# Sustainability of Cascading Product Lifecycles: The Need for Adaptive Management to End-of-Life Supply Chains

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## The need for adaptive management to end-of-life supply chains

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**Abstract.** Product lifecycles can contain several waste management steps after the production of a product. At each step, 'end-of-life' supply chains can separate, each emerging supply chain representing an intended lifecycle or an unintended, though not necessarily inferior lifecycle in terms of sustainability. This variety demonstrates the complexity arising at the end-of-life and indicates that not necessarily a single actor coordinates these supply chains. The cascade use methodology targets this complexity by identifying sustainable supply chains, possibly managed by alternative actors. This study applies the methodology to a novel case of vehicle reuse and conversion discussing its sustainability and implications for decision makers. The authors argue for more adaptive management approaches to address sustainability in product lifecycles more holistically.

**Keywords:** Cascade use, recycling, reuse, remanufacturing, product lifecycle management, closed-loop supply chains, open-loop supply chains

## 1 Introduction

The circular economy is popular in industry, policy, as well as research, and as such widely supported [1–3]. The concept of a circular economy reinforces triple bottom line objectives: i) conserving environmental and ii) economic resources (such as materials, energy, labor and capital value) that are incorporated into products as well as iii) contributing to the social dimension of sustainability [3].

The waste management hierarchy (WMH) considers different strategies for resource conservation in a descending order of its environmental friendliness from prevention of (primary) production to recovery and disposal of products and materials. For products (after production), the subsequent steps of reuse and recycling aim to preserve resources in the form of products (reuse) or materials (recycling). The second to the last step, recovery, aims at recovering energy from materials. After energy recovery, disposal remains as the final, generally undesirable treatment option [4].

adfa, p. 1, 2011.

Reuse and recycling transactions are fundamental for a functional circular economy and they regularly form some sort of cascade utilization. Product lifecycles can contain several of the WMH steps after the production of a product, namely reuse, recycling and recover. Reuse contains various circular strategies that relate to different degrees of additional treatment and resource inputs, i.e. direct reuse (without further treatment), repair, refurbish or remanufacturing [5]. At each of these steps, 'waste' supply chains of end-of-life and end-of-use products could separate (end-of-life and end-of-use are hereafter subsumed as end-of-life for simplicity; for a more detailed discussion of end-of-life perspectives, the interested reader may refer to Kalverkamp *et al.* [6]). While some products (or components) remain at the reuse level, others move towards recycling or recovery. However, in reality, the corresponding supply chains may separate at each level of the WMH. Furthermore, each supply chain may represent an intended lifecycle or an unintended, though not necessarily inferior, lifecycle in terms of sustainability. This variety demonstrates the complexity at the end-of-life of products and components. It further indicates the importance of reuse and recycling as critical steps of the WMH where products potentially enter some sort of cycle not necessarily managed by one actor or a defined group of actors.

The objective of this paper is to demonstrate how the 'cascade use' perspective on product lifecycles relates to different types of supply chains by considering the complexity and market dynamics at products' end-of-life. The predominant consideration of either single businesses and their ('closed-loop') supply chains or product-service-systems sets boundaries that may neglect this complexity [7] and thereby undermine the sustainability potential of alternative supply chains, usually considered as 'forward' supply chains. This paper focuses on how the cascade use methodology can support alternative perspectives on the management of sustainable supply chains. Therefore, we outline the 'cascade use methodology' (section 3) and apply the methodology to a case that visualizes the dynamics of global used car markets and corresponding supply chains (section 4). The discussion highlights the potential for supply chain management to contribute to sustainability and derives practical implications for management and policy (section 5). An outlook on future research concludes this paper (section 6).

## 2 Product Lifecycles and Closed-Loop Supply Chains

The product lifecycle approach is fundamental in the development and management of sustainable products, such as in product design (e.g., design for repair) or corresponding business models [8]. In the context of reuse and recycling in product lifecycles, products return to the manufacturer or they reach third parties (e.g., remanufacturers or material recyclers). In this context, reverse supply chains support the management of product returns with different tools to establish circularity in product lifecycles, popularized under the term 'closed-loop supply chains' (CLSC). CLSCs are supposed to recover value from product returns and are usually dominated by a central actor who intends to control the entire product lifecycle [9]. Nevertheless, third-party organizations take advantage of materials dedicated to waste management or that 'leak' from CLSCs and thereby also close product lifecycles [10].

