State of the Art on Performability across the Sustainable Value Chain

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Abstract: This paper reviews recent and relevant literature on the role of performability across the sustainable value chain by first introducing pertinent material in green supply chains, life cycle analyses, and EcoDesign methodologies. A new sustainable product life cycle framework is then proposed to represent key lifetime stages of sustainable systems. New research in performability is covered across the value chain of a green enterprise regarding the collection, remanufacturing, reuse, and end-of-life support service systems. Finally, future research challenges in this field are identified and discussed.

Keywords: Performability, dependability, sustainability, product life cycle, eco-design, life cycle analysis

1. Introduction

The concept of performability was originally introduced in the 1980 to assess the performance of reliable computer systems, but has since been expanded to comprise dependability and sustainability [1]. This extended definition embraces the elements of performability [1,2] by investigating “the entire life cycle of activities of a product or system along with the associated cost of environmental preservation at each stage while maximizing the product performance” [2]. An extensive coverage of performability has been done in [2]. The two-step process for designing high performability systems, products, or services is first to devise them for dependability, and then introducing the aspects of sustainability [3] in the design.

According to the Brundtland report, sustainable development is “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [4]. This encompasses many more aspects, including: the levels of pollutants that can be released; the identification of new depletable resources; the exploitation of renewable resources while keeping them renewable; necessary lifestyle changes; and the influence of governments, technology, and market forces to coerce change [5]. Crucially, wasteful production and resource extraction should not degrade the terrestrial system through the contamination of air, water, soil, ozone, or induce climate change.

The best method to hedge against extraction, production, and pollution is through conservation. Conservation decreases consumption, reduces the impact to the environment, and mitigates against scarcity. Cohen’s study [6] illustrates the present rate of consumption and rates of depletion of some key materials such as zinc, indium, hafnium, and terbium. These shortages are exacerbated by the unsustainable “current business practice of extracting raw materials from the earth, manufacturing them into products, and then disposing of the products into landfills or incinerators after a short period of use” [7]. This mentality of instant disposal creates massive problems in not only conservation, but also waste generation and management. A solution to these problems of
unsustainability is to design quality products that operate better, last longer, and are easier to maintain – or in other words, products that are more dependable and sustainable.

The dependability of a system is the ability to deliver a service that can justifiably be trusted by its users [8]. An alternate definition for dependability is the ability to avoid service failures that are more frequent, and more severe than is acceptable [9]. Dependability can be perceived in terms of quality, availability, reliability, maintainability, safety, and/or security. This review will focus on the different aspects of dependability for an organization engaging in sustainable operations. Primarily, the overall business strategy must be established to ensure profitability for this sustainable endeavour. Products should be designed in a sustainable manner, such as utilizing EcoDesign techniques, and exploiting reprocessed components. Sustainability should be integrated in the logistics system of the company, including the engagement of suppliers and purchasers to meet and exceed environmental expectations [10]. Finally, the green enterprise must develop support services for the consumers using their sustainable products. Also, different remanufacturing activities can be applied to recover value from the product after each consumption cycle.

2. Green Supply Chains

Achieving corporate sustainability requires the consideration of social, economic, and environmental factors, all having a direct impact on each other [11]. This endeavour must also demonstrate that it generates value for the enterprise. Porter defines value as the amount that buyers are willing to pay for what a firm provides [12]. In other words, a company is considered successful if the value it generates exceeds the costs involved in delivering its products/services. A study demonstrating that 47% of consumers are willing to pay 17-19% more for green products is one example of the value of green products amalgamating the three facets of society, economy, and the environment [13]. This leads to the idea of a value chain, which encompasses all the actions an enterprise participates in, from the cradle to the grave of a product.

In the traditional product life cycle (PLC), a product is only monitored from its cradle to its grave; however there is now a need to also monitor a product after its grave. “Today, modern environmental management prescribes sustainable manufacturing practices that focus on prevention of waste and responsible care of the earth’s natural resources...described as ‘cradle-to-cradle’ resource management” [14]. The integration of environmental aspects into the traditional supply chain management (SCM) activity is known as green supply chain management (GSCM). It covers areas such as supplier selection, material sourcing, manufacturing processes, delivery of finished goods to consumers, end-of-life (EoL) and end-of-use (EoU) collection, and value recovery operations [10]. In a green/closed-loop supply chain, the product is considered over multiple cycles, each going from its cradle to its grave. Srivastava develop a framework to classify GSCM into areas of green manufacturing and remanufacturing; reverse logistics and network design; and waste management [15]. “The most common GSCM practices involve organizations assessing the environmental performance of their suppliers, requiring suppliers to undertake measures that ensure environmental quality of their products, and evaluating the cost of waste in their operating systems” [16]. Closed-loop supply chain design and management models have flourished during the past decade (See [15,17,18] for extensive reviews).

