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RESEARCH

Value-retained vs. impacts avoided: the differentiated contributions of remanufacturing, refurbishment, repair, and reuse within a circular economy

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Abstract

Value-retention processes (VRPs), a collective term that includes practices of direct reuse, repair, refurbishment, and remanufacturing, can facilitate the cycling of products and components within a circular economy (CE). VRPs are often presented as alternatives to conventional manufacturing and consumption, and as mechanisms for avoiding negative environmental impacts (e.g., landfill) and mitigating issues of material scarcity. However, these practices are typically lumped together under generic 'reuse' strategies within sustainable materials management programs and policies. Further, there is a lack of clarity and data regarding how VRPs differ, and the extent to which they contribute to the avoidance of negative environmental and economic impacts. Using novel integrated product-, process, and economy-level models, we quantify select environmental and economic impact metrics for VRPs and conventional manufacturing across six case study products, in two industrialized economies (USA and China). Using this novel methodology, we demonstrate a basis for clear differentiation of VRPs as distinct strategies within a CE, and show that each VRP offers differing forms of value (e.g. cost reduction, labor opportunity, and material retention) and differing degrees of environmental and economic impacts (e.g., primary material requirement, embodied emissions, process emissions). In all cases, the product- and process-level comparative analyses indicate that VRPs present a clear opportunity for significantly reduced environmental impacts, relative to conventional manufacturing. This novel methodology provides an adaptive, comprehensive model that can support the decision of whether or not to engage in VRPs. By quantifying and evaluating VRPs in terms of their relative environmental and economic performance, the distinct avenues, expectations and outcomes for CE can be better integrated across diverse industry and product portfolios (International Resource Panel [29]).

Keywords Value-Retention Processes · Remanufacturing · Refurbishment · Environmental impacts · Product life cycle · Service life

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Introduction

There is little disagreement that current production-consumption systems create significant environmental burdens and contribute to resource and material depletion. The largely 'linear' nature of these production-consumption systems – also referred to as 'take-make-dispose' systems [15] – requires substantial investment of primary materials and energy resources, and offers little opportunity for value retention or value recovery, with the majority of materials being disposed into the environment at their end-of-life (EOL). The consumption of materials at rates that exceed the earth's capacity to renew them is anticipated to constrain long-term economic growth and sustainability, in addition to the damage inflicted upon ecosystems and communities [28]. The dichotomy of economic growth versus environmental protection has recently been challenged via innovative concepts, frameworks and approaches, such as circular economy [15], decoupling [57], and resource productivity [38]. Some of the key proposed mechanisms for resource and/or impact decoupling that are integral to the concept of CE include product-level design, technological, and/or process innovations that can be used to reduce negative environmental impacts of production [18, 34],further, product- and process-level innovations may enable material intensity and marginal impact reductions that aggregate meaningfully when considering the total number of units produced and consumed at the economy-level [29].

Circular economy origins and transition frameworks

Common understanding of the concept of CE continues to evolve over time, influenced by origin concepts including but not limited to performance economy [54], cradle-to-cradle [41], biomimicry [6], the blue economy [49], industrial ecology [23], and the laws of ecology [10]. More recent contributions to literature present key perspectives on CE adoption and practice, i.e., regarding the use of design and business model strategies to close resource loops [7], the use of materials and energy over multiple phases within closed or circular flows [63], innovation strategies within technical vs. biological systems within industrial economies [15, 61], and the unique role and considerations for remanufacturing within a CE [2, 32]. Despite a comprehensive foundation in the literature, CE is sometimes presented as an essentially contested concept (ECC) [20] due to its origin in practice [35], the lack of systematic and critical research approaches [27, 35], and significant concerns regarding the limitations of CE with regard to rebound effects [24, 64]. However, there is emerging data to support the potential for CE activities to contribute to other sustainable development objectives including reduced primary material and resource consumption, and reduced associated upstream extraction and processing impacts [8, 16, 29, 42, 61].

Issues of materials

Many industrialized economies are dependent upon materials that are increasingly scarce, either due to short-term supply chain disruptions (e.g., natural disaster), or due to actual physical scarcity [3, 21]. U.S. Presidential Executive Order 13,817 defines a "critical mineral" as a mineral or mineral material that is "…essential to the economic and national security of the U.S., is from a supply chain that is vulnerable to disruption, and that serves an essential function in the manufacturing of a product, the absence of which would have substantial consequences…" [19]. Many of the 35 critical minerals listed for the U.S. are essential inputs to the automotive industry for the production of catalytic converters, steel alloys, and advanced battery technologies for electric vehicles [21]. Appropriate adoption of CE strategies focused on materials retention can help to mitigate or reduce the environmental impacts of continued extraction (e.g., by reducing demand for primary materials), and build resilience into material supply chains and economic markets by establishing alternate sources for material and spare part feedstocks [3, 21, 29, 50].

The potential and challenge of Value-Retention Processes (VRPs)

Practices of direct reuse, repair, refurbishment and remanufacturing (hereafter referred to collectively as "Value-Retention Processes" or "VRPs") are central activities within the technical material and product cycles of a CE [29]. VRPs are recognized as long-standing sustainable materials management practices and waste diversion, and as part of circular material- and product-systems [29]. For the purposes of this study we adopt VRP definitions as presented by the International Resource Panel (IRP) of the United Nations Environment Programme (2018) (Refer to Supporting Information (SI) file, Sect. 1): *Manufacturing*—The output product from traditional linear manufacturing production activities, which create a first life cycle for a product. This relies entirely on primary material inputs, and is performed by the original equipment manufacturer (OEM); *Direct Reuse*—The using again of a product that is not waste, for the same purpose for which it was conceived, without the necessity of repair or refurbishment; *Repair*—The fixing of a specified fault in a product and/or replacing of defective components, in order to make the product a fully functioning product to be used for its originally intended purpose; *Refurbishment*—The modification of a product that takes place within maintenance or intermediate maintenance operations to increase or restore performance and/or functionality or to meet applicable technical standards, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended; and *Remanufacturing*—A standardized industrial process that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance or better.

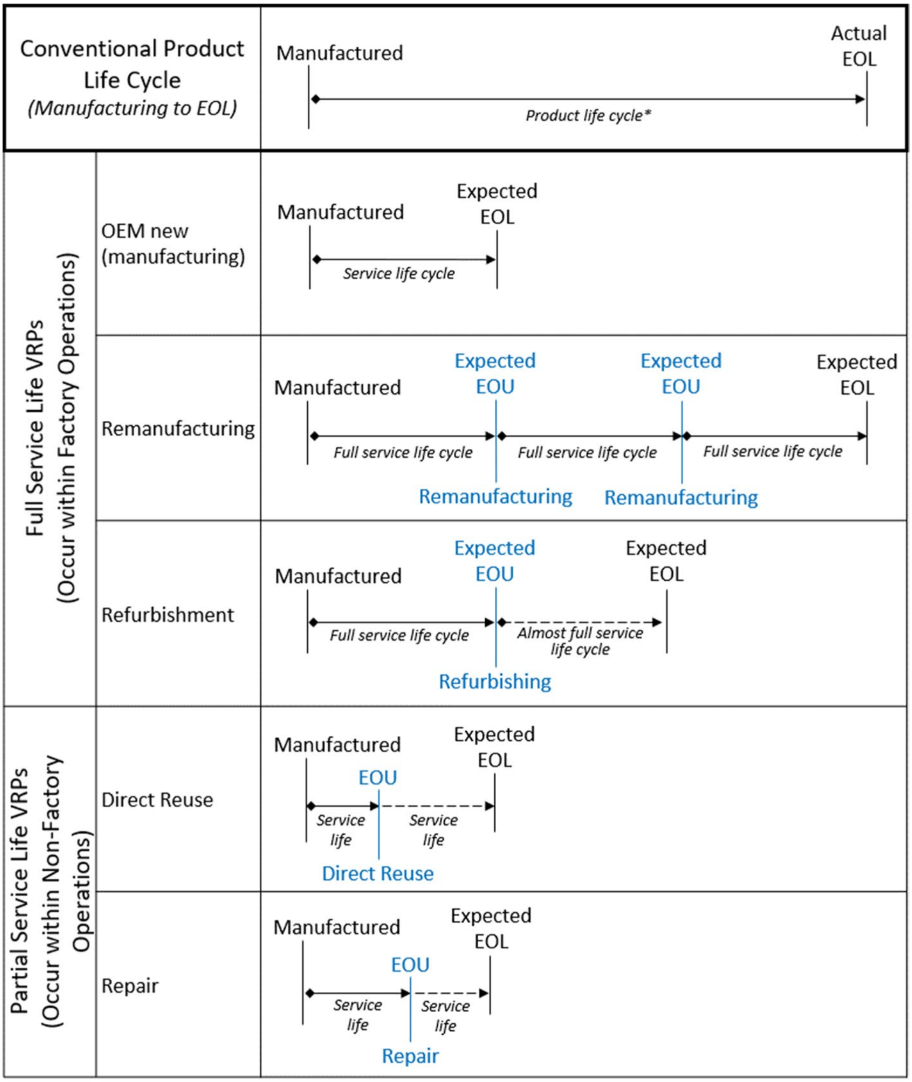
The emerging CE conversation has provoked a re-framing of VRPs to emphasize their contribution to the objective of value-retention (via the maintaining of a product or component's inherent functional form) within consumption-production systems (Product-level environmental impacts section). Fundamentally, VRPs allow for the cycling of products over multiple use cycles, keeping the inherent product form intact, and therefore allowing for either product life extension or the potential for additional service life cycles. The service life of a product refers to the product's lifetime during which it can be used economically (e.g., in years), or the time during which it is used by one owner, from the point of sale to the point of diversion for reuse [via VRPs], or to the point of disposal [13, 29], p. 26). Thus, the length of a service life can be reflected temporally (e.g., in years), and products within a CE can undergo multiple service life cycles (e.g., first cycle, second cycle), facilitated by the use of VRPs.