The term ‘product lifecycle’ is used differently throughout literature [11]. Two lifecycle perspectives are predominantly considered, namely a marketing [12] and a technical/engineering [13] one. The marketing perspective identifies up to five stages: introduction, growth, maturity, saturation and decline [12]. When considering different product classes, forms and models, the complexity of this perspective increases substantially [12]. The more technical perspective usually considers three phases, beginning-of-life; middle-of-life; and end-of-life [14]. Prominent domains using this technical view are life cycle assessment, business process management and product lifecycle management. The latter uses data and information technology to enable product lifecycles [13, 14]. These two perspectives are relevant when considering the real-world complexity of market-oriented manufacturing in the context of sustainability [11]. For increasing sustainability, it is especially relevant to consider the end-of-life ‘and beyond’ from both lifecycle perspectives.

In addition to the outlined lifecycle perspectives, there is a process-related perspective in marketing that comprises all market transactions from the (primary) seller to the final consumer, also referred to as ‘transvections’. These transvections reflect the technical processes ‘from extraction to consumption’ eventually merging in the concept of supply chain management [15]. This illustrates linkages and interdependencies of the two different lifecycle perspectives in common business practice.

Illustrations in literature model the product lifecycle differently with a variable number of process steps or different allocations of reverse flows, although often with the focus on reverse supply chains that connect with actors of the forward supply chain to enable CLSC’s [16, 17]. This leads to an implicit or explicit focus on central actors that manage these supply chains hence the product lifecycles. Consequently, an implicit assumption made by most stakeholders and many researchers is that products need to be returned to the original producer; this, however, limits the field of vision and underestimates end-of-life complexity and possibilities.

## 3 The Cascade Use Methodology

The authors refer to those lifecycles that split-up at the reuse level eventually flowing into yet again different ‘steams’, i.e. supply chains, at the recycling level as ‘cascading utilization’. The cascade use methodology aims to integrate the broad variety of end-of-life options into the management of product lifecycles. The cascade use methodology acknowledges the complexity at the end-of-life, and shows how products and eventually materials cascade through reuse and recycling to recovery (ideally avoiding landfill). The idea of cascade use derives from the biomass domain where it describes the different processes that renewable resources happen to pass before treated as an energy source (e.g. from wood through boards and recycled fibers to fibers as fuel for energy production) [18]. In addition to the biomass domain, the term ‘cascade’ is used in contexts of lifecycle management and reuse. Related to quantitative approaches in CLSCs, Guide and van Wassenhove [19] use the term ‘cascade reuse opportunities’; they further state research gaps regarding a ‘life-cycle approach’ that considers all the different types of product returns. Therefore, there is no general definition for the term ‘cascade’.

However, the cascade from the biomass domain serves as a blueprint that is combined with the WMH steps ‘reuse’, ‘recycle’ and ‘recovery’. Fig. 1 shows the cascade use methodology and depicts clearly the increasing complexity and variety of end-of-life options at the levels reuse, recycle and recovery. The downwards inclination conceals that products and materials can remain at each cascade level through iterations of reuse (e.g. remanufacturing) or recycling (up-/down-cycling). In addition, this cascade does not consider landfill, because landfill does not contribute to circularity [4].

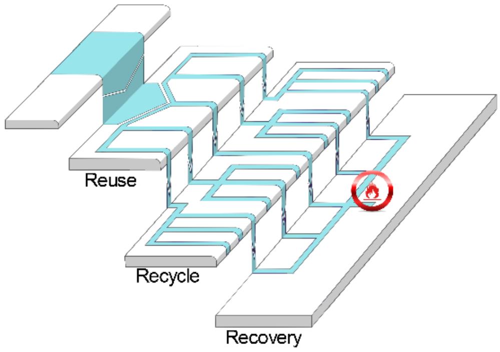


**Fig. 1.** Cascade Use Methodology [6]

Thinking in cascades influences the product lifecycle from the start, for example, through design principles facilitating cascade levels. This applies similarly to components replaced during the product lifetime. However, even products that were designed for lifecycle iterations or that are part of a circular business model do not always reach the corresponding CLSC. In such cases, third parties may take advantage of these flows and perform activities mimicking the CLSC. Therefore, various supply chains can co-exist at the reuse level and, similarly, at the recycling level of the cascade.