The sustainable product life cycle (SPLC) framework shown in Figure 1 illustrates this cradle-to-cradle type resource management activity, particularly focusing on remanufacturing [19].
In Figure 1, the major categories are: EoU/EoL collection (in red), triage, test, & grade (in orange), value recovery (in gold), production (in blue), and use (in purple). These activities commence with the procurement of raw materials, which are then manufactured into a finished product through the steps of fabrication, part, module, and product assembly. The complete product is then sold to the consumer, where they enjoy its usage until its EoU or EoL. This part of the diagram is often characterized as the traditional cradle-to-grave PLC.

The closed-loop activities are initiated through the collection of EoU/EoL products. From here, the products are sent to be sorted, cleaned, tested, triaged, and graded. Based on their state, they undergo one of four value recovery procedures (repair, refurbishing, reconditioning, or recycling), or are disposed of [19,20]:

- When minimal effort is needed to restore the product to working order, the recovery option usually selected is repair. The repair operations are carried out on a limited number of failed components or modules, which are fixed or replaced by new or reconditioned spare parts.
- If the product requires more effort and a higher standard of quality, the recovery option selected is refurbishing, where the product is disassembled into modules, which are inspected, repaired, replaced, or upgraded.
- If even more effort is required, the reconditioning recovery option can be considered. In this option, products are disassembled, and good quality parts are recovered to be used in other options with or without further quality enhancement to bring them to a like-new condition. The remaining items are disposed of, or recycled.
- Finally, recycling is an energy intensive exercise reserved for products or parts that are unfit for the previous three recovery options. Recycling involves sorting, shredding, and melting to generate materials that can be used to fabricate individual parts, and conserve virgin materials. Within the WEEE framework, the recycling processes are defined as the three steps of: disassembly, upgrading, and refining [21,22].

The value recovery activities yield modules, parts, and/or materials that can be reused in the production process, exclusively or in conjunction with new parts before being sent back into the marketplace for consumers to use. Thus, the amalgamation of both value recovery and production processes as depicted in Figure 1 may be viewed as the definition...
of remanufacturing (in green). However, before remanufacturing can efficiently take place, the engineered products and systems must be designed, manufactured, and assembled with the forethought of value recovery and reprocessing.

3. Life Cycle Assessments

Every product, process, or service will exert and leave an environmental impact or footprint. Many approaches have been proposed to evaluate the sustainability of these activities and products. The most commonly used technique is the life cycle analysis/assessment (LCA) and its variants. The LCA is a tool used to gauge the environmental costs and benefits associated with a product’s entire life cycle from the procurement of materials (new or recycled) to their end (disposal or reuse). It examines the resources and materials used in each system as well as the emissions generated [23]. The purpose is to find the greenest product with a given process, so that the damage to the environment is minimized. An amendment to the LCA was proposed to classify environmental effects into independent dimensions such as: resource depletion, human toxicity, ecotoxicity, acidification, and nutrientification to develop physical measures and derive quantitative ratings for a considerable number of resources, pollutants, and nutrients [24]. A key criticism of the LCA is that there has been inconsistency with its use of units with regards to mass, energy, and emissions; complicating the comparison between product/process alternatives. Furthermore, there is also a concern that many LCAs concentrate too much on energy, and pay little attention to other considerations.

One approach that has been proposed to address this issue is the material intensity per service unit. This method adds up the overall material inputs to make a product or provide a service. It is measured in mass/service, and is conceived to encourage sustainability by reducing consumption. An outcome of this technique has been the growth of purchasing locally-grown food in an effort to reduce transportation expenses. Emergy accounting is another approach to incorporate sustainability into product design by “including the contribution of natural ecosystems, data relative to human labor and process implementation” [25]. Finally, the ecological footprint technique appraises “the resources necessary to produce the goods that an individual or population consumes… offers a simple and intuitive estimate of the production inputs for a given consumption level” [26]. In spite of this, the LCA with all of its faults still remains the superlative procedure to assess environmental impacts. LCAs also facilitate the concurrent design of new sustainable products/systems by incorporating environmental requirements. This is known as EcoDesign, and the next section will present multiple approaches and discuss how a manufacturing firm can use them to fulfil its sustainability strategy.