In the context of VRPs, end-of-use (EOU) must be differentiated from end-of-life (EOL), as these critical terms clarify where opportunity for VRPs exist. During the design of new products, expectations regarding the approximate specifications for the product's expected service life duration (e.g., in years), are established. The expected service life of a product, combined with data from product testing, can be used to inform the designed durability and duration of the product: how many cycles, runs, miles, hours, etc. it should perform before maintenance interventions are required to ensure performance (e.g. repair, refurbishment); and, how many of these can be performed before the product will degrade beyond use, or reach EOL. Product EOL signifies that there are no other options for the product, but to be recycled or disposed into the environment. However, if any other option exists to keep the product, and/or its components, within the market – via VRPs – then the product has only reached EOU. It is important to note that EOU may occur without any product issue at all: The owner may simply no longer want or need the fully-functioning product due to more advanced features in newer products or degraded performance, even though it has not yet fulfilled its entire expected service life. The opportunity for VRPs lies in determining and understanding how a seeming product *EOL* may actually only be product *EOU*. Once a product or component has reached EOU, it may be directed into EOL options of recycling or disposal – or, where infrastructure exists, it can be recovered via reverse-logistics systems, or directed into a secondary market that provides spare parts and/or 'cores' for VRPs instead.

As clarified by the International Resource Panel [29], VRPs can be organized into two categories that differentiate the resulting utility (value-retention) that is enabled by the VRP (Fig. 1): Equivalent Full Service Life processes refer to processes that enable the fulfillment of a *complete new life* (an equivalent expected service life in years) for every service life of the product, and includes manufacturing (OEM new), remanufacturing, and refurbishment. These processes take place within factory settings and industrial operations. In contrast, Partial Service Life Processes refer to processes that enable the *completion of, and/or slight extension of*, the service life, through direct reuse, repair, and in some cases, refurbishment. These processes take place within maintenance or intermediate maintenance operations. Please note that the length of the lines in Fig. 1 are only intended to reflect relative service life duration enabled by different VRPs, and do not suggest quantified actual service life duration. The dotted lines reflected *potential* service life extensions enabled by each VRP, as compared to the service life *guarantees* indicated by solid lines.

Compared to a 'new' product manufactured for its first use cycle (hereafter referred to as a service life cycle), VRPs are undertaken with subsequent service life cycles in mind. Assuming the completion of a product's first service life cycle (culminating at EOU, per Fig. 1), the objective of VRPs is the continuation of the product's service life through extension (e.g., VRPs extend the product's lifespan, such as repair), or complete regeneration (e.g., VRPs enable additional service lives for the product, such as remanufacturing), and this can be accomplished in a range of ways. From the direct reuse of a product that has not yet completed its first service life cycle (e.g. direct reuse), through to rigorous industrial processes that fully-restore every aspect of the product to meet or even exceed the original product specifications, thus enabling a complete *new* additional service life (e.g. remanufacturing) [29] (Refer to SI file, Sect. 1, for detailed VRP definitions).

Unfortunately, without clear understanding and quantification of VRP impact differentials, two challenges are presented. First, this lack of clarity and data regarding how VRPs differ, and the associated economic and environmental impacts of VRPs, make it difficult for industry decision-makers and policy-makers to optimally and appropriately incorporate VRPs into their CE strategy, operations, policy, and programming [45, 58, 59]. For example, despite the fact that remanufacturing has been studied extensively [40, 53], and continues to be a central aspect of advanced engineering and digital transformation research [22, 31, 39, 47], VRPs (including remanufacturing) are often lumped together under generic 'reuse' strategies within sustainable materials management hierarchies programming [11, 43, 60]. Interest in unpacking this generalization has been increasing, i.e., recent work by Subramoniam et al. [55] explores how the digitization of a product's different life cycle stages (e.g., development, introduction, growth, maturity, and decline [48],



*Through VRPs, a single product life cycle can consist of multiple service life cycles

Fig. 1 Descriptive economic system model utilized for top-down analysis

may enable improved effectiveness and efficiency of the reverse supply chain via strategic life cycle based interventions.

A second challenge is that in the context of CE, VRPs are proposed as alternatives (when appropriate) to conventional manufacturing processes, and thus, there is need for methodologies that allow for comparative environmental and economic impact analyses that can demonstrate the relative differences between VRPs and incumbent conventional ‘new’ manufacturing. Such a methodology requires the incorporation of a value-retention lens to enable the quantification of environmental and economic impacts that are *incurred or created* throughout a product’s life-cycle [9, 12, 24], as well as the impacts that are *not* incurred, and value that is *not* lost, degraded, or depreciated (potentially, value that is even captured and re-created through VRPs) [29]. As an example of this challenge, the commonly referenced framework by Gutowski et al. [24] proposes a categorization of product characteristics and conditions that are needed to optimize the decision to engage in VRPs based on use-phase energy requirement and energy efficiency. This work explored potential rebound effects that could be incurred by keeping older technology (e.g., lower energy efficiency, and higher energy demand) in the market for longer, but did not take into account the additional service life cycles that would be enabled by performing the VRP for the product, nor the location in which the VRP was being conducted [24].

We address these challenges, developing a novel, comprehensive methodology and model to differentiate VRPs and quantify their relative environmental impacts and resource requirements across select metrics (Methodology section). We demonstrate the model using case studies of ten products, representing two different industries (vehicle parts and industrial digital printers), and two different economies (U.S. and China) (Results section). From the model and analysis, we extend the framework introduced by Gutowski et al. [24] to consider additional factors relevant to VRPs in a CE, including the residual value of component parts [29, 30, 44, 46], and the material composition of the product, which can affect cumulative life cycle energy requirements across multiple product service lives [5, 36]. Alongside other proposed frameworks designed to support decision-making within CE transitions, such as the Circular Economy Product and Business Model Strategy Framework [7], the Framework for Evaluating Design for Reuse Options [12], and the Sustainable Consumption Business Model Framework [56], we present this novel methodology and the resulting framework (Extended Framework to Assess the Appropriateness of Undertaking VRPs) in response to the rising interest in, and adoption of CE practices (Discussion section). Fundamentally, we present this work as a contribution to support decision-making as to whether or not VRPs should be undertaken, applying environmental and economic impact considerations.

Methodology

When considering CE and VRPs, it is important to appropriately account for what causes a product/component to reach (EOU) and become eligible for another service life through VRPs so that accurate material, energy and emissions impacts can be assessed. In addition, it is important to understand the implications of scaling VRP activities within an economy, especially with regard potential effects upon traditional linear production. To enable a comparative analysis across VRPs, our selection of case study products was grounded on several requirements. The case study product must: 1) be commonly-known to have multiple (i.e., more than one) VRPs undertaken as product life-extension practices to allow for such comparison; 2) be represented in sufficient scale as part of the sample economies to enable meaningful modeling approaches; and 3) be available for empirical study, through close collaboration with interested industry partners. In review with industry experts, seven case study products were selected: industrial digital printers (Production printer, printing press #1, and printing press #2); and vehicle parts (traditional engine, lightweight engine, alternator, and starter motor). Primary and secondary data were collected from more than 15 multi-national industry member companies, across three sectors and four countries, and the methods and results were validated by more than 60 independent experts, who confirmed the individual data points and assumptions for product- and process-level data (Refer to SI file, Tables SI-2 through SI-4) via iterative reviews and comments with the research team [29], p. 1).

