Multiple Life-Cycle Products: A Review of Antecedents, Outcomes, Challenges, and Benefits in a Circular Economy

Abstract:

The importance of design and its contribution to society is heavily emphasized in the literature. Multiple life-cycle products are based on the ideology value retention of components, products, and materials after its use phase and utilize it for the next life cycle. With that, it contributes to economic growth by reducing resource consumption and environmental impact. The objective of this research is to conduct a systematic literature review to understand what antecedents are involved in the generation of multiple life cycles. This review analyses 87 papers on the multiple life cycle products that use design for sustainability principles (Reuse, Refurbish, Remanufacturing, Recycle). The review highlighted that DfS can contribute to multiple life cycle generation by enabling the products to be recoverable at the end-of-use or the end-of-life. The analysis identified antecedents being important for the product and related them to the outcome, benefits, and challenges. Managers need to carefully select the appropriate model for the design of a product, evaluation of recovery alternatives, and prices of new and remanufactured products keeping in mind return uncertainty, quality, and volume of used products.

Keyword: Design for Sustainability (DfS), Circular Economy (CE), Reuse, Refurbish, Remanufacturing, End-of-Life (EoL)

1. Introduction

Our society is rapidly growing and with the time, we are becoming more dependent on technology and services. Current patterns of production and consumption are putting pressure on the environment and have become the major source of pollution, global warming and resource scarcity (UNEP, 2012). The manufacturing industry has big role to play in the sustainable development of society. The Production system, which generates waste and emits carbon, fetches criticisms from the regulatory bodies and the consumers. On the other hand, people are becoming sensitive towards the product performance in the use phase and they are attracted towards those brands that ensure superior experience, technology, design, features, and finally services. It is also noticed that technology is changing at a fast pace and in every ten years approximately, we see new products, appliances, and equipment with performance, guarantee and innovative design. Technology obsolescence exerts a negative influence on the life a product and consumers throw away the used goods, which finds a place in the recycling centre. Such a scenario highlights the importance of product function, attributes, and architecture as in many cases those aspect don’t allow the recovery process to execute as it may result in the loss of product integrity (Khan et al., 2018). There are many products whose inferior design restricts their performance and such products have a short life span and at the end-of-life (EoL) stage, designers struggle to explore ways to recover the material and energy (Diaz et al., 2020). Another problem frontier relates to mindless consumption by the customers who don't care about the resource scarcity and their action causes climate deterioration and thus, consumption pattern requires to be radically changed to allow the manufactures to introduce recyclable materials in the product (Lee et al., 2021). To mitigate these imbalances, the design must allow the cyclic flow of product, materials, and components from the point of consumption to the manufactures through the collection and dispatching partners to enhance the reusability and recovery of product. The measures that need to be adopted demands deeper understanding of product design, service network, and customer preferences.

Multiple life-cycle products have evolved from eco-friendly design, which integrates product life cycle and environmental performance. Product design is one of the tenets of sustainable business development (Gunasekaran and Spalanzani, 2012) and it goes beyond the boundaries of life-cycle design thinking. The eco-design concept or design for the environment (DfE) is function-oriented (Devanthan et al., 2010) and contains product safety, recyclable material, and lower energy consumption ideologies to have a low impact on the environment and assumes a bigger part in the product life-cycle management (Schöggl et al., 2017). To achieve the multiple life-cycle thinking, the designer to transit from functional thinking and adopt multi-purpose use and systematic approach to product manufacturing (Braungart et al., 2007; Spangenberg, 2013). Design for Sustainability (DfS) overcomes the limitation of design for environment (DfE) principles as it combines social aspects into the early design. Design for Sustainability (DfS) boasts of system-wide innovation with a radical shift in the design of products and services and provides a transformative pathway for the multiple life-cycle. With systematic thinking, DfS proposes sustainability strategies for their use by the designers and redefines the existing product design by including the use and re-use factor to ensure waste reduction, recovery of biological and technical nutrients, and use of recyclable and renewable material. It acts as both facilitator and influencer for the supply chain-wide adaptation in product and process, product life extension, and reusing of components or material for the next life-cycle (Go et al., 2015). Three prominent EoL alternatives contribute to generating multiple life cycle by forming inner circular loop – repair and maintenance, refurbish (upgrade), remanufacturing– that reverses the material, component, and sub-assemblies into the same loop or another loop for extended utilization. Thus, DfS is the founding principle of a multiple life-cycle product and creates sustainable values with the inner loop of reuse, refurbishment and Remanufacturing. To operate the loop, the firm need to explore ways to align its business strategies with the emerging customer needs and capability of the supplier and service partners (Ma and Kramer, 2016).