4. EcoDesign Methodologies

The design of sustainable products encompasses the strategies of: production, consumption, dematerialization (using less materials), and waste prevention [27]. One method of dematerialization in future production is disassemblability, which is how easily a product has been designed to be dismantled. High disassemblability decreases the production costs of the original equipment manufacturer (OEM) as well as the remanufacturer’s recovery and production costs [28]. Conversely, if the OEM competes directly with remanufacturers, then they would enter a price-war with remanufacturers being able to under-cut them. A multi-period model consisting of an OEM and a remanufacturer is portrayed in [28]. The product is amassed, remanufactured, and sold in the second period. In the second period, both participants compete directly with each other, resulting in many strategic decisions. The remanufacturer must decide whether to
target the green market segment (high-pricing strategy), or the whole market (low-pricing strategy). Similarly, the OEM must decide the level of disassemblability in the product’s design. Zwingmann et al. [29] develop a framework to identify all the feasible disassembly sequences for a multi-component product, and to find an optimal disassembly sequence, according to specific criteria such as cost, duration, and profit. A procedure is proposed in [30] that is based on a digraph and matrix method for the evaluation of a maintainability index of mechanical systems. Their procedure is useful in the design and development of maintainable systems. Recently, a safety-based availability assessment method to be used at the design stage was developed in [31].

Standardization also drives down the cost of remanufacturing by allowing interchangeable components among many manufacturers. One aspect of standardization is modularity, which “permits components to be produced separately and used interchangeably in different product configurations without compromising system integrity” [32]. A mixed-integer programming (MIP) model that maximizes profit by using modular product design to fabricate products at different quality levels was developed in [33]. Sherwood et al. describe different types of failure and scrap modes in the automotive industry, and then conduct statistical analysis to determine conditions for the design of repair and remanufacturing [34]. Furthermore, Byggeth and Hochschorner describe a valuation technique to assess trade-offs in different EcoDesign tools [35].

Luttropp and Lagerstedt [36] developed 10 golden rules for EcoDesign which accentuate design comprising of accessability, labelling, modules, breaking points, and using as few joining elements as possible in order to facilitate upgrade, repair, and reprocessing. Other considerations are: minimizing energy, and resource consumption; using recycled and simple materials (no blends/alloys); investing in and using high quality materials to reduce maintenance and promoting long life; not using toxic substances; and utilizing closed-loop supply chains. There is a clear emphasis on disassembly, modular design, and highly reliable products, making Design for Recycling (DfR) an important aspect of the EcoDesign pursuit. DfR facilitates easier assembly, disassembly, and lower production costs via modular construction [37]. DfR requires the consideration of conceiving future products using some of the current components. The particular component’s usage must be kept constant through imminent generations or its utility would be lost [37]. Complementary to this, a reliable acquisition network is required to not only recover the products for EcoDesign, but do so in good condition.

5. Collection and Recovery Networks

Product value recovery consists of diverting EoL and EoU products from the waste stream and capturing their remaining value via reuse, recycling, and/or re-manufacturing. This reduces the use of virgin natural resources and environmental pollution, while easing the burden on limited landfill space [38]. EoL, EoU, and consumer returns are three types of returns for a used product. In the first type, EoL returns are typically no longer functional, and are very old. EoU returns are usually functional, have had significant use, but are no longer technologically current. Finally, with consumer returns, the products are generally not defective, have gone through minimal use, and are technologically current. These returns, if properly collected, can provide a non-negligible source of materials at various levels of quality. The diminishing amount of raw materials will force manufacturers to implement design methodologies, use materials more efficiently, and recover the products at their EoL [39]. Product recovery management (PRM) refers to the responsibility that a manufacturer has for the “management of all used and discarded products, components, and materials” [20]. This may be voluntary, or forced through government intervention.
Governments have introduced extended producer responsibility (EPR) legislation in an attempt to reduce waste by placing the obligation on the beneficiaries (producers and consumers). EPR can be implemented via advance recovery fees, recycling subsidies, unit-based pricing, and deposit-refund schemes. There are two types of EPR models: collective and individual producer. In the collective, manufacturers jointly share the costs and receive waste in terms of market share; while in the individual producer, each producer is responsible for the EoL/EoU waste that they indirectly generate. In the latter, there is a belief that since the costs of recycling are heavily dependent on the product type, individual producer models are more likely to generate incentives for recyclable product design [40]. Nevertheless, the largest EPR mandate globally has been the WEEE Directive, which is a collective model and enforces producer responsibility for EoL electrical and electronic waste in Europe. With the WEEE Directive, “producers are physically and financially responsible for meeting certain recycling or recovery targets, while the member states must guarantee that 4 kg of such waste is collected per capita per year, at no cost to the end users” [40]. Producers and manufacturers then have to set up their activities to conform to these regulations in the most beneficial way.