A hybrid top-down and bottom-up modeling approach connected data collection across three dimensions of CE: 1) Product-level; 2) Process-level; and 3) Economy-level. Additional details regarding the modeling approach are included in the SI file, Sect. 2. An attributional approach that identified and accounted for specific states and impacts of the relevant processes at the product- and economy-levels, was incorporated. The key primary comparative metrics that were ultimately modeled and analyzed for each case study product and VRP in this study include:

- Primary material offset (kg) (product-level);
- Embodied material energy (MJ) (product-level);
- Embodied material emissions (kg CO_2-eq.) (product-level);
- Process energy (MJ) (process-level);
- Process emissions (kg CO_2-eq.) (process-level);
- Cost to user/buyer ($ USD) (product-level);
- Employment opportunity (Full-time equivalent worker, or FTE).

While emissions impacts (kg CO_2-eq.) reflect direct environmental impacts, additional measures of material use, energy requirement, and economic indicators of cost and labor requirement are included to more broadly account for indirect environmental, social, and economic implications. Complete nomenclature for the various models and aggregated impact formulas is presented in the SI file, Table SI-1.

Data collection

With support from USA-based industry collaborators, product- and process-level data collection was completed empirically. Comprehensive material-level data was collected for each case study product, ensuring that 80% (minimum) of the product's Bill of Materials (BOM), by weight, were accounted for. *Component-level* data points included material type (assuming recycled-content) and material weight (by type). Using the material weights provided by the BOM for each component, material-based global averages for embodied energy (MJ/kg material) and emissions (kg CO2-eq./kg material) were calculated based upon the Circular Ecology Inventory of Carbon and Energy [25] (Refer to SI file, Table SI-2). *Product-level* data collection focused on key design attributes: average service life length (e.g. time in years to EOU); designed useful-life of the product-platform (e.g. time to EOL); primary characteristics of components (e.g. weight, material, common reasons that products may fail to work or perform); types of VRPs commonly conducted for the product; and the potential reusability of each component via VRPs (Refer to SI file, Table SI-2).

Process-level data collection was completed with USA-based industry collaborators, who facilitated on-site visits during which VRPs for case study products were observed, along with management team interviews regarding each process's cost and labor requirements. Process-specific data, including per-unit at-the-meter process energy (MJ/unit) and production waste (kg/unit), were collected at the facility-level (Refer to SI file, Table SI-3 and Table SI-4). In cases where process-level data could not be collected directly, secondary data from recent life cycle assessment (LCA) and engineering literature were utilized.

Product-level modeling

A key advantage of circulating/recirculating products and components via VRPs is the reduction in required primary materials, and associated waste, energy, and emissions impacts of extraction and processing activities. To best reflect the potential multiple service lives enabled via VRPs, a component-level approach was utilized. Equations 1, 2 and 3 were used to model the product- and process-level requirements and impacts for each VRP, and modify the approach presented by Yang et al. [62], which focused on the evaluation of material selection for purposes of remanufacturing.

Primary materials requirement

With some inputs sourced through a circular system, the requirement for primary material inputs is offset, along with associated waste, energy, and emissions impacts of extraction and processing activities. To best reflect primary material reuse (vs. requirement) through VRPs, and to capture the potential multiple service lives enabled via VRPs, a component-level approach was utilized:

$$M^i_{j,m} = \sum_s \sum_c \frac{\alpha_{j,m,c}\gamma_{j,m,c,s}\delta_{j,m,c,s,h}}{\eta_{c,s}} \forall i,j \tag{1}$$

where M is the total material requirement of process i (OEM new, direct reuse, repair, refurbishment, remanufacturing) for each material type, assuming an average mix of primary and secondary material content; α is the material weight, Υ is the material intensity (e.g. material reuse, accounting for processing and/or machining scrap) or waste factor, δ is the end-of-life burden multiplier (waste = 100%, 0 < Recycling Efficiency < 100%) and η represents the number of expected service life cycles. Subscripts j, m, c, s, and h represent the product, material type, component, service life cycle, and end-of-life route, respectively. Complete nomenclature for model variables is presented in the SI file, Table SI-1.

Embodied energy and embodied emissions implicationsThe extension of material requirements to reflect associated embodied energy per product (Γ) and embodied emissions per product (ρ) is calculated linearly as an extension of Eq. 1. With material-based embodied energy requirements reflected via τ (MJ/kg) and associated embodied emissions reflected via ω (kgCO$_2$-eq./kg), the environmental impacts associated with the material requirements of different processes are described in Eqs. 2 and 3.

$$\Gamma^i_j = \sum_m (M^i_{j,m} \times \tau^i_m) \forall i,j \tag{2}$$

$$\rho^i_j = \sum_m (M^i_{j,m} \times \omega^i_m) \forall i,j \tag{3}$$

Values obtained to support the calculation of Eq. 2 and Eq. 3 are taken from the Inventory of Carbon and Energy (ICE) database, from Circular Ecology [25] (Refer to SI file, Table SI-2). Please refer to the SI file, Sect. 2.1 for a description of the model via Eq. 1, 2, and 3, and Table SI-1 for model nomenclature.

Process-level modeling

The process-level implications of case study product features and characteristics were analyzed using a stochastic MATLAB model in which a Monte Carlo simulation is performed to obtain estimated primary material requirement for the average component, by material type, during a single VRP service-life cycle (Refer to SI file, Figure SI-1). To determine whether the component would be reused for additional service lives, the program imported component-level reusability and material data to simulate multiple service-lives against randomly-generated probabilities.

Component-reusability potential

Three reusability mechanisms were used in the product-level model and analysis. These mechanisms reflected the common cause of failures at the component-level, and enabled the modeling of likely reuse/replacement potential of each component, based on weight and material type, for each VRP. One of the three primary reusability mechanisms outlined below was assigned to each component within the BOM within the product-level model, and reusability mechanisms were assumed to be the same across subsequent product service lives (if any):

- **Fatigue**: Applied to components that typically fail over time and have a durability curve applied to their useful life. The product-level model accounts for these components using Weibull distribution.
- **Hazard:** Applied to components that typically fail due to misuse by the user or shipping damages (e.g. damage during transport or from impact). The product-level model accounts for these components using a cumulative exponential distribution over multiple service life cycles.
- **Predetermined**: Applied to components that wear-out, i.e. through repeated use cycles, in a manner designed by the original equipment manufacturer (OEM). The product-level model accounts for these components using a step distribution over multiple service life cycles, during which the component will be used/reused until it reaches its predetermined EOL.

A construct of three variables was used to construct account for component reusability within the model: 1) A failure mechanism was assigned to each component (e.g., predetermined vs. fatigue vs. hazard); 2) A measure of the probability of salvage, a value between [0—1] in which complete destruction of the component was reflected as “0”, whereas no damage or change to the component was reflected as and “1”. This probability [0—1] was informed by the nature of the component and the failure mechanism that was assigned, as informed by consultation and confirmation with industry collaborators; and 3) The expected number of service life cycles (η) anticipated for each component, given industry best- and common practices. These reusability assumptions were reviewed and confirmed through interviews with industry members.

It is important to note that component failure may occur for different reasons across different service life cycles, i.e., failure due to fatigue in the first service life cycle, and failure due to hazard in the second. However, for the purposes of modeling, the most common reusability mechanism for each specific component was assumed to be the same across every modeled service life cycle.

Once the product BOM data was imported, the number of simulations, or representative *products*, ($n = 1000$) was defined. Each component (c) was run through multiple service-life cycles (η) until it ultimately ‘failed’ according to the reusability mechanism (fatigue, hazard, or predetermined). Component failure was determined for each component within the BOM through the comparison of a random distribution variable to the reusability mechanism distribution for each specific component and service-life. The model then returned to the next component and repeated the process. After each of the components were assessed, the program stored the results for the product, and moves on to the next simulation. Each product started out with the original material composition necessary to complete a single intended service-life (first, original service-life). After the initial service-life, the product could undergo any one of the VRPs. Each VRP had varying levels of failure/reusability embedded within the component analysis.

