economy and cascading

3.1. *Circular economy operationalisation*

CE encompasses multiple production and consumption strategies, which crucially can operate in varying forms and at different scales, with different approaches pursued at the micro (company or consumer level), meso (eco-industrial parks) and macro (nations, regions, provinces and cities) (Ghisellini *et al.*, 2016, p. 12; Murray *et al.*, 2017)

CE practices are described as following the R-imperatives, sometimes referred to as R-hierarchies or strategies *(Reike et al.*, 2018). There are various numbers and sequences of Rs, which normally relate to product value retention options. For our analysis, we adopt a synthesis of 69Rs into a 10R typology outlined by (Reike *et al.*, 2018) (Table 1). Such Rs represent value retention strategies that occur B2B (business-to-business), B2C (business-to-consumer) or C2C (consumer-to-consumer). Yet, whilst such ‘R-hierarchies’ are commonly discussed, this does not mandate a prescriptive set of ‘R-interventions’ within a material or product lifecycle, merely a set of value retention options that can be initiated to derive added/additional value. Indeed, indefinite and perpetual recyclability is not thermodynamically feasible (Korhonen *et al.*, 2018), nor, in the case of material recycling, always environmentally and economically beneficial when a cut-off point for these benefits is reached (Ghisellini *et al.*, 2016). Thus, some broader considerations and trade-offs complicate emerging CE approaches that must be considered when implementing R-strategies.

3.2. *Cascading historical overview*

According to Sirkin and ten Houten (1994, p. 215), a cascade chain can be described using the analogy of a “river flowing over a sequence of plateaus”, where water falls from one level to the next, dissipating energy and matter into other forms until it reaches equilibrium at the lowest level. This depiction idealises the theoretical vision for any potential resource exploitation – at a specific time – to the point of equilibrium and represents the most seminal and detailed elaboration of the cascading principle (Sirkin and ten Houten, 1994). In recent years, authors have assigned the origin of material cascading primarily to the biomass domain (Kalverkamp *et al.*, 2017). However, cascade chains have a historical association with developing interconnected food, energy and nutrient chains and IE (Olsson et al., 2018).

In practical terms, cascading is seen in IE applications, most noticeably in eco-industrial parks. In such arrangements, formerly separate industries (re)organise and become engaged in multiple interplays of resource and by-product exchanges. Such industrial symbiosis arrangements between firms emerge either in a prescriptive planned or spontaneous arrangements (Ghisellini *et al.*, 2016). The most famous (and referenced) example of the latter (spontaneous) is the eco-industrial park in Kalundborg, Denmark. Here, various separate industries, e.g. power plant, an oil refinery, a biotech and pharmaceutical company, a producer of plasterboard, and a soil remediation company engage in B2B cascading of water/steam and residual energy (Chertow and Ehrenfeld, 2012; Jacobsen, 2006).

IE research engages with the organised recycling of low-quality materials, often discarded consumer items, which is known as *cascade recycling* (Graedel and Allenby, 2003). Proponents in the 1990s, conceptualised 'hierarchies' of material use of products post-use, specifying 'higher' uses of secondary materials was desirable. From a policy perspective, this was evident in the Lansink Ladder in the Netherlands, which promotes recycling over incineration and landfill (Lansink and Veld, 2010). From an organisational perspective, IE has proposed 'preferable' material recovery options, e.g. in tyres, which includes retreading, engineering applications, granulation and energy recovery options (Ayres and Ayres, 1996). Cascading strategies have similarly been connected to regional self-sufficiency, where material 'throughput' relies on replacing imported non-renewables by cascading 'roundput' flows that relies on regional wastes and renewables (Niutanen and Korhonen, 2003). Much of this early work focused on technological feasibility, overlooking the importance of the complexities of societal organisations, which can complicate the implementation and success of IE (Vermeulen, 2006); although such contextual complexities, such as existing regulatory frameworks, have subsequently received attention (Deutz *et al.*, 2017).

3.2.1. Cascading and policy: benefits and complexities

Research on cascading wood has illustrated the material and environmental benefits that can result from replacing fossil fuels whilst conserving forest stock (Mantau, 2012; Suter *et al.*, 2017). A study of the forest industry in Switzerland showed the need for a systems perspective to weigh the substitution and cascading effects. Following a supply chain perspective, Bais-Moleman *et al.* (2018) compared two cascading scenarios of wood use demonstrating the potential GHG emissions could be reduced by 42% and 52%. Mehr *et al.* (2018) modelled 200-year horizon of wood cascading compared to immediate incineration of wood, concluding there is high climate mitigation potential. Similarly, Garcia and Hora (2017) discuss the German Renewable Energy Act, which promotes the cascading of untreated or only mechanically treated wood; they argue that peak availability, competing market demands, collection logistics and the location of recycling facilities are crucial parameters that must be considered to promote non-fuel uses. Although there are material benefits from cascading, uncertainty exists over the number of cascade steps (reuse, recycling etc.) and their environmental impacts; which are affected by the subsequent application and alternative material substitution (Höglmeier *et al.*, 2017). Whilst the studies mentioned have modelled the potential benefits, less research has examined the social context for facilitating it; namely, the policy implications and key mechanisms that direct decision-making for a cascading process. The focus of the cascading studies mentioned here, reflect the priorities of European Union towards carbon mitigation.

Cascading is often associated with consecutive utilization bio-materials. Olsson *et al.* (2018) provide a comprehensive overview of policies for cascading wood. From the late 1990s, cascading was connected to improving the material efficiency of wood consumption and recycling practices (see Lafleur and Fraanje, 1997). Early cascading frameworks stressed the need to develop cross-sectoral policy structures to alleviate the competition risks between different end-users (Haberl and Geissler, 2000; Olsson *et al.*, 2018). This issue arose as a consequence of increased demand for bioenergy in the European Union in the 2000s, where cascading remerged as a model to reconcile these competing demands and contribute to mitigating climate change (see Brunet-Navarro *et al.*, 2018). Keegan *et al.* (2013) built on this on-going energy vs. materials debate in the context of biomass, arguing for supply chain logistics that facilitate reuse, integrated sectoral decision-making and a policy framework geared towards the production of bioenergy. Nevertheless, critical issues concerning cascading and biomaterials include the quality of materials, various market barriers (e.g. competition with upstream materials), and policy issues between different sectors have remained (Vis *et al.*, 2016). This indicates the strategic and competing considerations ingrained within cascading decision-making processes, particularly competing sectoral and policy demands.

Indeed, as Olsson *et al.* (2018) argued, policies which impose prescriptive material hierarchies to achieve greater levels of cascading are challenging to implement and can cause competing demands from actors if a certain process is prescribed as more economically valuable than another. The interdependencies between actors in a cascading process and the potentially unequal benefit sharing provide additional complications (Vis *et al.*, 2016). This raises a question of what the underlying purpose is for pursuing a cascading approach, with examples being extracting the maximum value, increasing the circulation time of materials, or mitigating environmental burdens (Olsson *et al.*, 2018). Whether the economic and energy aspects of cascading outweigh the material circulation benefits remains an open issue (Vis *et al.*, 2016). Whilst Olsson *et al.* (2018) touched on the social challenges of using cascading, they do not establish exactly what the conditions or innate decision-making contexts are in order to successfully implement and realise a cascading system. Thus, Olsson *et al.* (2018) suggest that such systems should emerge organically, instead of imposed through "politically determined hierarchies". Yet, there is limited research into the specific contexts in which such successful outcomes have emerged.