EPR is meant to encourage recycling and reduce consumption of virgin material. The intent is to embolden manufacturers to have standardization across the industry, design their products for disassembly, and subsequently participate in remanufacturing. This will ultimately enable the cost of remanufacturing to go down, and enlarge the scope of what can be remanufactured in an economical fashion.

Another strategy is the design and fabrication of products constituted of recycled material. Chen and Liu study the pricing and design decisions for products composed of recyclable material, specifically aluminum, cardboards, and PET [41]. Chari et al. develop a two-phase approach to efficiently schedule the collection and compaction of recyclables while minimizing travel time and greenhouse gas emissions [42].

Dependability in a collection network deals with the quality, reliability, and safety of the returned products. This is true for both EoL products and recyclable waste. Mathew et al. have developed a systematic methodology for assessing the remaining life of electronic products [43]. In [44] an analytical model is proposed to evaluate optimal acquisition price and quantity policy based on the quality of returned used products that are subsequently used for remanufacturing. Zikopoulos and Tagaras investigate how the profitability of reuse activities is affected by uncertainty regarding the quality of returned products [45]. Some companies may attempt to acquire EoL products even if legislation is not present for the intrinsic opportunities that they provide. Some consumers make these returns voluntarily, although typically some monetary incentive has to be provided by the firm. Usually, this is in the form of rebates for repair or a future product from the same organization. Recently, a study has been conducted into “buy[ing] back broken products in order to improve control of both demand for spare parts and supply of recoverable parts” [46]. Another method of guaranteeing a volume of returned EoL products, thus its dependability, is by leasing a product instead of selling it outright. In the lease structure the consumer only owns the product for a limited time, and pays for it during that period. The residual value of product can then be exploited by the OEM. A further benefit of the lease is that it enables the customer to upgrade to newer equipment more frequently and on a predictable time interval. Aras et al. develop a model where a new product is leased, and at its EoL, it is remanufactured and sold [47]. This is a dynamic programming model to establish the optimal price of remanufactured products, and optimal payment structure for the leased products by maximizing the profit.
6. Dependability Issues in Product Remanufacturing

Remanufacturing is considered to be a value-added operation that can be of both economic and environmental benefit to a corporation and consumers, because it has the potential for higher profitability [48]. Since parts and components can be reused, the “process of remanufacturing is almost always less expensive than producing a brand new unit of the product” [49]. Remanufacturing procedures correspond to different types of upgrade actions. Repairing a product by replacing one or two broken parts with like-new or new spares will amount to a minimal repair from a reliability point of view. Reconditioning a part or module to an “as-good-as-new” condition can be modelled as a perfect repair. Refurbishing a product can be modelled as a general imperfect repair process. These reliability considerations of remanufactured products have significant maintenance and service implications. This section will present upgrade, maintenance, and warranty models developed and used for product remanufacturing.

After EoL/EoU products are recovered and dismantled to generate re-usable components, upgrade activities are usually carried out to bring the recovered components to a better condition, and thus effectively reducing their age. The cost of this rejuvenating/refreshing/upgrading action is proportional to the upgrade level carried out, and is an expense that can increase the sale price of the reconditioned system. Upgrade actions are procedures that improve the reliability (dependability) of a component. By paying for the upgrade at this early stage, the cost of servicing the product’s warranty is reduced in the future. Failures during the warranty period are costly to service, especially when dealing with reconditioned components. In the continuum of all upgrade actions the two bounds are: perfect repair, where the component is restored to a condition as if it were new; and minimal repair just restores the component to an operational state, without affecting its effective age. The intermediary levels in between the bounds represent some of the infinite upgrade possibilities that can occur. There are three commonly used approaches that model the effect of the upgrade action on the reliability: virtual age, improvement factor, and probabilistic [50]. The effective age of the EoL component is diminished in the virtual age approach [50,51], whereas the failure rate of the item is reduced in the improvement factor approach [52]. In the probabilistic approach, the EoL component undergoes either a perfect repair with a given probability or an imperfect repair as a function of the aforementioned [53,54]. The virtual age model has been used the most frequently in the reviewed performability literature.