Process-level energy requirements

Process energy requirement (MJ/unit) is based upon the at-the-meter (gate-to-gate) production process-cycle energy requirement (MJ/unit), by product, empirically collected for USA production activities. Within the mathematical modeling presented in subsequent sections process energy represented as φ. Empirically collected observations and data reflect that the vast majority of energy used in the production processes for case study products is electric in nature. For the purposes of modeling, energy inputs were assumed to be the form of electricity, and, at-the-meter process energy values were then multiplied by the electricity infrastructure efficiency factor for each economy to determine an estimated total process energy requirement. This approach also informs the calculation of process-related emissions, which is presented in the SI file, Tables SI-3 and SI-4.

Process-level emissions impacts

Process emissions impact (kgCO_2-eq./unit) were calculated by multiplying process energy requirement (MJ/unit) by the economy-specific GWP 100a factor (kgCO_2-eq./MJ) for medium-voltage market group electricity. Within the mathematical modeling presented in subsequent sections process emissions is represented as *б*. These data were derived from the Ecoinvent 3.3 database, which utilized the IPCC 2013 methodology and reflect the conservative estimate where variance and/or a range of data points were present. Economy-specific conditions, i.e., electricity infrastructure efficiency factors, and process emissions were accounted for.

The process-emphasis of our study led to the exclusion of impacts from forward- or reverse-logistics transportation. Use-phase impacts were also excluded on the basis that the products and processes are commensurable: Processes were assessed relative to the exact same product, and thus our results do not reflect the impacts that could stem from a change in materials, an upgrade, and/or a more energy efficient version of the product, beyond the modeled product case studies.

Economy-level modeling

The product-unit basis of process-level impact and requirement measurements ensured that these impacts could be aggregated, based on domestic production and import volumes, to reflect the overarching impacts and requirements of OEM new and VRP production activities for studied products and economies. A simplified top-down system-model, developed using MATLAB, was used to simulate the dynamics of installed base (in-use stock) and flows of products within a CE via VRPs, for the USA and China, over the course of a seven-year period (Fig. 2).

Installed base, stocks

To reflect projected economic growth, market evolution, and compounding complexity (e.g. the implications of policy changes) in a realistic, but meaningful way, the base-case (status) quo scenario was simulated over a seven-year period. Initial market share, or production mix percentage (%), was estimated for each product by production process (OEM new and VRP) based on available data from each sample economy. Using estimated total size of the initial installed based ($IB_{t=0}^{j,k}$), a starting volume for each product (j) by production process (i) was determined for each sample economy (k). In each of the simulation periods ($t=7$), installed base was adjusted dynamically to account for products reaching the end of service life and becoming available for collection, and the products entering the economy as a result of new demand. A detailed description of the model and approach is included in SI Sect. 2.3, from which the fundamental circular economy system model (Eq. 4, or in the SI file, Eq.SI-7) is developed.

$$IB_t^{i,j,k} = \left(IB_{t-1}^{i,j,k} + D_{t-1}^{i,j,k} - C_{t-1}^{i,j,k}\right)\forall i,j,k \tag{4}$$

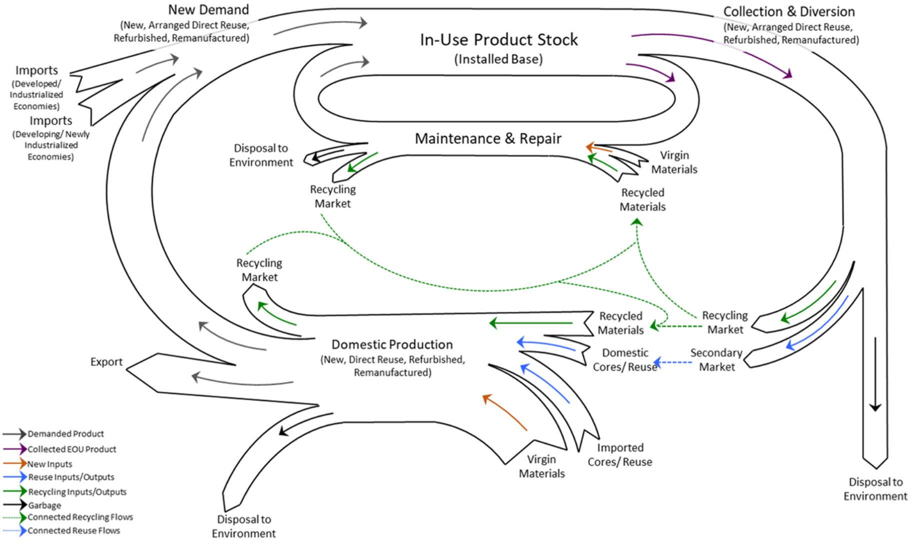


Fig. 2 Summary of value-retention processes differentiation within the context of end-of-use (EOU) and end-of-life (EOL) [29] (Adapted from

Accordingly, the dynamically modeled installed base of each case study product ($IB_t^{i,j,k}$) is a function of the installed base of the previous period ($IB_{t-1}^{i,j,k}$), demand from the previous period ($D_{t-1}^{i,j,k}$), and the products that became available for collection in the previous period as a result of reaching expected end of service life, or experiencing some form of product failure ($C_{t-1}^{i,j,k}$). More detailed and comprehensive equations provide insight into the development and dynamics of the economy-level model (Refer to the SI file, Eq.SI-4a through Eq.SI-18).

Economy-level modeling incorporated considerations and indices regarding comparative electricity infrastructure efficiency and global warming potential (GWP) derived from the Ecoinvent 3.3 database for USA and China. Production waste estimates, tied to production process efficiency, and labor productivity were also incorporated into the model. A lack of micro-level data necessary for fully modeling and forecasting adoption rates for VRPs in the studied economies prevented more comprehensive inclusion of user preferences and behaviors.

Results

Product-level environmental impacts

The impacts of VRPs can differ by product, material, and market. Based on the averages for the case study products, select relative environmental impact reduction potentials for each process, per additional service life year that is enabled, are shown in Fig. 3 (industrial digital printers) and Fig. 4 (vehicle parts, assuming cast iron engine block). Material-level data and analysis for industrial digital printer sector case study products can be found in the SI file, Tables SI-3 and SI-4. Material-level data and analysis for case study products representing the vehicle parts sector can be found in the SI file, Tables SI-5 and SI-6.

Figures 3 and 4 demonstrate that even when accounting for the differing service life extension enabled by VRPs, the environmental impacts of primary material use and

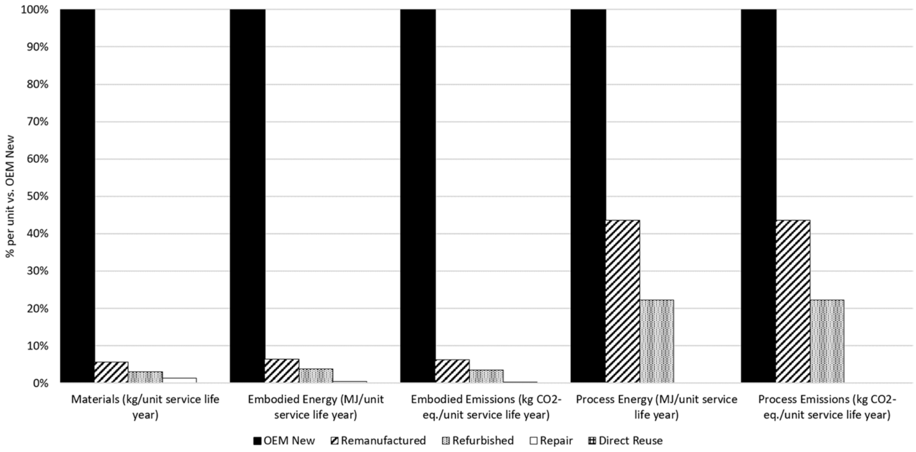


Fig. 3 Impact reduction potential for USA via value-retention processes for industrial digital printers, compared per expected service life (in years) per unit produced via VRPs (unit service life year). Supporting data is presented in the SI file, Table SI-5