3.2.2. Circular economy and cascading

Recently, interests in cascading bio-based materials have also been interrelated with the emerging discussion on CE. A popular imagine of CE, as proposed by UK consultancy the Ellen MacArthur Foundation (2013), shows a technical and biological cycle of materials, with cascading presented as a key concept in the latter cycle. Subsequently, questions have been posed over what the bio-economy can learn from cascading successes (Jarre *et al.*, 2019; Mair and Stern, 2017). The notion of a circular bio-economy has been ascribed to the cascading and valorisation of bio-based wastes in bio-refinery processes (Venkata Mohan et al., 2016; Zabaniotou and Kamaterou, 2019). Additional studies have connected these concepts in the context of utilizing co-waste streams from agriculture, fisheries and poultry (Egelyng *et al.*, 2018) and secondary wood streams (Husgafvel *et al.*, 2018).

Examples of CE and cascading discussed in the literature includes product-service systems in the Dutch textile industry (Fischer and Pascucci, 2017), secondary construction and demolition streams (Husgafvel *et al.*, 2018), end-of-life product management (Kalverkamp *et al*, 2017) and cascading as a CE action for new businesses models (Lüdeke-Freund *et al.*, 2018). Most noticeably, Mair and Stern (2017) reviewed the conceptual interlinkages between CE and cascading; calling for both concepts to be combined, as both are concerned with extending the use of products/materials. However, they do not explicitly show *how* these concepts can be practically combined. Thus, we propose using cascading as a more fundamental concept that goes beyond biological nutrient cycling.

3.3. Cascading frameworks

In their original cascading framework, Sirkin and ten Houten (1994, p. 215-16) presented it as a design tool "meant to be applicable, in general, for the utilization of all resources". Resource cascading is determined through the interaction between two sets of theoretical entities: (1) a dimensional model concerning resource economy and (2) principles that modify them. Both these entities together guide a cascading approach. The dimensional model of resource economy contains

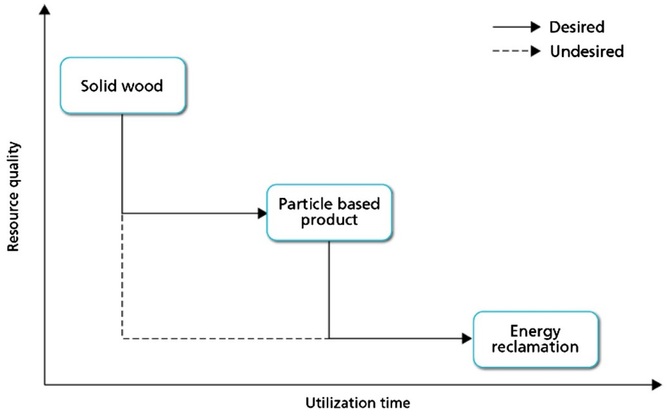

Fig. 2. Basic cascading example based on Sirkin and ten Houten (1994) (own creation).

four sup-elements: **Resource quality**, defined as an expression of the capacity to perform various tasks, or denoting its potential functionality, i.e. embedded energy, or structural organisation and chemical composition; **Utilization time** (Fig. 2), which is the timespan and together with resource quality stipulate the higher the material quality, the better its potential to perform demanding tasks; **Salvageability**, the resource quantities of a material that can be recirculated into secondary closed-loop cascades or alternative chains; and **Consumption rate**, how the present consumption rate will affect future stocks.

Sirkin and ten Houten (1994) modify the above resource economy dimensions with the following four principles:

1 **Appropriate fit:** qualities of the utilised resource to match the scope and demand level of the task to be performed. Low-quality tasks should not be done with high-quality materials, i.e. primary plastics should not be used for a task that recycled plastics can perform, e.g. shampoo bottles;
2 **Augmentation:** increasing the resource utilization time by counteracting decline (repair) and developing systems to extend lifespan;
3 **Consecutive relinking:** determining the optimal and highest value pathway for materials, including into alternative value chains;
4 **Balancing resource metabolism:** establishing a balance between the rate of resource consumption and the rate of resource extraction. This dimension seeks to incorporate the importance of inter-generational thinking within material uses and product cycles.

This framework has been adopted or modified in subsequent research. Kim *et al.,* (1997) examined the allocation burdens in the life cycle of a cascading recycling system. They assert that a cascading recycling framework should consider quality degradation (e.g. appropriate fit) and environmental pressures in assigning materials, and proposed a method that accounted for material quality in each lifecycle system (e.g. consecutive relinking). Lafleur and Fraanje (1997) outline a six-step methodology to achieve more sustainable use of primary wood, arguing that cascading is an essential step for sustainability. This involves an input-output analysis of primary wood, reducing the (end) use of wood-derived products, determining the appropriate fit (by applying resources to highest quality products), cascading, increasing efficiency processes and finally evaluating the process (Lafleur and Fraanje, 1997). Mellor *et al.* (2002) developed an acceptance criterion for extended producer responsibility organisations using waste polymers, to determine the potential utility of said waste in different applications.

All the above frameworks provide little indication of *how* the decision-making process should be carried out and the context of *where* cascading operations materialise, i.e. the socio-governmental context (cf. Vis *et al.*, 2016). A cascading process includes multiple use phases to (ideally) maximise the highest value of the product or material. Yet, this requires multiple sets of actors in the value chain, which raises the question how these processes should be governed to assure that the appropriate fit and subsequent use considers the other aspects of cascading, e.g. balancing resource metabolism, without compromising on other indicators, e.g. energy use. Sirkin and Houten (1994) describe this as a problem of product design, requiring both a resource management policy aimed at sustainability and incentives for designing for cascading that promote *resource quality,* not market value. Instead, a cascading process must be understood from a dual perspective. First, through the physical dynamics of sequential material use, and second, through the social dynamics of the individual actors embedded within the broader societal system (Vermeulen and Witjes, 2016). This social dimension highlights a significant challenge for instigating a cascading process, particularly concerning the decision-making, e.g. regulatory and market context, and the mechanisms that determine the appropriate fit of materials.

3.4. Cascading case studies

Recent articles call for learning from cascading (Jarre *et al.*, 2019) and integrating it with CE (Mair and Stern, 2017). However, a comprehensive CE-cascading framework to examine and facilitate decision-making is lacking, particularly one that considers ‘consecutive relinking’, i.e. determining the highest value pathway for a material. Therefore, to integrate cascading and CE, understanding how cascading has been empirically operationalised is important (Table 2).

The results from Table 2 show a limited diversity of cases. However, the concept has been explored in various sectors such as textiles, automotive and food processing; still, this analysis confirms previous claims that wood receives the highest attention in conceptual and empirical attention (cf. Mair and Stern, 2017). Thus, cascading not been universally integrated within product/material decision-making processes, from either product design to macro policy approaches across multiple material streams. Except for tyres, all of the cases reviewed focus on material streams, not specific products, indicating the limited focus on detailing product or component cascading.

Cascading operations have primarily taken place on the macro scale, with the exchanges of materials overwhelmingly occurring B2B. This raises questions about geographical proximity and economic conditions on site that allow such exchanges (cf. Vis *et al.*, 2016). The maximum number of direct cascade chain links presented is four (Korhonen, 2001), with a maximum of seven single links (Zabaniotou and Kamaterou, 2019). The majority of these exchanges occur through primary recycling (R7), i.e. B2B exchanges of by-products, which is advantageous over secondary recycling, i.e. mixed collections through municipalities (Stahel, 2010). Moreover, all R-imperatives are apparent in cascading processes, except R0 (Refuse), R1(Reduce), R6 (Repurpose) and R9 (Re-mine). Whilst not evident within the existing literature, R1 and R6 are still appropriate strategies, in the design phase of product (Reduce) and the potential usage of material (Repurpose). Imperatives R0 (Refuse) and R9 (Re-mine) do not seem applicable once a cascading strategy has been adopted.