Over time, the condition of a product deteriorates, so that maintenance and repair services are needed to keep it in working order. Since remanufactured products will usually have different (higher) failure rates, their maintenance strategies must then be adapted to account for their current age. With these products, repair may occur sooner, more frequently, and therefore add an extra financial burden to the servicing firm. There are two types of maintenance procedures: corrective maintenance (CM) and preventive maintenance (PM). With CM, the failed products are restored through minimal, perfect, or imperfect repair to be operational without any cost to the consumer. PM on the other hand, occurs before the product fails, with the intent to reduce the risk of failure and degradation. The type of maintenance procedure(s) implemented depends on the useful life of the product. A product with a relatively short useful life should involve only CM actions, whereas with a long useful life, PM actions should be considered to reduce the future costs to service the warranty [55].

Yeh et al. propose two periodical age reduction PM models for a second-hand product with known age and a pre-specified length of usage [56]. Their objective is to obtain the
optimal number of times of PM action, and the optimal degree of each PM action such that the total expected maintenance cost is minimized. Pongpech et al. propose a mathematical model to determine the optimal upgrade and preventive maintenance actions that minimize the total expected maintenance and penalty costs for used equipment under lease [57]. Khatab et al. investigate the relationship between rejuvenation/upgrade decisions of recovered EoL systems and the subsequent maintenance costs incurred during their second life as refreshed products. They develop a mathematical model for the joint determination of the optimal upgrade level and imperfect preventive maintenance strategy. A numerical example is provided to illustrate the validity of their model [58].

After an upgrade, an appropriate warranty policy is necessary to complement the resale of the product. Warranty can be thought of as a contract where consumers will have their faulty product repaired/replaced at no cost or at reduced cost, and also at the same time insinuate reliability [59]. Warranty models incorporate the additional costs that would come from addressing the failed item including the warranty costs per unit sale, per unit time, over the lifetime of an item, and over the product life cycle [60,61]. Recently, new models have been introduced to account for warranty claims due to misuse, and/or failures caused by various human factors [62]. An up to date review of warranty data analysis can be found in [63]. The reasons of why consumers have a preference towards products with a longer warranty are two-fold. The first reason is that the assurance from the manufacturer to have the product repaired/replaced is extended over a longer horizon. Secondly, when the warranty periods are longer, the consumer assumes the product is of a higher quality and reliability. Conversely, a longer warranty on a less reliable product, forces the company to set aside a larger reserve fund to service these failures. Therefore, the profitability of an enterprise can be maximized by accurately setting decision variables pertaining to the servicing of a product, such as its warranty length and price.

In order to generate demand for reconditioned or second-hand products, manufacturers or dealers/brokers have had to resort to a combination of initiatives to promote and infer the quality of their products. These initiatives include significant price reductions and generous warranty coverage (same coverage length as new systems, free preventive maintenance in the first year of the refreshed system, etc.). Research on warranty models for refreshed/reconditioned/upgraded products is still in its nascent stages. Shafiee and Chukova provide a current summary of warranty models developed in this area. They propose a three-parameter optimization model to determine the optimal upgrade strategy, warranty policy, and sale price of a second-hand product to maximize the dealer’s expected profit. Chattopadhyay and Murthy presented an expected warranty cost equation for second-hand products [61]. A one-dimensional unlimited free-replacement warranty policy with replacements carried-out with reconditioned products is developed in [64]. This model maximized the net profit by determining the optimal warranty duration, age of reconditioned products, and profit margin. The demand for the product is modelled to be proportional to the length of the warranty period to translate the consumers’ perception of better reliability through longer warranty. The preceding has been then extended by introducing a fourth design parameter, proportion of reconditioned components, to determine the optimal composition of new and reconditioned components [65].