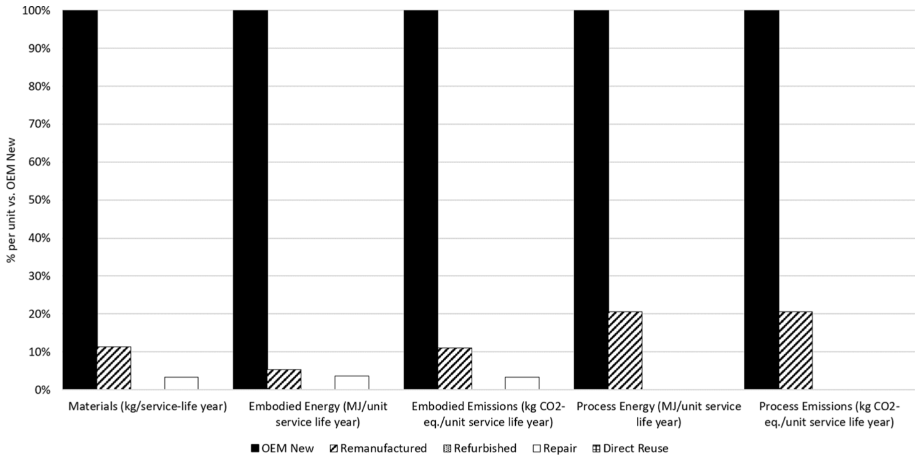


Fig. 4 Impact reduction potential for USA via value-retention processes for vehicle parts production with 100% cast iron engines, compared per expected service life (in years) per unit produced via VRPs (unit service life year). Supporting data is presented in the SI file, Table SI-6

associated embodied energy and emissions are significantly lower relative to the new product (~ 95% reduction for industrial digital printers; ~ 90% for vehicle parts). This is largely driven by the fact that VRPs enable the avoidance of upstream material extraction and primary processing activities that are required to produce new (replacement) products. Further, because VRPs take advantage of components and parts already in their functional form, the activities and inputs required to return the product to a new service life, requires 50%—75% less process energy and generates a similar reduction in process emissions (vs. new).

An example of current design trends that have implications for VRPs is the light weighting of vehicles. Light weighting has been pursued as a design priority in the automotive industry in the past two decades, via redesign of parts and substitution of materials in order to achieve enhanced fuel efficiency. Given the potential material efficiency implications of redesign and material substitution, a brief exploration was conducted into the potential difference in *material-level* environmental impacts associated with VRPs for a lightweight vehicle engine that utilizes a cylinder block of cast aluminum. Extensive research on production-level impacts and fuel-efficiency related advantages of the cast aluminum engine cylinder block are further documented in life-cycle analysis literature [33, 37]. The majority of life-cycle impacts associated with a cast aluminum engine block (vs. cast iron) occur during the extraction and primary processing phases, and the benefits (e.g. fuel efficiency and emissions reductions) experienced during the use-phase of the engine block. However, from a CE perspective the use of VRPs to ensure multiple service lives of light-weighted vehicle parts still leads clearly to a significant reduction in material-use, embodied material energy, and embodied material emissions per additional service life year enabled by the VRP. The detailed data and analysis supporting the comparative assessment of VRPs for the lightweight aluminum cylinder block engine product are presented in the SI file, Tables SI-9 and SI-10. It is important to note, in accordance with the literature, light weighting achieved via material substitution may also decrease suitability for remanufacturing, particularly in cases where the substituted material (e.g., aluminum) is more fragile [26, 62].

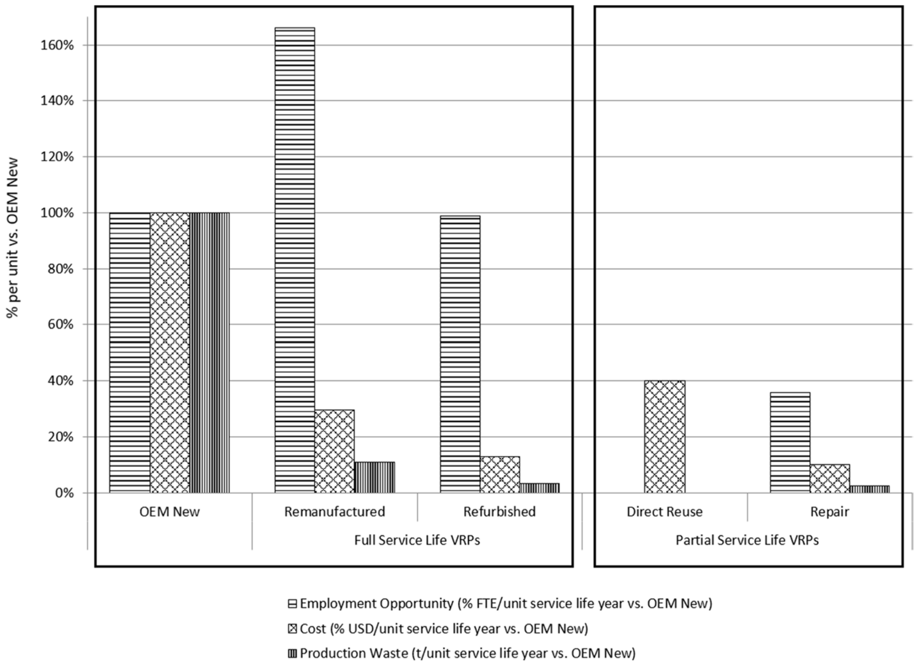


Fig. 5 Example unit-level economic opportunities created via VRPs for Industrial Digital Printing Press #2, compared per expected service life (in years) per unit produced via VRPs (unit service life year). Supporting data is presented in the SI file, Table SI-7

Product-level economic impacts

With regard to the select economic metrics included in this study, Fig. 5 (industrial digital printers) and Fig. 6 (vehicle parts, assuming a cast iron engine block) depict the relative employment opportunity, production waste generation, and buyer/user cost metrics per additional service life year that is enabled.

The employment opportunity (labor requirement) for each case study product was determined using the number of full-time labor hours required, on average, to complete each production process. Measured in FTE requirement per unit, this data was obtained from our industry collaborators. The steps and activities undertaken to complete a VRP are substantially different from those required for manufacturing. For example, the remanufacturing process requires additional time and skill relative to traditional manufacturing; this is due to the need for additional process steps (reverse-logistics, sorting, quality assessment, disassembly, cleaning, testing, and upgrading) that do not occur within the traditional manufacturing process. In addition, these processes are often more complex than traditional assembly activities, requiring specialized training, equipment, and worker experience. As such, we see a relative increase in the employment opportunity from remanufacturing, and an equal opportunity from the comprehensive refurbishment of industrial digital printers (Fig. 5). Similar conditions exist for the remanufacturing of vehicle parts (Fig. 6). It is also important to note that, of the partial service life VRPs, direct reuse activities create little, to no, direct employment opportunity, whereas repair enables ~ 15% to ~ 40% of the employment opportunity that manufacturing creates for these case study products. Please note that

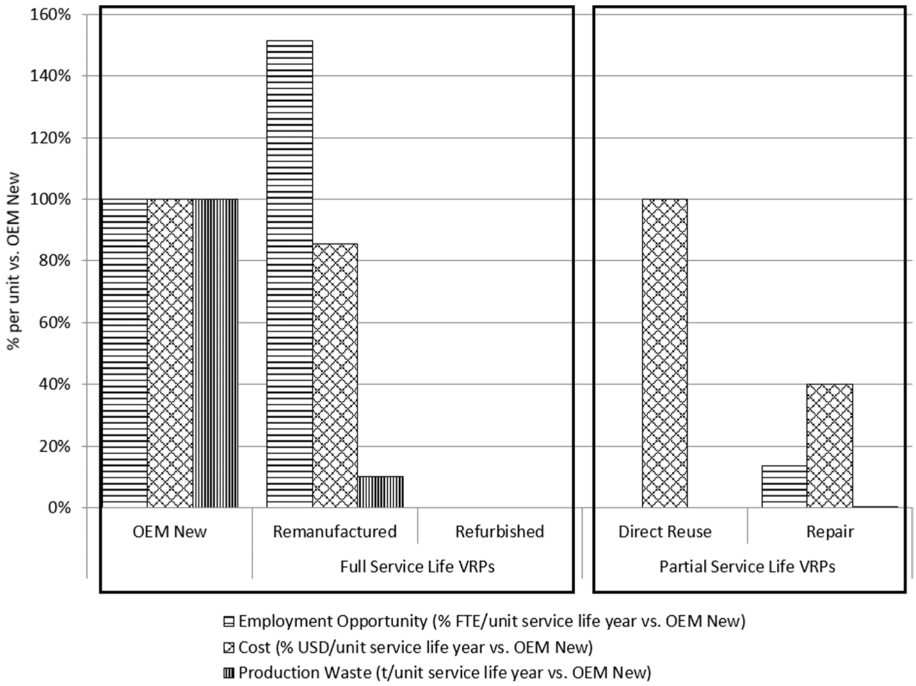


Fig. 6 Example unit-level economic opportunities created via VRPs for the Traditional Vehicle Engine, compared per expected service life (in years) per unit produced via VRPs (unit service life year). Supporting data is presented in the SI file, Table SI-8

the labor requirement for manning direct reuse centers and/or facilitating reverse-logistics for direct reuse purposes is not included.