There is a noticeable temporal disparity between the number of chain links presented in the studies, with earlier (wood) cases presenting multiple sequential uses (Lafleur and Fraanje, 1997; Korhonen, 2001; Sathre and Gustavsson, 2006; Dodoo *et al.*, 2014) and subsequent cases detailing multiple additional single uses of materials (De Besi and McCormick, 2015; Teuber *et al.*, 2016; Fischer and Pascucci, 2017; Egelyng *et al.*, 2018; Gontard *et al.*, 2018; Husgafvel *et al.*, 2018; Echeverria *et al.*, 2019; Zabaniotou and Kamaterou, 2019). This disparity might reflect the longer practice of cascading wood compared to the more recent emphasis given to waste valorisation within the CE.

The above cases are highly specific, detailed and often technical processes, and highlight the specific opportunities for valorising and

Table 2
Examples of the cascading principle in the scientific literature

Cascaded material(s)	Scale	Exchanges			Cascading chain links	Value retention options	Citation
		Sectors	*Within/between*	*B2B, B2C or C2C*			
Wood	Meso	Forestry, paper mill, pulp mill and energy generation	Between	B2B	Four	Recycling (R7) and Recovery (R8)	(Korhonen, 2001)
Recovered wood	Macro	Forestry, particleboard, building sector, energy generation	Between	B2B	Two	Recycling (R7) and Recovery (R8)	(Sathre and Gustavsson, 2006)
Wood	Unspecified	Forestry, wood processing, energy generation.	Between	Unspecified	Three	Recycling (R7) and Recovery (R8)	(Dodoo, *et al.*, 2014)
Wood	Macro	Forestry, processing industry, consumer use, post-consumer uses	Between	B2B	Three	Recycling (R7) and Reuse (R2)	(Lafleur and Fraanje, 1997)
Wood (recovered)	Macro	Sawing, planning and impregnation, mountable parquet manufacturing, the joinery industry, wood package manufacturing, the furniture industry and the recycling industry	Between	B2B & C2C	Five additional individual chains	Recycling (R7) and Reuse (R2)	(Husgafvel et al., 2018)
Wood polymer composites	Unspecified	Wood sector	Within (wood)	B2B	Six additional individual chains	Recycling (R7)	(Teuber et al., 2016)
Textiles	Micro	Textile	Within	B2B & B2C	Unspecified	Reuse (R2), Refurbish (R4), Remanufacturing (R5) and Recycling (R7)	(Fischer and Pascucci, 2017)
Textiles	Macro	Retail, Assembly, Manufacturing, Extraction. Textile and building	Between	Unspecified	One additional chain	Recycling (R7)	(Echeverria et al., 2019)
Foods	Macro	Processing industries (meat/fish/vegetables) to innovations (chemical processing and consumer goods)	Between	B2B & B2C	One	Recycling (R7)	(Egelyng et al., 2018)
Biomass	Unspecified	Unspecified	Unspecified:	Unspecified	One additional chain	Reuse (R2), Recycling (R2) and Recovery (R8)	(De Besi and McCormick, 2015)
Agricultural residues	Macro	Agricultural, anaerobic digestion and biochemical	Between	B2B	One additional individual chain	Recycling (R7)	(Gontard *et al.*, 2018)
Coffee grounds	Micro	Waste collectors and biorefinery	Between	B2B	Seven additional individual chains	Recycling (R7)	(Zabaniotou and Kamaterou, 2019)
Tyres	Macro	Automotive and recycling	Between	B2B & B2C	Four	Reuse (R2), Repair (R3), Recycling (R7) and Recovery (R8)	(Kalverkamp *et al.*, 2017)

utilizing waste. This can involve the cascading of specific products in multiple iterations of use, e.g. through Repair and Reuse activities (Kalverkamp *et al.*, 2017). Yet, understanding cascading processes (in the broadest sense) we propose to think beyond specific materials, to the more encompassing concept of Product/Material Combination (PMC). However, what is lacking is an understanding of how the valorisation of the product or material was undertaken at each stage or chain within the cascading process. Thus, understanding how the highest value pathway is determined within CE and cascading processes is important (consecutive relinking, Section 3.3), which necessitates exploring how value is perceived, conceptualised and ascribed.

4. Up/downcycling and value considerations

CE activities can preserve or derive added value from materials and products while cascading involves the sequential use of resources. Both processes involve context-dependent valorisation of a PMC and decision of its subsequent application. This section explores the terms ‘upcycling’ and ‘downcycling’, which are used to describe the valorisation of a specific material process, to illustrate how the allocation, i.e. the processes of assigning their use, is categorised.

4.1. *Definitions and examples*

Downcycling is recycling “something in such a way that the resulting product is of lower value than the original item” (Ortego et al., 2018, p. 25). Here, downcycling concerns value or purpose lost in comparison to the original item, which indicates a loss of material/product functionality due to quality. Downcycling is usually attributed to describe a product's material properties, their level of degradation, or, in the case of metals, if they have become impure, which leads to a loss of economic value (Koffler and Florin, 2013; Stotz *et al.*, 2017; Worrell and Reuter, 2014). For example, Stotz *et al.* (2017) discuss the process of aluminium recycling, arguing that downcycling occurs when the cycled materials lose their original purity. Material functionality can also be understood in terms of the quality of a material to perform or not perform tasks relative to that of virgin materials; such as the use of recycled polymers in low economic applications due to degradation (La Mantia, 2004). Also, Di Maria *et al.,* (2018) argue that the use of construction and demolition waste in backfilling in many European countries is a low-grade low-value application. Thus, downcycling is commonly ascribed to demarcate the lower physical properties of a material.

Upcycling involves the conversion of waste material(s) into a more valuable product(s). “It can be purely artistic, scientific, or anything simply useful” (Pol, 2010, p. 4753). Some studies claim upcycling results in products with higher quality and performance than the original, using refurbishing and remanufacturing strategies (Stahel, 2010). However, the literature is inconsistent with what constitutes upcycling. Consequently, we use two descriptive thematic classifications that traverse materials, products and sectors (Table 3). *Value-added* upcycling involves turning wastes into new products, i.e. creating new value (monetary or environmental) from nothing. *Extracting higher-value* describes how a ‘higher-value’ use could be obtained by changing the specific material trajectory, thus creating increased value in either monetary terms or environmental performance, e.g. salvaging rare materials.

4.2. *Value considerations for allocation choices*

The cases in Table 3 illustrate the literature is inconsistent on classifying and assigning the up/downcycling characterisation. Extrapolating from this, there is an implicit issue of how to determine a material trajectory (i.e. consecutive relinking) of a material at a specific stage in its lifecycle. No uniform normative criteria exist for governing the appropriate trajectory and determining the appropriate fit, with the literature suggesting these are all materially, geographically and

Table 3
Varying examples of the use of the terms up/downcycling

Characterisation	Example (description)	Citation
Value-added	Harvesting silicon from waste sludge as input for high-performance lithium batteries.	(Bao *et al.*, 2015)
	Using agricultural wastes and by-products in anaerobic digestion to produce high-value bioproducts and bioenergy. These wastes are recommended over using arable land to cultivate bioenergy stocks.	(Gontard *et al.*, 2018)
	Using discarded geomembranes applied in fracking, which can be repurposed into pellets used for railroad tires, structural beams and noncontainment products.	(Stark *et al.*, 2013)
	Using offcuts from the aerospace industry in the US, previously landfilled, to go into applications including prosthetic feet, skateboards and constructional material.	(Nilakantan and Nutt, 2015)
	Strategies to turn waste plastic into carbon nanotubes post-consumer use.	(Zhuo and Levendis, 2014)
	Turning fish, meat, fruit and vegetable co-streams from the Norwegian food industry as inputs for activities including using second-grade vegetables for smoothies and potato peels for biodegradable plastics in the vegetable (potato) processing industries.	(Egelyng *et al.*, 2018)
Extracting higher value	Using waste paper as the basis for textile fibres, which is justified given the global demand for fabrics and current low-value use of cycled paper.	(Ma *et al.*, 2016)
	Using recycled aggregates as inputs for concrete, instead of backfilling within roads.	(Vandecasteele *et al.*, 2013)
	Substituting natural aggregates, e.g. sand, with crushed and sieved concrete demolition waste.	(Weimann *et al.*, 2003)
	Using collected recycling glass into glass-ceramic lightweight aggregates. These are then employed in construction processes where they have a higher economic value.	(Velis *et al.*, 2014)