Expected profit models have been developed using decision variables of: upgrade action, warranty period, past age, and sale price [50,66]. Saidi-Mehrabad et al. developed reliability improvement strategies for second-hand products sold under multiple warranty policies including: failure-free warranty, rebate warranty, and a combination of free replacement and lump sum policies [67]. Matis et al. design a multi-period warranty policy for repairable items, optimizing for the pro-rata warranty length and product price.
In the first period, the product is either replaced or repaired for free, and the second follows a pro-rata policy. This research encourages the integration of reconditioned components into a multi-stage warranty policy incorporating a pro-rata element. Lo and Yu develop a mathematical model for the determination of the optimal upgrade level and warranty length to maximize the expected profits for used products [69]. They provide a practical application to used cars. Naini and Shafiee propose a joint optimal price and upgrade level model for a warranted second-hand product. They present an application of their model to solve a second-hand electric drills remanufacturing problem.

The remanufacture of spare parts in a two-stage optimal control theory model of an MRP-based production plan using new and reconditioned parts is handled in [19,70]. A mathematical model is derived to find the cost-optimal production strategy that incorporates reconditioned components in the manufacturing effort. New and reconditioned parts are used to carry out replacements upon failure under an unlimited free replacement warranty policy. Key production decisions, such as when remanufacturing should commence, how long the warranty period should be, and how many returned parts should be reconditioned are answered. The availability of reconditioned parts and their discounted costs are incorporated in this model. Interactions between these decisions and their impacts on the manufacturing system and the consumer are investigated. A case study on aircraft rotatable spare parts is presented in [70].

7. Future Work

Based on this review, future research efforts should be directed towards the following areas of performability across the value chain:

1. **Quality and Safety Models for EoL/EoU Systems.** Second-life decisions will be better modelled if accurate degradation and usage data is available for the recovered systems. Test benches are used to evaluate the current state of recovered products and parts, in order to assess their expected remaining life, reliability, and level of safety. Some monitoring technologies such as radio-frequency identification (RFID) have been tried, unfortunately current tracking systems do not yield sufficient health data, and not all products or parts can be tested before a remanufacturing option is chosen. Better tracking and usage reporting technologies are needed along with mathematical models to process the data collected and support the selection of the appropriate remanufacturing options.

2. **Reliability Models for Remanufactured Systems.** Remanufactured/refreshed systems have the unique characteristic of being comprised of components/parts of different ages, making the reliability analysis extremely complex. The overall failure rate of such a composite system composed of a mixture of parts, and its net impacts are an important consideration. Other relevant questions are: What burn-in procedures should be applied? How is the optimal level of repair determined? Should there be multiple upgrade actions to continuously extend the longevity of the product? If so, what is the ideal number of upgrade actions? Have the products been designed to facilitate upgrade operations?

3. **Maintenance Models.** Very few maintenance models have been developed specifically for refreshed and upgraded systems. The impacts of the rejuvenation of multicomponent systems on their subsequent lifetimes and operation should be investigated. What maintenance policies are most appropriate for these systems? If reconditioned parts are available, what are the conditions under which these can be used to carry out maintenance replacements?
4. Warranty Models. Few warranty models have been developed for refreshed and upgraded systems. Several topics can be investigated, such as: warranty models for leased equipment going through several cycles of upgrade and refreshing, warranty models accounting for past usage and perfect or imperfect health monitoring information, and warranty policies for refreshed systems with replacement carried out with reconditioned components.

8. Conclusions

In this paper, the most recent advances in performability throughout the value chain are reviewed. Initially, green supply chains, LCAs, and EcoDesign methodologies are defined to lay the foundation for a sustainable product life cycle framework. This is a closed-loop model employing a cradle-to-cradle resource management scheme to facilitate remanufacturing. The sequence begins with the acquisition of EoU/EoL products and discovering ways of making the collection more dependable, chiefly by ascertaining the availability of ample products of adequate quality. Next, in the remanufacturing stage, the dependability is founded on assessing and improving the reliability of products prior to assembly and resale. Finally, reliability and maintainability are used to determine multiple decision variables such as: upgrade action, warranty period, past age, profit margin, sale price, and proportion of reconditioned components when conceiving a suitable warranty/maintenance strategy. In this review it was discovered that there are many more emerging research opportunities in the subject of performability across the sustainable value chain, specifically in quality and safety models for EoU/EoL systems, reliability models for remanufactured systems, maintenance models, and warranty models. Additionally, many more possible prospects for research exist in the fields pertaining to EcoDesign, remanufacturing, and support services, indicating a great deal of promise for the near future.

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References


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For **Claver Diallo**’s biography, see page 542.

For **Uday Venkatadri**’s biography, see page 542.