The cost reductions experienced by the VRP producers are typically extended to the buyer/user to in the form of price discounts intended to motivate a purchase decision (Fig. 5). However, as shown in Fig. 6, the cost benefit to the buyer/user is relative to the number of additional service life years that the VRP enables. In the case of remanufactured vehicle parts, the average cost discount per additional service life year is ~ 15% (over a service life of 12 years); In the case of repair and direct reuse of vehicle parts (partial service life VRPs), the value to the user created as a result of the significant price discount (vs. new) is almost entirely offset by the significant reduction in additional service life of the repaired or reused part (6 years) that is enabled. Finally, Figs. 5 and 6 describe the relative production waste generation level, which is significantly lower for VRPs than manufacturing (~ 90% min. reduction for both industrial digital printers and vehicle parts). In the context of industrial activities, the reduction in production waste directly translates into some degree of operating cost reductions, in addition to the general, indirect environmental benefits of reduced waste stream volumes.

Economy-level contribution of value-retention processes

The economy-level model analysis was conducted to gain insight regarding how product- and process-level impacts can aggregate in the broader context of complex

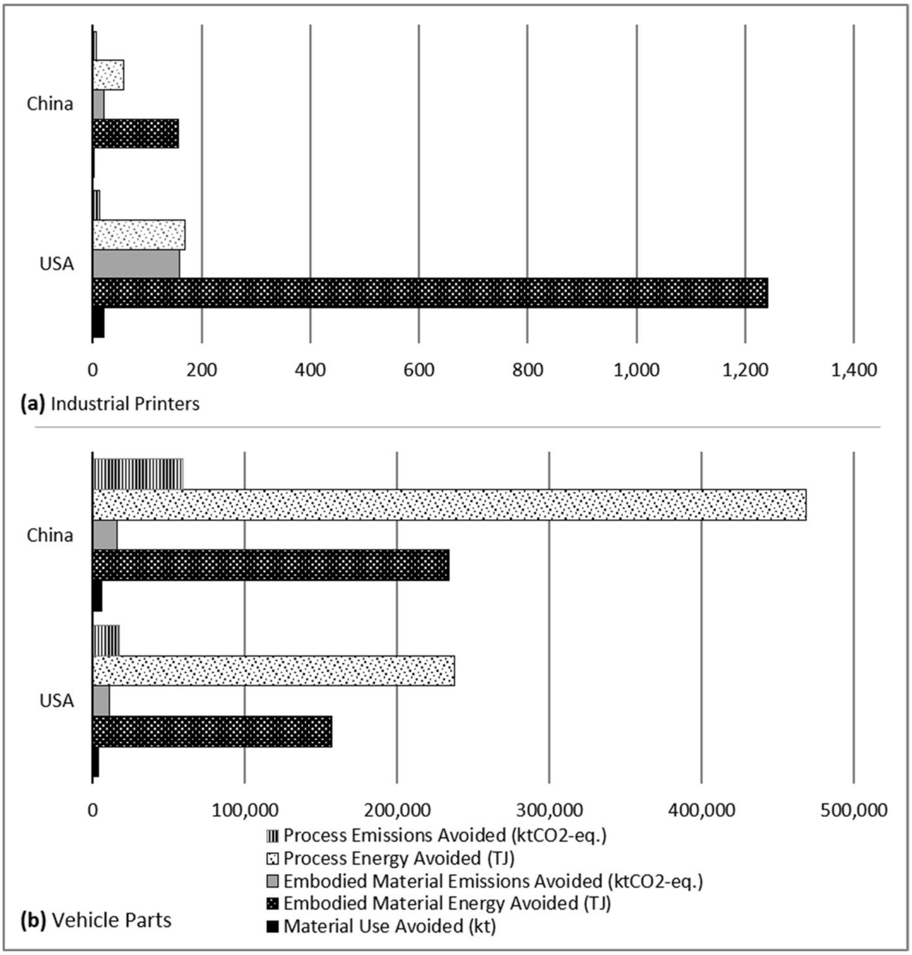


Fig. 7 Estimated Aggregate Impacts Avoided via VRPs for (**a**) Case Study Ind. Digital Printers, USA and China; and (**b**) Case Study Vehicle Parts, USA and China. Supporting data is presented in the SI file, Tables SI-11 and SI-12

consumption-production systems. The extensive model equations, and A detailed description of the model, including extensive equations, is presented in the SI file, Sect. 2.3. To demonstrate the potential benefits of VRPs in a CE, economy-level model insights (Fig. 7) are presented in terms of the environmental impacts that are *avoided* when, instead of purchasing or replacing a product with a new version, the buyer/user elects for a VRP version of the products. Aggregated over a simulated model period of seven-years, the model accounts for sector- and economy-specific growth rates, regulatory conditions, technological conditions, and market conditions.

The insights from Fig. 7 confirm the complexity of CE approaches, and the need for customized VRP strategies that are appropriate for diverse products, sectors, and economies. Of particular interest is the implication of the 'consumption-production mix' (the % mixture of new vs. VRP versions of the case study products that constitute the installed base) upon resulting environmental impacts of VRP adoption. For example, among other barriers to VRPs, China restricts the import of VRP products, and projected levels of domestic VRP production for industrial digital printers are quite low relative to the USA (Fig. 7, panel (a); also, refer to the SI file, Table SI-11). Hence, the *avoided* environmental impacts associated with VRPs (vs. new) for industrial digital printers are relatively lower for China (Fig. 7, panel (a)). In contrast, the USA has higher VRP production levels for industrial digital printers, and regulatory conditions allow for the import of VRP; thus, the potential environmental impact avoidance enabled via scaled VRP adoption is substantially greater (Fig. 7, panel (a)). Within the industrial digital printers' sector of both economies, the greatest environmental 'benefit' from scaled adoption of VRPs is the avoidance of embodied material energy enabled by the reduction in primary material use.

As shown in Fig. 7, panel (b), the marginal impact avoidance of VRPs for vehicle parts is relatively smaller than for industrial digital printers; however, the scale of the vehicle parts sectors of both economies enables significantly greater environmental impact avoidance potential through the adoption of VRPs. China's more significant share of low-impact (partial service life) VRPs, and efforts to expand vehicle parts remanufacturing, leads to significantly greater environmental impact avoidance, despite its import restriction against VRP products and the relatively higher GWP of China's energy grid mix. For the vehicle parts sector of both economies, the greatest environmental 'benefit' from scaled adoption of VRPs is in the avoidance of process energy consumption enabled via VRP product alternatives to newly manufactured replacement vehicle parts.

Discussion

Differentiated impacts and requirements of VRPs

There are significant product-level *environmental benefits* generated every time a case study product, its life extended via VRPs, is purchased instead of a newly manufactured version: Approximately 90% reduction in primary material used and associated embodied material impacts and a 55% reduction in process-related solid waste, energy, and emissions impacts for each year of additional service life enabled by a VRP (Figs. 3 and 5). In the case of scarce or critical materials, the material retention rate of 90% confirms that VRPs present an important strategy for mitigating material issues within an organization's value chain. Further, our assessment of the light-weight engine block indicates that, from a material-use perspective, VRPs present a clear advantage relative to manufacturing, requiring ~ 95% fewer primary material inputs, regardless of material type (cast aluminum vs. cast iron). Note that this analysis does not intend to compare across material-types, rather to suggest that the material type should not discount the undertaking of VRPs as part of a CE strategy at the product-level.