temporally contextual. Implicit in these discussions is the issue of how 'value' should be determined for materials with cascading potential which can determine its trajectory and continued allocated use. Olsson *et al.* (2018) describe this as a tension between market value and inherent value. Whilst Sirkin and ten Houten (1994, p.221) argue that resource quality refers to its *inherent and intrinsic qualities*, i.e. "qualities that cannot be altered by the landscape of human interest" (e.g. energy or enthalpy contents) or *human interests,* e.g. private economic interests, socio-cultural importance or global environmental significance. Therefore, value contains a physical and interpretive element. Thus, value determination - how 'value' is determined and by whom - is a fundamental issue at the interception between theoretical conceptualisation and practical/fundamental application of the cascading principle. There is a subjective element to how value is ascribed, in addition to market context, which can connect with its inherent or interpreted properties and physical attributes, with this process a factor in the subsequent allocation outcome.

The inevitable loss of material quality has commonly seen materials sequentially utilized in lower grade downcycling applications. Yet, this can partly reflect how a process is labelled, with the term upcycling also being ascribed to degraded materials. This categorisation interconnects with the valorisation process, e.g. the innate perception of that material or product at a specific point in time. We observe several broader mechanisms through which valorisation occurs that more explicitly consider the innate characteristics of a material. These include material quality (Stotz *et al.*, 2017), natural capital replacement, i.e. replacing virgin material in production processes (Di Maria *et al.*, 2018), or thermodynamic rarity, i.e. the exergy cost (kJ) required to extract and process the given material from cradle to gate, and the hypothetical exergy cost required if the given mineral must be restored to its initial conditions of composition in the original mine (Ortego et al., 2018).

While the debate over the fundamental purpose of the benefits of becoming circular differs between contexts (Section 1), there are underlying concerns with waste generation, resource supply and the reduction of virgin material consumption (Murray *et al.*, 2017; European Commission, 2018). Therefore, the implications for integrating cascading with CE requires a reflection on what the appropriate value consideration is, and the underlying purpose of the process, i.e. what are the innate value considerations that drive CE preferences, and whether the allocation choice, e.g. the chosen R-imperative is also preferable over others from an integrated sustainability perspective (see Section 5).

5. Proposing a framework interlinking CE practices and cascading

The above review outlined the concept of cascading, as a framework that promotes the consecutive and sequential use of materials. This consecutive use contains a dual element: (1) the physical properties and subsequent uses of the product/material and (2) the social context in which decision-making processes occur, i.e. the application context, which contains actors involved in material exchanges, the regulatory and market context in which they operate and eventual value considerations of the material. The application context is neglected in the literature on cascading.

Common visualisations of a cascading process (e.g. Fig. 2) depict it as a simple sequential process (cf. Sirkin and ten Houten, 1994; Olsson *et al.*, 2018). These imply an automatic transfer of the PMC from one use to the next (focusing solely on original PMC quality), without reflecting the social complexities (or energy considerations market conditions) that decide what (if any) the subsequent use is. Like cascading, the concept of CE is engaged with measures to close material cycles; yet there is also a contextual question of how allocations choices are directed. We argue CE practices can be integrated within a cascading framework using the 10Rs (Reike *et al.*, 2018). Cascading is a preferable overarching framework as it gives a systems perspective, e.g. intergenerational perspectives and resource constraints contextualised with the individual allocation actions of a PMC, as opposed to specific CE R-imperatives that describe exchanges between specific actors/users.

Fig. 3 depicts the value chain actor configuration for any PMC, from initial mining, material production, to eventual retailing, consumer use, collections and processing. We use the 10R framework of Reike *et al.*, (2018) to describe the initial PMC flow and potential value retention options within the same actor configuration. Fig. 3 also includes useful design inputs, e.g. design for recycling. In a previous paper, we outlined two distinct lifecycles: product production and use lifecycle and product concept and design lifecycle (Vermeulen *et al.*, 2018). Different R-imperatives apply to different actors in the lifecycle. For example, concerning the product production and use, with R0→6 relating to the product and R7→8 relating to the material. Refuse (R0), Reduce (R1), Resell (R2), Repair (R3) and Recycling (R7) are applicable for consumers including product-service system business models. Whilst Resell (R2), Repair (R3), Refurbish (R4), Remanufacture (R5), Recycling (R7), Recover (R8) and Re-mine (R9) for producers, businesses and retailers.

A first exploration of integrating the CE R-imperatives and cascading is shown in Fig. 4. The figure demonstrates the cascading process for any PMC, from the first combination to the final use phase (n), including energy recovery options (R8) in each phase. We exclude the CE imperative Re-mine (R9) as that occurs post-user, although, the framework applies to subsequent application of the re-mined materials. Once in use, keeping a PMC in its highest quality form is the first value retention consideration (requiring longer-lasting products), which can be pursued through counteracting decline (Augmentation, Section 3.2),

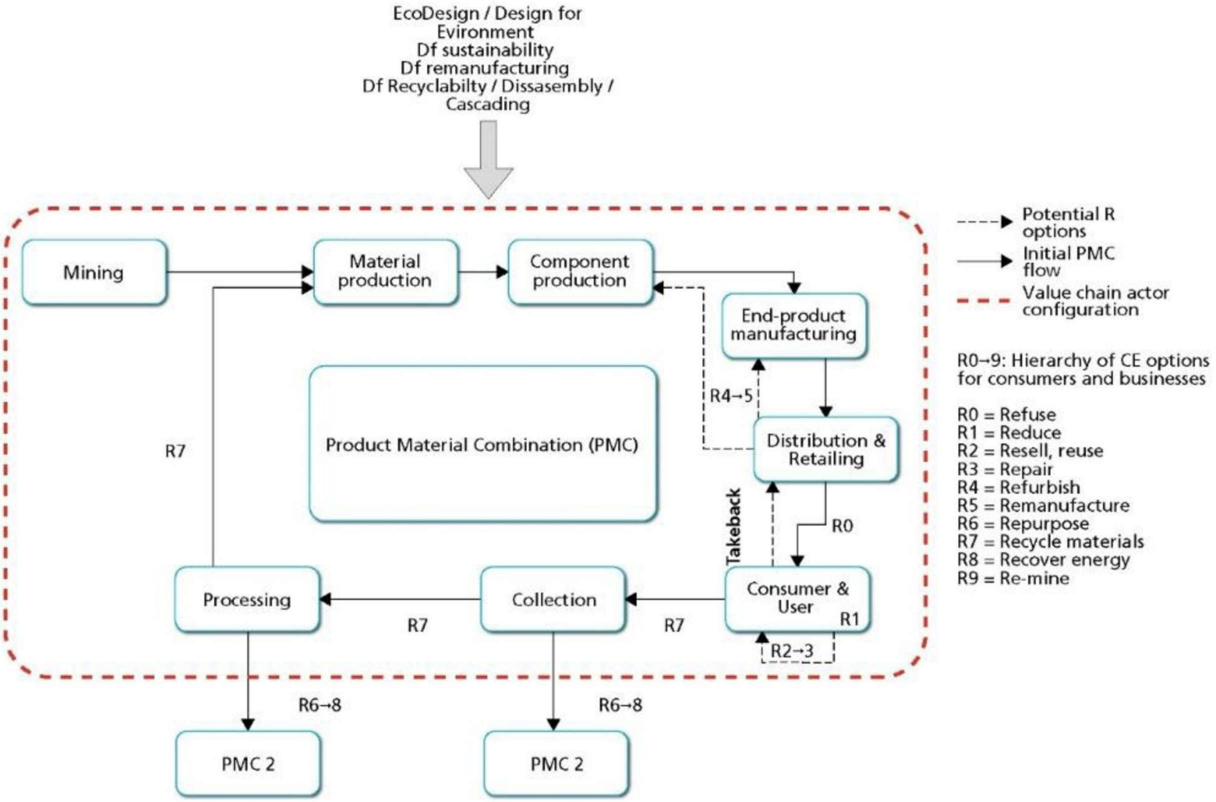

Fig. 3. Actor configuration of a product or material value chain and potential R-strategies

e.g. through repair (R3), refurbishing (R4) and remanufacturing activities (R5). Or, when a new product is made available which has lower environmental impacts than the one in use (cf. van Nes and Cramer, 2006).