The visualization of different cascades fosters alternative end-of-life solutions, in supporting decision makers to identify economic and environmental potential in the different ‘streams’ of the cascade. It integrates market realities of trade with used products and of changing end-of-life options. The realities at the end-of-life are neither a perfect circular flow towards known stakeholders nor are they as one-directional as critics of classic forward supply chains may claim. Hence, the narrow perspective on a predefined lifecycle potentially supported through CLSC management limits the view on opportunities for alternative and maybe even more sustainable subsequent lifecycles. The cascade use methodology acknowledges these different supply chains and recognizes that one supply chain owner can hardly manage all potential end-of-life scenarios.

## 4 Results

Challenges regarding used-product collection in general, further complicated by dynamics on real-world markets, foster the previously described complexity. The cascade use methodology, applied and discussed below, addresses this gap regarding new and alternative actors in the management of product lifecycles with a real-world case. The methodology further underlines that the management of product lifecycles must consider additional supply chains than those corresponding to the originally planned product lifecycle. The cascade use methodology has been demonstrated and applied before using two original cases [6]; those cases focused on product components (vehicle parts). This paper applies the methodology to a novel case focusing on the product (vehicles) through a similar empirical, case-based approach. However, a distinct emphasis is placed on the supply chain perspective. The product perspective motivated the case selection reasonably complementing the preceding methodology applications. The presented case addresses vehicle reuse across different markets with details on the quantities of end-of-life products that reach the reuse level and split into different supply chains. The case contextualizes the discussion on CLSCs at the reuse level and provides details on notable deviations from predicted supply chains due to market dynamics.

### 4.1 From Japan to Chile: Notable Used-Vehicle Export Supply Chains

Despite some differences and somewhat slowing sales, new car sales in developed countries of the European Union, North America and Japan result in numerous used vehicles that enter reuse at local or export markets or directly to material recycling. Between 2009 and 2013, the U.S. exported on average 762,000 cars per year mainly to lower-income countries [20]. In 2014 the US and Canada reached a combined export value of used cars of USD 1.4 billion [21]. The EU officially exports approximately 1.2 million used cars per year. However, the real number of exported used cars is not known and can be safely assumed to be significantly higher considering that the number of cars classified as ‘unknown whereabouts’ reached 4.75 million vehicles in 2014. Some of these vehicles reach unofficial recycling channels, others are simply exported legally but not monitored [22]. Japan exports approximately one million passenger cars per year [23] especially to Asian, Oceanic and African countries—but also to South America [24]. Fig. 2 shows the top-ten export destinations of used vehicles from Japan in 2015. Noteworthy are two destinations in this list that are strict right-hand traffic countries that, as best determined, do not allow right-hand-drive vehicles on their roads. Japan is a left-hand traffic country hence exports used right-hand-drive vehicles.

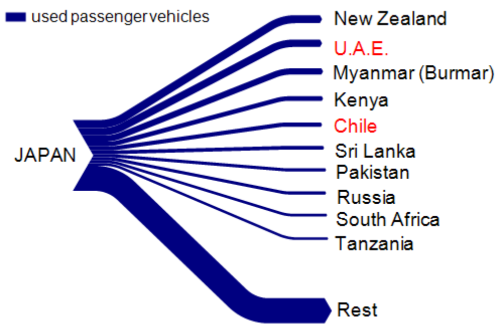


**Fig. 2.** Top10 export destinations of used passenger cars from Japan (strict left-hand-drive countries marked red; own representation, data source: http://jevic.com)

These streams of used vehicles at the reuse level of the cascade usually appear in classic forward supply chains through the transfer of ownership. Even if vehicles were previously managed in a CLSC facilitated by leasing or renting business models, these CLSCs eventually become forward supply chains for reuse. Either way, for the case of Chile, the transfer of ownership after a first use in Japan results in a transfer into a different region with different rules and legal obligations. Furthermore, the repair and recycling infrastructure may be different in the importing region.