As shown in Fig. 6, full and almost-full service life VRPs generate differential *economic impacts*: alongside the significantly greater opportunities for employment presented by full service life VRPs (e.g., remanufacturing), there are also meaningful cost reductions enabled. The cost reductions experienced by the VRP producers are typically extended to the buyer/user to in the form of price discounts intended to motivate a purchase decision [1, 4, 14]. However, as shown in Fig. 6, the cost benefit to the buyer/user is relative to the number of additional service life years that the VRP enables: In the case of remanufactured vehicle parts, the average cost discount per additional service life year is ~ 15% (over a service life of 12 years),In the case of repair and direct reuse of vehicle parts (partial service life VRPs), the value to the user created as a result of the significant price discount (vs. new) is almost entirely offset by the significant reduction in additional service life of the repaired or reused part (6 years) that is enabled. Effectively, partial service life VRPs have lower impacts, but also enable lesser service life and functionality. This reflects a trade-off that must be considered by both users and VRP-producers. Finally, Fig. 6 describes the relative production waste generation level, which is significantly lower for VRPs than manufacturing (~90% min. reduction for both industrial digital printers and vehicle parts). In the context of industrial activities, the reduction in production waste directly translates into some degree of operating cost reductions.

The increased labor requirement (employment opportunity) for remanufacturing is largely driven by the additional process steps and testing that are required by these more intensive full service life processes (Fig. 1). While greater labor requirements should lead to higher operating costs for full service life VRP-producers, the increase in labor costs is typically more than offset by the significantly lower costs for primary materials and process-related energy (Fig. 5), as well as higher value-retention via the enabling of a full new service life; this enables the remanufacturer to charge a relatively higher price (vs. reuse or repair), and maintain acceptable profit margin [29, 45, 58, 59].

Systems-thinking across VRP scales: product-level, process-level, and economy level

A major implication of the economy-level findings is the insight that industry- and economy-specific approaches are needed, and that a "one-size-fits-all" assumption regarding the adoption of VRPs will be less effective and may lead to unintended consequences. Per Fig. 7, when these impacts are aggregated at the economy-level, and reflective of the actual production-mix and conditions (e.g. energy-grid mix) of the economy, we see several insights worth noting: First, the ability of VRPs to contribute to enhanced material efficiency and emissions reduction targets is dependent upon how extensively they are adopted into an economy's production activities. The larger the share of VRPs within the production-mix, the greater the impact reduction and value-retention opportunity, as demonstrated by the avoided impacts enabled via VRPs within the industrial digital printers' sector in the USA (Fig. 7, panel (a)), and within the vehicle parts sector in China (Fig. 7, panel (b)). As long as a paradigm of economic *growth* is pursued (as is the current state is most major economies), the increased integration of appropriate VRPs into the production-mix of large-scale industry sectors can yield meaningful opportunities to avoid environmental production impacts, when VRPs offset a newly-manufactured version. Second, economy-level conditions are an important consideration for the appropriate undertaking of VRPs. For example, in economies that have relatively higher global warming potential (GWP) as a result of the energy-grid mix, the decision to undertake higher energy-intensive VRPs (e.g. remanufacturing) will result in lesser environmental benefits being achieved than if the VRP was undertaken in an economy for which the energy-grid mix yields a lower GWP. In such economies, increased emphasis and adoption of partial service life VRPs (e.g. repair and direct reuse) may provide a viable option for achieving climate change mitigation goals, while also enhancing economic access opportunities for users through these lower-cost options.

In general, while use-phase energy requirements and fuel efficiency impacts remain a critical consideration (albeit, not included in this study), the significant reduction in material requirement, and associated embodied energy and emissions, demonstrated for every VRP and case study product, have meaningful implications from both material-security, climate change mitigation, and cost perspectives, at the economy-level. The conditions of individual firms and economies will differ, as will their objectives for economic and environmental performance. Thus, policy-makers and industry decision-makers must consider each VRP process, relative to the others, as one element within a broader strategic plan for CE.

Across each VRP there are clear impact reduction and value-retention opportunities. The environmental impact reduction opportunities enabled by the more intensive full service life VRPs of remanufacturing is typically less than those of direct reuse and repair, however these full service life VRPs tend to enable greater value-retention within the system, overall. The clear implication of this finding is that, while it may be easier to prioritize partial service life VRPs (e.g., repair and direct reuse) low-impact CE strategies, these offer far less value-retention and value-creation opportunity when compared to full service life VRPs such as remanufacturing and refurbishment. The marginal impact reduction potential of VRPs must also be considered within their economic context: The ability of VRPs to contribute to enhanced material efficiency and emissions reduction targets is dependent upon their adoption rate within an economy's production activities. The more significant the share of VRPs within the production mix, the greater the impact reduction and value-retention opportunity, as demonstrated with industrial digital printers in the USA (Fig. 7, panel (a)), and with vehicle parts in China (Fig. 7, panel (b)).

Extended framework for assessing the appropriateness of VRPs

It is clear that there can be no single strategy for CE, and our findings regarding differential impacts of VRPs contribute to a growing understanding of the appropriate use of VRPs within CE. In this section, the underlying data and assumptions for Extended Framework to Assess the Appropriateness of Undertaking VRPs is presented. Drawing from this research, four different example products are used to explain the rationale behind the framework's structure (Fig. 8). These examples reflect product's having relatively more complex subsystems, such as Example Product A (e.g. medical imaging equipment, Fig. 8, panel (a), Example Product C (e.g. industrial digital printer, Fig. 8, panel (c), and Example Product D (e.g. cellular phone, Fig. 8, panel (d); as well as products having a relatively simpler subsystem, such as Example Product B (e.g. office furniture, Fig. 8, panel (b). Each example product reflects a general category of product type that may qualify for VRPs, and we use these examples to demonstrate that product design and sub-system complexity, alone, do not necessarily determine which VRP is appropriate, or whether VRPs are appropriate at all.

We build upon the work of Gutowski et al. [24], who proposed a categorization of product characteristics and conditions that are needed to optimize the decision to remanufacture, emphasizing use-phase energy requirement and energy efficiency. We extend this insight and demonstrate an extended framework for assessing the appropriateness of VRPs that integrates our product- and process-level findings, including the interaction between the product and its sub-systems, with use-phase energy use considerations [24]. While Gutowski et al. [24] focus on remanufacturing specifically, the proposed extended framework reflects full-service life VRPs (e.g., refurbishment and remanufacturing), and can also be adapted for partial service life VRPs (e.g., repair and reuse) where appropriate.

Given the range of product- and process-level characteristics and conditions that can exist, the following framework categories are proposed:

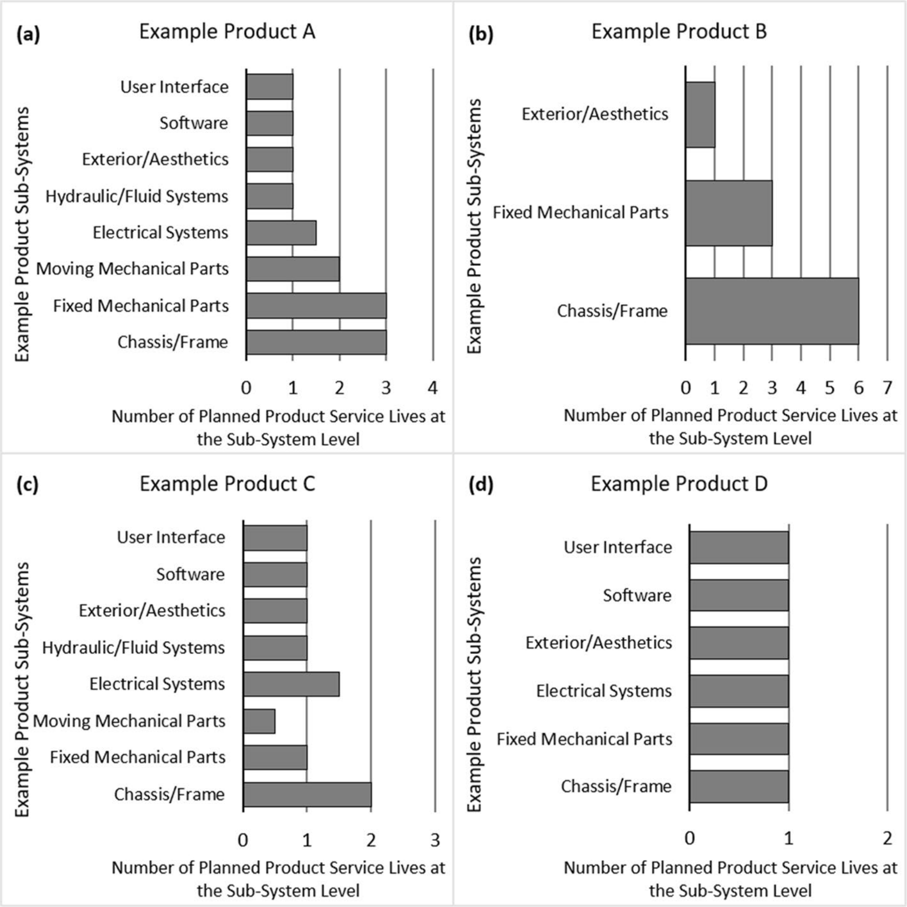


Fig. 8 Estimated Planned Service Lives of Product Sub-Systems for Example Products (**A**, **B**, **C**, and **D**) [29] (Adapted from