R-imperatives 0→7 are applicable within this original 'closed-loop' value chain. The crucial question concerns the subsequent and sequential material allocation of the PMC, e.g. when the PMC leaves its original user or actor configuration and moves to a new one. We show this by separating different value chain actor configurations, using the CE R-imperatives 2→7 to describe the potential exchanges of the PMC between different users and actors. For example, if the PMC moves to a new user/actor configuration the specific value consideration will result in a particular R-imperative being adopted, e.g. Repair (R3) or Recycling (R7). In this way, we recognise that the subsequent PMC use (s) are - at their essence - a social, geographical and temporally contextual phenomenon; moving between actor configurations (as outlined above) through either B2B, B2C or C2C exchanges.

Central in this depiction is the moment when a PMC moves between users or actor configurations. Here, we suggest, resides the innate value considerations of specific decision-making contexts. This exchange between actors represents the moment which can steer or decide where the subsequent PMC is used or value retention considerations adopted (up/downcycling). Instead of an automatic sequential use, we contend there are likely multiple options or actor configurations and preferences

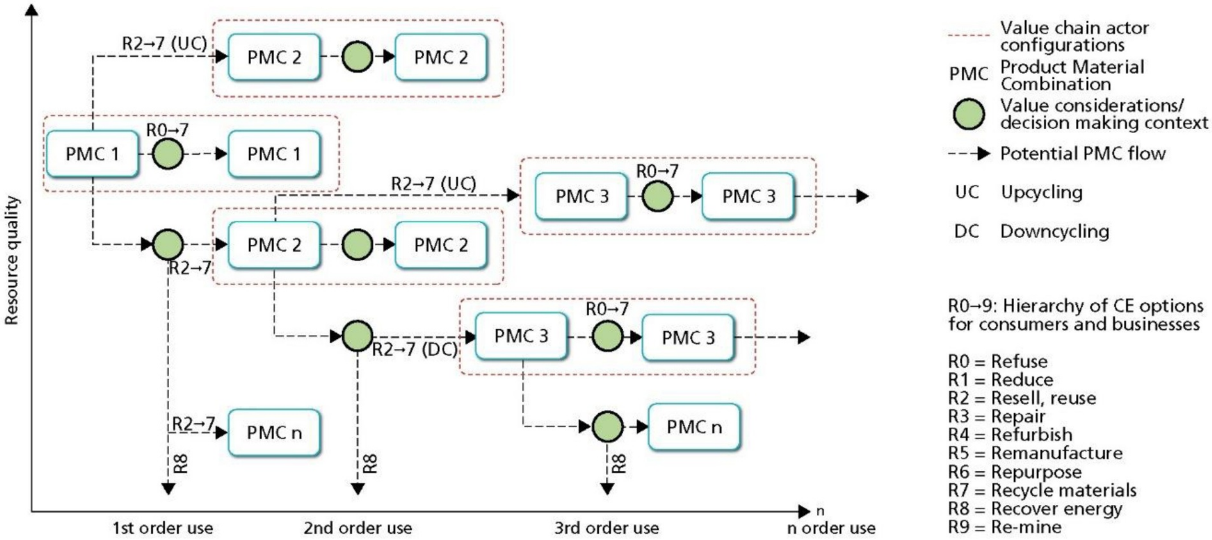

Fig. 4. Product or material cascading in a circular economy

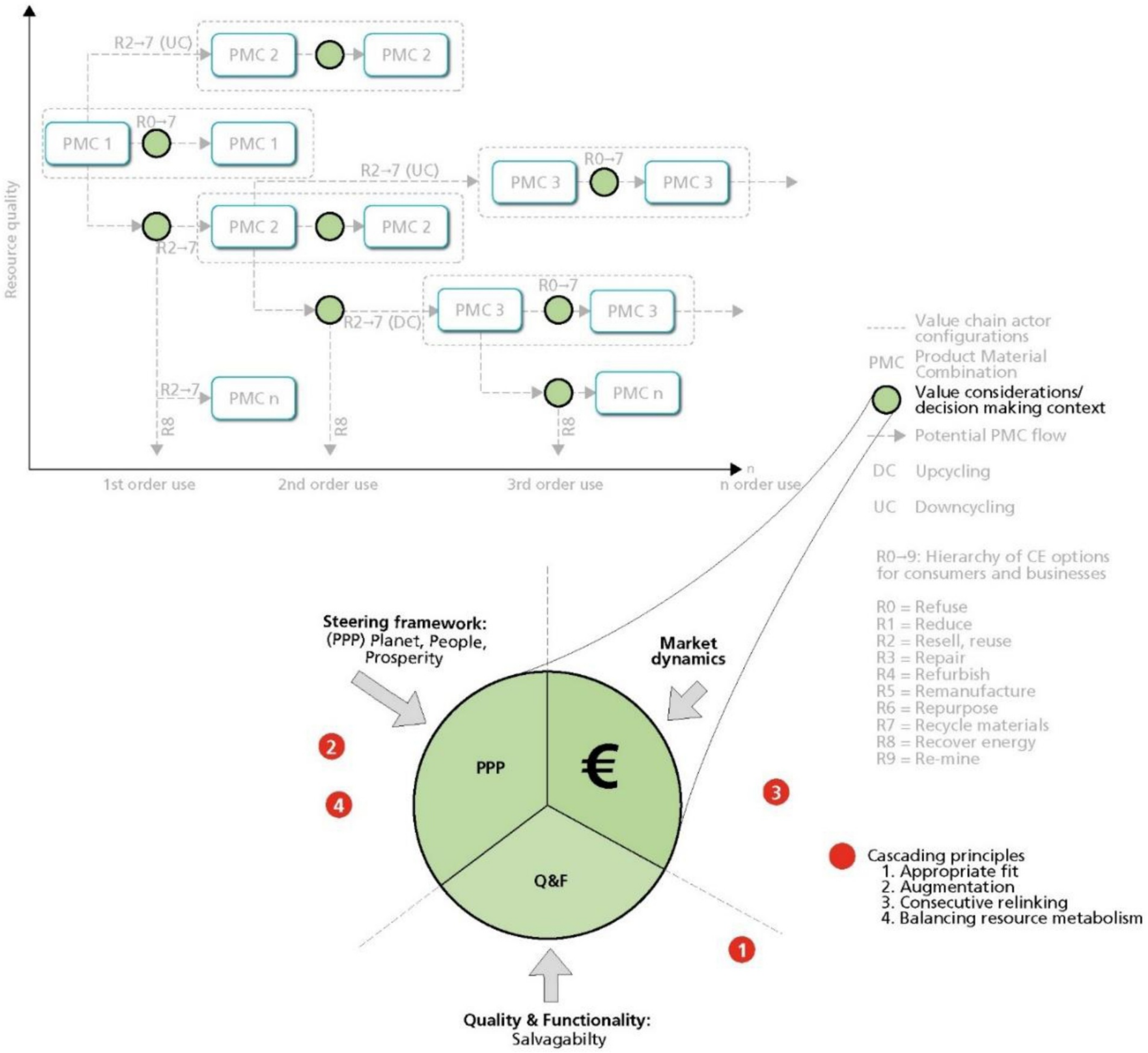

Fig. 5. Value considerations/decision-making context of cascading in a circular economy