### 4.2 'Cambio Volante': Market Dynamics Spur Remarkable Reuse Activities

The authors followed the export supply chain of Japanese used vehicles to a remarkable reuse activity in Chile in the port of the city of Iquique, which is part of the free trade zone ZOFRI (Zona Franca de Iquique). Tax exemptions and a demand for low-cost transportation in the surrounding region of Tarapacá and neighboring countries like Peru and Bolivia, as well as Paraguay, provide demand for used-vehicles. Although used-vehicles from Japan are relatively young (generally ~6-7 years; some only 4 years according to local source) and in relatively good condition, they need to be converted to left-hand-drive to be used in these countries. Thus, in the vicinity of the port of Iquique, mechanics convert vehicles in so-called 'cambio volante' (steering wheel 'change-over') workshops. Although this case may raise concerns about the safety of converted vehicles, it is notable that Japanese exporters provide conversion kits and even full conversion services that are conducted in Japan before export (see for example, www.japan-partner.com/LHD-conversion.php; www.globalauto.co.jp/reason_e.html), which indicate some formal acceptance of the conversion process. Nevertheless, the conversion workshops suffer from shortages with regard to parts that must be replaced, such as the steering rack. Other parts, like the ventilation ducts and the A/C unit, can be refitted with limitations. In general, all these parts are readily available as new spare parts (for left-hand-drive vehicles) provided within Japanese-sourced conversion kits. However, either the workshops cannot afford the retail prices of OEMs or such parts are not exported to Chile. In few cases, some OEMs install convertible components such as steering racks that can be 'flipped' hence used both in left-hand-drive and right-hand-drive vehicles. Such solutions substantially facilitate the conversion process. Workshops further intend to source alternative parts such as copies though often the identification of suppliers is difficult and the transport and import costs can raise to a prohibitive level. Used parts are an alternative to new parts (whether original or copies) though it can be difficult to acquire such in the required qualities or quantities. Therefore, the workshops constantly search for parts that cannot be 'flipped' such as steering racks. However, they manually rework and modify parts that need to be converted (e.g., the dashboard and retrofitting of A/C components), which establishes reasoned objections against conversion. Fig. 3 depicts the case and its supply chains using the cascade use methodology.

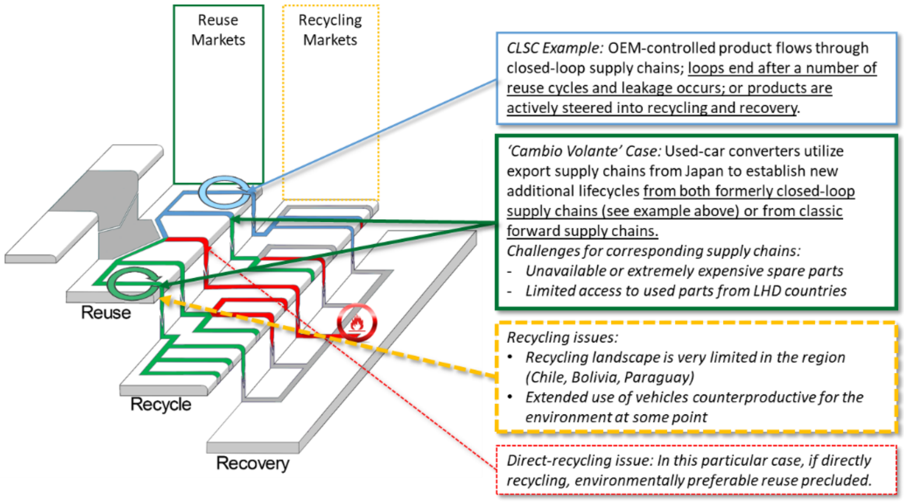


**Fig. 3.** Lifecycle and supply chain cascade for used-vehicle exports from Japan to Chile (the direct recycling route in red is not discuss in detail; adopted from Kalverkamp *et al.* [6])