- *Group 1 –VRP-Appropriate (Example Products A and B):* Refers to products which, for the relevant time-period being considered, have not generally undergone design modifications that significantly affect the product's use-phase energy requirement, or that significantly affect the material composition of the product. Design changes in recent versions of the product have not resulted in improved use-phase energy efficiency, and/or have resulted in the replacement of lower energy-intensive material/components with higher energy-intensive materials/components. In addition, the use-phase of the product has not overly degraded or diminished the functionality of its primary components. There must be sufficient value retained within the functional form of the product that the additional investment into the VRP does not negate the potential for profit.
- *Group 2—Complex, Potentially VRP-Appropriate (Example Product C):* In many cases, modifications to product or component design may result in a complex outcome of associated life-cycle energy requirements. For example, a design enhancement that increases the share of higher energy-intensive materials/components may also be accompanied by a use-phase energy efficiency improvement. In these cases, a more

comprehensive assessment of the retained value of the product, as well as the costs and benefits of engaging in VRPs are needed before an informed business decision can be made. Examples may include light-weight design strategies that leverage advanced polymers and/or aluminum, as well as energy-system advances that introduce new chemicals into the product-system.

- *Group 3—Not VRP-Appropriate (Example Product D):* Refers to products which, for the relevant time-period being considered, have generally undergone design modifications that significantly affect the product's use-phase energy requirement, or that significantly affect the material composition of the product. Where design changes have resulted in improved use-phase energy efficiency, or have resulted in the replacement of lower energy-intensive material/components with higher energy-intensive materials/components, these products may not be generally appropriate for VRPs. Other conditions where VRPs may not be appropriate include if the use-phase of the product results in overly degraded and diminished functionality of primary components, requiring extensive investment to return them to as-new condition. In this case, the required investment likely exceeds the value of the product both in the sense of the retained value of the functional form, as well as the profit-potential of the product in the market.

All product examples selected for these case studies (industrial digital printers and vehicle parts) are considered to belong to Group 1 or Group 3. This approach was used to enable comparison across the range of VRPs, to demonstrate the product-level opportunities, as well as aggregate economy-level insights about VRPs within the context of CE.

These categories and insights are summarized and clarified via Table 1, the Extended Framework to Assess the Appropriateness of Undertaking VRPs. Using this framework, the specific conditions and characteristics of each component, product, and process may be more fully considered and evaluated for VRP appropriateness.

This framework clarifies that VRPs are not necessarily appropriate for all products, based on product characteristics and design, as well as characteristics of the VRP itself. The decision to engage in VRPs must remain with decision-makers and strategists, taking into consideration the costs and requirements unique to each respective product-system [1, 9, 17, 51, 52].

Conclusion

While a primary objective of this study was to evaluate the relative benefits and contributions of different VRPs to environmental and economic improvement, it is important to clarify that not all VRPs are appropriate for all products. Drawing from seven case study products from two industries, and incorporating economy-specific considerations to contrast economy- and geography-based implications of VRPs, we present a novel model that bridges material-, product-, process- and economy-level considerations with regard to VRPs as part of a CE. These quantified results provide a basis for clear differentiation of VRPs across key metrics that reflect select environmental impacts, material consumption, and economics. These case studies demonstrate that, across the metrics of interest, all VRPs are preferable to the newly manufactured version of the product. Our results show that there are clear trade-offs between VRPs that incur relatively lower environmental impact (e.g., reuse) and VRPs that result in relatively higher value-retention and economic costs (e.g., remanufacturing). Thus, the decision to engage in VRPs is one that must

Table 1 Extended Framework to Assess the Appropriateness of Undertaking VRPs

Characteristics & conditions to inform VRP decision-making (Product-, process-, & design-levels) *Using the descriptive characteristics and conditions below, assess whether VRPs are appropriate for the product/component*		Are VRPs appropriate?		
		VRP-Appropriate	(Potentially) VRP-Appropriate	Not VRP-Appropriate
Product-Level Characteristics & Conditions (*including examples)*	The product is *complex,* having a chassis/frame, and/or moving mechanical parts with the potential for multiple service lives (*e.g. medical imaging equipment, industrial generators*)	X	X	
	The product is *complex,* having functional modules and/or software components that can be relatively easily upgraded (*e.g. industrial digital printer, personal electronics*)	X	X	
	The product is *complex,* having components and sub-systems that do not have the same expected service life duration as the whole product (*e.g. parts for vehicles, equipment, aerospace, locomotive and heavy-industry applications*)	X	X	
	The product is *simple*, having a chassis/frame (or fundamental materials) that is durable enough to retain functionality via VRPs (*e.g. office furniture; tires*)	X	X	
	The use-phase/service life of the product does not overly-degrade the functionality of the primary components	X	X	
	The product chassis/frame and majority of other components have only a single (or < 1) expected service life cycle			X
Product-Level Design Considerations *(including examples)*	Newer versions of the product's design have been modified to significantly improve use-phase energy-efficiency.* (e.g., refrigerators, washer and dryers)		X	X
	Newer versions of the product's design have been modified to significantly increase share of high-energy materials composition (e.g., cast-steel vs. cast-aluminum vehicle engines)		X	X
	Newer versions of the product's chassis/frame design have been modified (e.g., older components not compatible with new versions)		X	X
	Newer versions of the product have increased product functionality and/or upgradeability (e.g. to be multi-functional) (e.g., older components not compatible with new versions)		X	X

Table 1 (continued)

Characteristics & conditions to inform VRP decision-making (Product-, process-, & design-levels) *Using the descriptive characteristics and conditions below, assess whether VRPs are appropriate for the product/component*		Are VRPs appropriate?		
		VRP-Appropriate	(Potentially) VRP-Appropriate	Not VRP-Appropriate
Process-Level Characteristics & Conditions	The material value that can be retained via VRPs exceeds the investment required to bring to as-new condition	X	X	
	The cost reduction (e.g. materials, energy requirement) per unit that can be achieved via VRPs exceeds any associated increase in labor requirement and cost	X	X	

* This consideration incorporated, per Gutowski et al. [24]

consider the interplay between directly-avoided impacts (e.g., reduced GHG emissions) versus secondary benefits that can be accrued (e.g., extended product life and value retention, which leads to reduced consumption). Further, it is possible that the inappropriate use of VRPs may lead to greater environmental impacts if specific characteristics and conditions of the product and product-system are not considered.

Using insights from this research, we present a framework to support the assessment of whether a VRP is appropriate for a particular product. Applying a broad systems-perspective, this framework takes into account specific factors relevant to VRPs in a CE, including the residual value of component parts and the material composition of the product, which can affect cumulative life cycle energy requirements across multiple product service lives. We show that both the nature and design of the product are primary factors in determining the extent to which VRPs should be engaged, as well as the potential for value-retention. It should be noted that, in cases where VRPs are not deemed appropriate, for economic or environmental reasons, responsible recycling or disposal should be pursued as alternative EOL options. Accordingly, producers have an important opportunity to incorporate essential VRP considerations into the product design phase.

From these findings, it is recommended that future research opportunities should focus on the development of additional case studies and data collection to build-out a more comprehensive data set for modeling and analysis, the completion of more comprehensive LCA's and carbon footprint assessments for VRPs that can be integrated into this model, and further testing and validation of the model across different product categories and economies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13243-022-00119-4.

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Data availability Data generated or analysed during this study are included in this published article [and its supplementary information files]. Additional data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability N/A.

Declarations

Conflict of interest/Competing interests The authors declare no conflict of interest or competing interests.

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