which can be chosen from, all of which relate to the temporal, geographical, economic and innate value choices over the particular PMC. For example, an upcycling process could include turning used plastic bottles into high-quality jumpers, e.g. Patagonia, instead of conventional recycling into pellets. Alternatively, in Northern European waste management systems, a PMC is discarded by consumers, processed by recyclers and finally sold/used in a subsequent value chain. Whilst the recovery of materials in Europe has been steadily increasing, research has suggested these systems fail to recover critically scarce rare earth metals (Ortego *et al.*, 2018). There is a question of *how* such processes are governed and *what* the current mechanisms and decision-making processes are that occur in these contexts, which facilitate (or not) a CE-cascading process, i.e. an R-imperative with the best sustainability outcomes. In different contexts, for example developing countries, we would perceive different governance contexts and value perceptions, which would alter *what* the appropriate fit of the PMC is. Such context is lost in the strictly technical debate. We further explore and detail the potential value considerations and decision-making context below (Fig. 5). For this, we reviewed a key selection of sustainability reviews (see Supplementary Materials) and selected the integrated perspective as proposed by Vermeulen (2018).

Such value considerations integrate the original cascading principles as outlined by Sirkin and ten Houten (1994) (Section 3.3) with a synthesis of sustainability indicators. We develop three dimensions and broader considerations that should guide every step of the CE-cascading decision-making and valorisation processes. These three dimensions and their explanations are:

i **Monetary value**, guided by market forces, which in principle covers labour costs and energy requirements and the cascading principle of consecutive relinking;
ii **Quality and functionality** of the material in question. Understood as it's physical or interpreted properties (see Section 3.3) resulting in the salvageability, i.e. the quantities of a PMC that can be circulated into subsequent uses. This is guided by the user requirements (e.g. appropriate fit), which also interconnect with market forces; and
iii The **steering framework**, or governance approach, guided by the triple-P (People, Planet, Prosperity), including the cascading principles augmentation and balancing resource metabolism.

We contend to use cascading, integrated within CE, as a socially contextual concept used to contribute to the broader sustainable development agenda. Two of the above dimensions are easily understood: market dynamics and quality and functionality (see Section 3.3). The third, the steering framework, represents the overarching governance approach to promote cascading between and above all actor configurations and is (likely) organised at the macro scale (see Section 3.4). This can potentially modify the other dimensions to reach a certain outcome. There are numerous comprehensive works on sustainability that can be used to outline integrated ambitions (cf. Giddings *et al.*, 2002; Gupta and Vegelin, 2016; Mebratu, 1998; Parris and Kates, 2003; Vermeulen, 2018). A recent synthesis of sustainable development indicators proposes the triple-P (Planet, People, Prosperity), displaced the original triple bottom line (Planet, People *Profit*), to provide a means of reaching both planetary and human well-being (Vermeulen, 2018). Planet refers to the ecological threats, e.g. resource depletion, land use degradation, climate change etc. related to production and consumption activities. People refer to direct threats to individuals linked to those systems. Prosperity refers to well-functioning social systems, e.g. value-chain actors and socio-economic institutions (Vermeulen, 2018; Vermeulen and Witjes, 2016). This framing accounts for intergenerational justice (time) and displaced impacts (place), and should represent the steering framework for organising a cascading system. This framework goes beyond the immediate fixation of CE, e.g. waste, climate change and resource security to a more holistic conceptualisation with applicable assessment indicators. This synthesis provides the analytical basis for the proposed cascading steering framework which can direct individual exchanges between users and actor configurations.

Using such a framing allows for goal orientation relating to the direct actions, long-term outcomes and the desired end state of a CE and cascading process. This expands conventional CE narratives beyond resource fixation towards more holistic goals, e.g. worker well-being, community livelihoods, etc. This can be realised by specifically steering PMCs towards a specific user or actor group that score well on these goals. Whilst this is currently discussed in more abstract terms, this allows for the development of problem framing, policy development, implementation and evaluation of both macro (nation-state) and micro (a company or firm) involved in existing (or potential) cascading processes. Thus, this provides the basis for practitioners to engage with a more holistic description of higher-value upcycling options regarding the specific allocation choice of a PMC.

6. Discussion and conclusion

This article reviewed the principle of cascading, to understand its theoretical and empirical underpinning and to integrate it with CE. Cascading is a useful tool to examine and direct product and material exchanges and transfers; through matching a particular product or material to its highest-value use at a specific point in time. We connect the framework of Sirkin and ten Houten (1994) and CE, as operationalised through the 10Rs of Reike *et al.* (2018), to describe the exchanges or transfers of PMC's between individual value chain actors (Fig. 3) and between different actor configurations (Fig. 4). This process contains a dual process (1) the physical properties of the PMC and (2) the social context, the *how* and *where*, in which decision decision-making and value (economic or inherent) are ascribed and the preferential allocation realised, and which has so far which is under-explored in the cascading literature.

We argue this decision-making context is one moment to examine and direct the subsequent allocation. The sequential allocation of a PMC represents an exchange or transfer of a specific PMC combination (within a specific actor configuration) to another group. This requires decision-making to transcend individual PMC or value chain actors, relating to the coordination and decision-making procedures. However, such value chains are likely isolated, meaning this exchange is in the hands of the sending and receiving actors based on the PMC quality, market value and economic conditions. The CE literature of up/downcycling provides an insight into the varied value considerations over material applications which relates to the innate or socially contextual value perception of a PMC. These have primarily been interconnected with the innate physical properties and market demand. Yet, in the cascading literature, this assumes an automatic allocation of such PMC's to the highest functional use. Our analysis indicates the necessity of transcending specific PMC's, or sets of actor configurations, to an overarching level, i.e. the governance structure, which shapes the decision-making context. We build on this further, proposing three dimensions that capture current and potential CE-cascading mechanisms and decision-making contexts. Guiding the steering framework for specific cascading systems (micro to macro) we propose the triple-P (People, Planet, Prosperity) as an analytical basis to analyse existing R-imperative exchanges. This expands CE-cascading systems beyond resource supply and waste generation, to evaluate the social and environmental processes in which they are embedded.

This framework raises further questions about how current allocation choices are steered. In particular, a question emerges of what the existing institutional design for decision-making between and/or above actor configurations is, e.g. extended producer responsibility organisations. Furthermore, the question of governance raises questions not, as yet, detailed in either the cascading or CE literature. Namely, the coordination of, knowledge generation for, and decision-making procedures currently existing in cascading(-like) processes. For example, what the institutional design is for existing allocation choices for materials and what is further needed for materials to reach their highest-value (monetary or otherwise) use. Future research will test the validity of the above framework by examining existing CE-cascading like systems, their spatial, geographical and sectoral contexts, and the value considerations and the decision-making that facilitates these systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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References

Ayres, R.U., Ayres, L.W., 1996. Industrial Ecology. Books.

Bais-Moleman, A.L., Sikkema, R., Vis, M., Reumerman, P., Theurl, M.C., Erb, K.-H.H., 2018. Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union. J. Clean. Prod. 172, 3942–3954. https://doi.org/10.1016/j.jclepro.2017.04.153.

Bao, Q., Huang, Y.H., Lan, C.K., Chen, B.H., Duh, J.G., 2015. Scalable Upcycling Silicon from Waste Slicing Sludge for High-performance Lithium-ion Battery Anodes. Electrochim. Acta 173, 82–90. https://doi.org/10.1016/j.electacta.2015.04.155.

Bezama, A., 2016. Let us discuss how cascading can help implement the circular economy and the bio-economy strategies. Waste Manag. Res. https://doi.org/10.1177/0734242X16657973.