## 5 Discussion

The exemplary case of vehicle conversion in Chile represents one of the many different supply chains that emerge from vehicle end-of-life in Japan. Similar forward supply chains may reach other countries too. Exports of used vehicles in developed countries before their optimal end-of-life makes vehicle reuse through these supply chains reasonable from an environmental perspective. In addition to the benefits in these supply chains due to trade gains and for customers due to affordable individual mobility, the (re-)manufacturing-like process of 'cambio volante' increases the demand for skilled labor, which addresses the societal dimension of sustainability. However, this particular cascading product lifecycle has limitations, such as stresses on the recycling infrastructure in the importing country, which may increase environmental impacts (compared to the home country) once the converted vehicle is reaching its ultimate end-of-life (in the import country). Furthermore, the export supply chain of used vehicles lacks an accompanying supply chain for spare parts or the parts provided raise the conversion costs to a prohibitive level. This may lead to a 'do-it-yourself' approach when converting vehicles and raises reasoned objections against such conversion. The case showed that some solutions exist, such as the design-stage solution of making steering racks that can be used both ways (left-hand-drive/right-hand-drive). Although it is more likely that OEMs designed these steering racks to improve their purchasing power and to reduce costs, it also facilitates the conversion of vehicles. However, further components and parts must be changed during the conversion process and their supply is limited as well.

From this case, the cascade use methodology highlights a hidden 'stream' in the automobile lifecycle and thereby indicates where additional product lifecycles emerge. The case makes evident that the complexity at the end-of-life involves many different actors in addition to OEMs and that ‘open-loop’ supply chains can complement CLSC to provide sustainable outcomes in supply chains.

From the perspective of the cascade use methodology, the Chilean case is an example where OEMs and other actors can contribute to sustainability by amending their product lifecycle and corresponding supply chain perspectives. For example, OEMs could provide certain components and parts to conversion workshops, potentially through special licenses. OEM arguments emphasizing product safety and risks due to the conversion can be anticipated, however, the conversion services by Japanese exporters indicate that some design thinking and a standardized conversion process is possible. Furthermore, the involvement of third-parties in activities such as remanufacturing is similarly criticized by OEMs despite the contribution of independent remanufacturers for sustainable outcomes of remanufacturing systems [25]. Such arguments seem to fall short in cases of contraventions that harm OEM customers, such as the recent and infamous emission scandal. Hence, this idea might not be popular with OEMs though should be discussed when sustainability is truly valued.

Other potential suppliers such as vehicle dismantlers and parts dealers, could be more prominent actors in ‘spare part supply chains for vehicle conversion’. These actors have the knowledge and access to used products. However, parts dealers from North America and Europe, being right-hand-drive regions, would be particularly relevant here, though trade is limited due to various barriers (such as taxes and regulations). Innovative solutions that improve the complex global reuse supply chains could support a safer conversion process. Recycling infrastructures have to accompany these developments in order to cover subsequent levels of cascading lifecycles.

Policy could utilize this knowledge and discuss tax exemptions for selected reuse-products or even develop strategies to attract refurbishing or remanufacturing businesses. Combined with an enforced extended producer responsibility for importers of new and used products (like the recycling legislation recently introduced by the Chilean government; http://leydereciclaje.mma.gob.cl) resulting in economic activities could contribute to all three dimensions of sustainability.

Neither CLSC nor product lifecycle management address unintended or unwanted supply chains emerging from the end-of-life. Those supply chains often develop due to dynamics on markets. The used product of one market can serve the needs at another market. The cascade use methodology sheds light on supply chains that complement CLSC in a sustainable manner without the management of a central actor. Therefore, the rather centralized control of CLSCs may require managerial approaches that complement existing supply chain strategies as a supporter of product lifecycle management. In addition, economic and environmental considerations may sometimes require governmental involvement to steer the streams of the cascade.

## 6 Conclusion and Outlook

The cascade use methodology aims to shed light on circular economy opportunities in addition to and beyond the CLSC. It broadens the perspective on market dynamics occurring at the end-of-life and affecting product lifecycles. The study recognized that less control over end-of-life decisions might not be the preferred choice for OEMs. However, if the variety of end-of-life waste streams were considered as an opportunity for lifecycle management, environmental and economic benefits could arise that also complement the originally designed lifecycle.

Complexity at the end-of-life and limitations in the current management of product lifecycles and in corresponding PLM solutions affect sustainability. The cascade use methodology suggests identifying the current cascades of a product to locate those cascade streams where a company can support reuse and recycling in a sustainable manner: Although concerned by less control over the value and supply chain, a motivation could be to regain certain influence over end-of-life decisions. However, the study only examined one case. Further cases are necessary to better assess the potential of 'open-loop supply chains' and to motivate practitioners and researchers to investigate the 'unseen or unwanted' supply chains. In addition, developing criteria for decisions on open- vs. closed-loop supply chains and investigating how management could benefit from open-loop supply chains provides fruitful ground for research.

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