Blomsma, F., Brennan, G., 2017. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. J. Ind. Ecol. 21, 603–614. https://doi.org/

10.1111/jiec.12603.

Brunet-Navarro, P., Jochheim, H., Kroiher, F., Muys, B., 2018. Effect of cascade use on the carbon balance of the German and European wood sectors. J. Clean. Prod. 170, 137–146. https://doi.org/10.1016/j.jclepro.2017.09.135.

Chertow, M., Ehrenfeld, J., 2012. Organizing Self-Organizing Systems: Toward a Theory of Industrial Symbiosis. J. Ind. Ecol. 16, 13–27. https://doi.org/10.1111/j.1530-9290.2011.00450.x.

De Besi, M., McCormick, K., 2015. Towards a bioeconomy in Europe: National, regional and industrial strategies. Sustain 7, 10461–10478. https://doi.org/10.3390/su70810461.

Deutz, P., Baxter, H., Gibbs, D., Mayes, W.M., Gomes, H.I., 2017. Resource recovery and remediation of highly alkaline residues: A political-industrial ecology approach to building a circular economy. Geoforum 85, 336–344. https://doi.org/10.1016/j.geoforum.2017.03.021.

Di Maria, A., Eyckmans, J., Van Acker, K., 2018. Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. Waste Manag 75, 3–21. https://doi.org/10.1016/j.wasman.2018.01.028.

Dodoo, A., Gustavsson, L., Sathre, R., 2014. Recycling of Lumber. Handbook of Recycling: State-of-the-Art for Practitioners. Analysts, and Scientists. Elsevier, pp. 151–163. https://doi.org/10.1016/B978-0-12-396459-5.00011-8.

Echeverria, C.A., Handoko, W., Pahlevani, F., Sahajwalla, V., 2019. Cascading use of textile waste for the advancement of fibre reinforced composites for building applications. J. Clean. Prod. 208, 1524–1536. https://doi.org/10.1016/j.jclepro.2018.10.227.

Egelyng, H., Romsdal, A., Hansen, H.O., Slizyte, R., Carvajal, A.K., Jouvenot, L., Hebrok, M., Honkapää, K., Wold, J.P., Seljåsen, R., Aursand, M., 2018. Cascading Norwegian co-streams for bioeconomic transition. J. Clean. Prod. 172, 3864–3873. https://doi.org/10.1016/j.jclepro.2017.05.099.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy. Ellen MacArthur Found 1, 1–96. https://doi.org/10.1162/108819806775545321.

European Commission, 2018. Circular Economy Strategy - Environment - European Commission [WWW Document]. URLhttp://ec.europa.eu/environment/circular-economy/(accessed 10.26.18).</bib.

Fischer, A., Pascucci, S., 2017. Institutional incentives in circular economy transition: The case of material use in the Dutch textile industry. J. Clean. Prod. 155, 17–32. https://doi.org/10.1016/j.jclepro.2016.12.038.

Garcia, C.A., Hora, G., 2017. State-of-the-art of waste wood supply chain in Germany and selected European countries. Waste Manag. https://doi.org/10.1016/j.wasman.2017.09.025.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.12.048.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.09.007.

Giddings, B., Hopwood, B., O'Brien, G., 2002. Environment, economy and society: Fitting them together into sustainable development. Sustain. Dev. 10, 187–196. https://doi.org/10.1002/sd.199.

Gontard, N., Sonesson, U., Birkved, M., Majone, M., Bolzonella, D., Celli, A., Angellier-Coussy, H., Jang, G.-W., Verniquet, A., Broeze, J., Schaer, B., Batista, A.P., Sebok, A., Paula Batista, A., Sebok, A., 2018. A research challenge vision regarding management of agricultural waste in a circular bio-based economy. Crit. Rev. Environ. Sci. Technol. 1–41. https://doi.org/10.1080/10643389.2018.1471957.

Graedel, T.E., Allenby, B.R., 2003. Industrial ecology. Prentice Hall.

Grant, M.J., Booth, A., 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. Health Info. Libr. J. 26, 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x.

Gupta, J., Vegelin, C., 2016. Sustainable development goals and inclusive development. Int. Environ. Agreements Polit. Law Econ. 16, 433–448. https://doi.org/10.1007/s10784-016-9323-z.

Haberl, H., Geissler, S., 2000. Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecol. Eng. 16, 111–121. https://doi.org/10.1016/S0925-8574(00)00059-8.

Höglmeier, K., Weber-Blaschke, G., Richter, K., 2017. Erratum: Potentials for cascading of recovered wood from building deconstruction—A case study for south-east Germany. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2015.10.030.

Husgafvel, R., Linkosalmi, L., Hughes, M., Kanerva, J., Dahl, O., 2018. Forest sector circular economy development in Finland: A regional study on sustainability driven competitive advantage and an assessment of the potential for cascading recovered solid wood. J. Clean. Prod. 181, 483–497. https://doi.org/10.1016/j.jclepro.2017.12.176.

Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Denmark. J. Ind. Ecol. 10, 239–255. https://doi.org/10.1162/108819806775545411.

Jarre, M., Petit-Boix, A., Priefer, C., Meyer, R., Leipold, S., 2019. Transforming the bio-based sector towards a circular economy - What can we learn from wood cascading? For. Policy Econ. https://doi.org/10.1016/j.forpol.2019.01.017.

Kalverkamp, M., Pehlken, A., Wuest, T., 2017. Cascade use and the management of product lifecycles. Sustain 9, 1540. https://doi.org/10.3390/su9091540.

Keegan, D., Kretschmer, B., Elbersen, B., Panoutsou, C., 2013. Cascading use: A systematic approach to biomass beyond the energy sector. Biofuels, Bioprod. Biorefining. https://doi.org/10.1002/bbb.1351.

Kim, S., Hwang, T., Lee, K.M., 1997. Allocation for cascade recycling system. Int. J. Life Cycle Assess. 2, 217–222. https://doi.org/10.1007/BF02978418.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.09.005.

Koffler, C., Florin, J., 2013. Tackling the downcycling issue - A revised approach to value-corrected substitution in life cycle assessment of aluminum (VCS 2.0). Sustain 5, 4546–4560. https://doi.org/10.3390/su5114546.

Korhonen, J., 2001. Regional industrial ecology: Examples from regional economic systems of forest industry and energy supply in Finland. J. Environ. Manage. 63, 367–375. https://doi.org/10.1006/jema.2001.0477.

Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular Economy: The Concept and its Limitations. Ecol. Econ. 143, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041.

Korhonen, J., Niutanen, V., 2003. Material and energy flows of a local forest industry system in Finland. Sustain. Dev. 11, 121–132. https://doi.org/10.1002/sd.212.

La Mantia, F.P., 2004. Polymer mechanical recycling: Downcycling or upcycling? Prog. Rubber. Plast. Recycl. Technol. 20, 11–24.

Lafleur, M.C.C., Fraanje, P.J., 1997. Towards sustainable use of the renewable resource wood in the Netherlands - A systematic approach. Resour. Conserv. Recycl. 20, 19–29. https://doi.org/10.1016/S0921-3449(97)01195-6.

Lansink, A., Veld, H.de V., 2010. De kracht van de Kringloop: geschiedenis en toekomst van de Ladder van Lansink. Vrilan, Apeldoorn.

Lüdeke-Freund, F., Gold, S., Bocken, N.M.P., 2018. A Review and Typology of Circular Economy Business Model Patterns. J. Ind. Ecol. 00, 1–26. https://doi.org/10.1111/jiec.12763.

Ma, Y., Hummel, M., Määttänen, M., Särkilahti, A., Harlin, A., Sixta, H., 2016. Upcycling of waste paper and cardboard to textiles. Green Chem 18, 858–866. https://doi.org/10.1039/c5gc01679g.

Mair, C., Stern, T., 2017. Cascading Utilization of Wood: a Matter of Circular Economy? Curr. For. Reports 3, 281–295. https://doi.org/10.1007/s40725-017-0067-y.

Mantau, U., 2012. Wood flows in Europe.</bib.

Mebratu, D., 1998. Sustainability and sustainable development: Historical and conceptual review. Environ. Impact Assess. Rev. 18, 493–520. https://doi.org/10.1016/S0195-9255(98)00019-5.

Mehr, J., Vadenbo, C., Steubing, B., Hellweg, S., 2018. Environmentally optimal wood use in Switzerland—Investigating the relevance of material cascades. Resour. Conserv. Recycl. 131, 181–191. https://doi.org/10.1016/j.resconrec.2017.12.026.

Mellor, W., Wright, E., Clift, R., Azapagic, A., Stevens, G., 2002. A mathematical model and decision-support framework for material recovery, recycling and cascaded use. Chem. Eng. Sci. https://doi.org/10.1016/S0009-2509(02)00282-8.

Murray, A., Skene, K., Haynes, K., 2017. The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. J. Bus. Ethics 140, 369–380. https://doi.org/10.1007/s10551-015-2693-2.

Nilakantan, G., Nutt, S., 2015. Reuse and upcycling of aerospace prepreg scrap and waste 59. https://doi.org/10.1016/j.repl.2014.12.070</bib.

Niutanen, V., Korhonen, J., 2003. Industrial ecology flows of agriculture and food industry in Finland: Utilizing by-products and wastes. Int. J. Sustain. Dev. World Ecol. 10, 133–147. https://doi.org/10.1080/13504500309469792.

Olsson, O., Roos, A., Guisson, R., Bruce, L., Lamers, P., Hektor, B., Thrän, D., Hartley, D., Ponitka, J., Hildebrandt, J., 2018. Time to tear down the pyramids? A critique of cascading hierarchies as a policy tool. Wiley Interdiscip. Rev. Energy Environ. 7, 1–11. https://doi.org/10.1002/wene.279.

Ortego, A., Valero, A., Valero, A., Iglesias, M., 2018. Downcycling in automobile recycling process: A thermodynamic assessment. Resour. Conserv. Recycl. 136, 24–32. https://doi.org/10.1016/j.resconrec.2018.04.006.

Parris, T.M., Kates, R.W., 2003. Characterizing a sustainability transition: Goals, targets, trends, and driving forces. Proc. Natl. Acad. Sci. U. S. A. 100, 8068–8073. https://doi.org/10.1073/pnas.1231336100.

Pol, V.G., 2010. Upcycling: Converting waste plastics into paramagnetic, conducting, solid, pure carbon microspheres. Environ. Sci. Technol. 44, 4753–4759. https://doi.org/10.1021/es100243u.

Reike, D., Vermeulen, W.J.V., Witjes, S., 2018. The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. Resour. Conserv. Recycl. 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027.

Saavedra, Y.M.B., Iritani, D.R., Pavan, A.L.R., Ometto, A.R., 2018. Theoretical contribution of industrial ecology to circular economy. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.09.260.

Sathre, R., Gustavsson, L., 2006. Energy and carbon balances of wood cascade chains. Resour. Conserv. Recycl. 47, 332–355. https://doi.org/10.1016/j.resconrec.2005.12.008.

Sirkin, T., ten Houten, M., 1994. The Cascade Chain A Theory and Tool for Achieving Resource Sustainability with Applications for Product Design. Resour. Conserv. Recycl. 10, 213–277.

Stahel, W.R., 2010. The Performance Economy. The Performance Economy, 2nd ed. Palgrave Macmillan, New York. https://doi.org/10.1057/9780230274907.

Stark, T.D., Miller, J., LaFiura, D., Fought, S., 2013. Sustainable geomembrane recycling and downcycling: Shale oil and gas open sustainability opportunities. Geosynthetics 31. https://doi.org/10.1061/9780784480144.005.

Stotz, P.M., Niero, M., Bey, N., Paraskevas, D., 2017. Environmental screening of novel technologies to increase material circularity: A case study on aluminium cans. Resour. Conserv. Recycl. 127, 96–106. https://doi.org/10.1016/j.resconrec.2017.07.013.

Suter, F., Steubing, B., Hellweg, S., 2017. Life Cycle Impacts and Benefits of Wood along the Value Chain: The Case of Switzerland. J. Ind. Ecol. 21, 874–886. https://doi.org/10.1111/jiec.12486.

Teuber, L., Osburg, V.S., Toporowski, W., Militz, H., Krause, A., 2016. Wood polymer composites and their contribution to cascading utilisation. J. Clean. Prod. 110, 9–15. https://doi.org/10.1016/j.jclepro.2015.04.009.

van Nes, N., Cramer, J., 2006. Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns. J. Clean. Prod. 14, 1307–1318. https://doi.org/10.1016/j.jclepro.2005.04.006.

Vandecasteele, C., Heynen, J., Goumans, H., 2013. Materials recycling in construction: A review of the last 2 decades illustrated by the WASCON conferences. Waste and Biomass Valorization. https://doi.org/10.1007/s12649-013-9239-6.

Velis, C.A., Franco-Salinas, C., Najorka, J., Boccaccini, A.R., Cheeseman, C.R., 2014. Up-Cycling Waste Glass to Minimal Water Adsorption/Absorption Lightweight Aggregate by Rapid Low Temperature Sintering: Optimization by Dual Process-Mixture Response Surface Methodology. https://doi.org/10.1021/es5003499</bib.

Venkata Mohan, S., Nikhil, G.N., Chiranjeevi, P., Nagendranatha Reddy, C., Rohit, M.V., Kumar, A.N., Sarkar, O., 2016. Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives. Bioresour. Technol. https://doi.org/10.1016/j.biortech.2016.03.130.

Vermeulen, W.J.V., 2006. The social dimension of industrial ecology: on the implications of the inherent nature of social phenomena. Prog. Ind. Ecol. An Int. J. 3, 574. https://doi.org/10.1504/pie.2006.012754.

Vermeulen, W.J.V., 2018. Substantiating the rough consensus on the concept of sustainable development as a point of departure for indicator development. In: Bell, S., Morse, S. (Eds.), Routledge Handbook of Sustainability Indicators. Routledge, London, pp. 59–92. https://doi.org/10.4324/9781315561103-4.

Vermeulen, W.J.V., Reike, D., Witjes, S., 2018. Circular Economy 3.0: Getting Beyond the Messy Conceptualization of Circularity and the 3R's, 4R's and More … CEC4. Europe Publications, pp. 1–6.

Vermeulen, W.J.V., Witjes, S., 2016. On addressing the dual and embedded nature of business and the route towards corporate sustainability. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.09.132.

Vis, M., Mantau, U., Allen, B., 2016. CASCADES. Study on the optimised cascading use of wood.

Weimann, K., Giese, L.B., Mellmann, G., Simon, F.G., 2003. Building materials from waste. Mater. Trans. 44, 1255–1258. https://doi.org/10.2320/matertrans.44.1255.

Worrell, E., Reuter, M.., 2014. Handbook of Recycling: State-of-the-Art for practitioners, Analysists, and Scientists, in: Worrell, E., Reuter, M.A. (Eds.), Elseview Inc. Elsevier Inc., London. https://doi.org/10.1016/B978-0-12-396459-5.00020-9</bib.

Zabaniotou, A., Kamaterou, P., 2019. Food waste valorization advocating Circular Bioeconomy - A critical review of potentialities and perspectives of spent coffee grounds biorefinery. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.11.230.

Zhuo, C., Levendis, Y.A., 2014. Upcycling waste plastics into carbon nanomaterials: A review. J. Appl. Polym. Sci. 131. https://doi.org/10.1002/app.39931.