1.1 Insights into Existing Literature Reviews

Table-1 summarizes the existing literature reviews on the various aspects of product design for sustainability. There are extensive works on different approaches to product sustainability connected to material reutilization including, reduction, remanufacturing, upgradation, repairing, recycling, and repurposing. These sustainability routes are enabled by modular design, design for disassembly and reassembly methods and design for multiple life-cycles and sixteen (16) reviews addressing those issues have been analyzed in this regard.

The design stage is crucial for product development as it influences the activity to be performed at the manufacturing, packaging, servicing at the use phase, and EoL. At this stage, designers decide how to introduce features, shapes, and attributes so that the final product will have a minimum number of sub-assemblies, a minimum number of fasteners, clear labeling on the component, and no permanent fasteners. Moreover, the role of designers is important as they analyze how to implement features that restricts user not to dispose of it carelessly, thus lessening the burden on the environment by giving a product next life. The multiple life cycles of a product under the umbrella of design for sustainability have been studied extensively with various DfX principles that improve the recovery potential and increases the reusability of the component or product.

Literatures have captured the various design for sustainability strategies right from the concept development to implementation. The role and importance of modularity in the product design and its benefits at the EoL stage have been studied (Ma et al., 2011; Sonego et al., 2017; Bonvoisin et al., 2016). Ma and Kremer (2016) studied design for modularity and excluded other parts. Sonego et al. (2017) also reviewed the role of modularity in sustainable product in the view of the life cycle. Though the analysis discussed the benefits of modularity when end-of-life stage is arrived, but the analysis didn’t relate modularization strategy to the recovery stage of the product. Sustainable product design has been reviewed with the viewpoint of eco-design and discussed tools named partial sustainable product design (P-SPD) and sustainable product design (Ahmad et al., 2018). This review was rather focused on the tools and methodology approach to sustainable product design. The research in sustainable product has also moved in the direction of upgradability (Khan et al., 2013) and remanufacturing (Peters, 2016). Thomé et al. (2016) conducted a systematic review and bibliometric analysis of sustainable new product development and the analysis didn’t consider multiple life cycle. This review mainly considered design for environment, life cycle, and green technology. Moreno et al. (2016) described the design for multiple life cycles (DFMLC) as circular design strategies and argued that DFMLC emphasizes resource recovery, which enables feeding of the material or component back into the system. The scholars have discussed various strategies that focus on the EoL product management to implement DFMLC, but the major limitation was that the paper discussed conceptual development and didn’t capture the application part. Go et al. (2015) defined DFMLC as a combination of Design for Environment (DfE), Design for Remanufacturing that covers the gamut of Design for Upgrade, Design for Assembly, Design for Disassembly, Design for Modularity, Design for Maintainability and Design for Reliability that implements, reduce, recycle, reuse strategies. The authors further elaborated the guidelines for each DfX principle and cited the example of BMW adoption of parts made of 100% recycled steel. Designers must envisage EoL processing at the early design phase and accordingly adopts DfX principles to recover the component or sub-assemblies. This review mainly discusses the concept of product sustainability with few examples, but didn’t capture the current progress on the multiple life cycle. Go et al. (2011) reviewed the methods to evaluate the dis-assemblability of end-of-life vehicles (ELV). It appears from the author’s argument that the manufacturer gains from remanufacturing if the returned or used product can be disassembled to some extent. The problem with this review is that it is focused on only one DfX strategy and excluded other parts such as Design for upgrade etc.

Arnette et al. (2014) extended the work on the design for sustainability and proposed design strategies for each dimension of sustainability. The economic dimension focuses on the ease of manufacturing, assembly, quality, flexibility, logistics, and improvement in supportability, maintainability, and serviceability. The environmental dimension concentrates on the design for the environment (DfE) and design for 3R (Refurbish, Remanufacturing and Reuse). Design for social responsibility comes under the periphery of the social dimension. The review mainly discussed the advantages of each principle without putting emphasis on the application area. The major limitation of work of Arnette et al. (2013) regards to the connection between DFX techniques and user behavior. A review of DfS models by Rocha et al. (2019) in product design includes strategic, tactical and operational decisions and missed the point of material and component recovery. That review revolves around the idea of design management and how the firm undertakes a sustainable product design at different levels and the limitation is related to the performance-oriented aspects of design for sustainability. From the existing review analysis, it appears that no reviews have analyzed the literature with product as unit of analysis and have identified antecedents contributing to multiple life cycle generation. We feel that a void exists in terms of limited understanding of how the next life cycle is planned for a product at its early design phase. To understand the multiple life cycles of a product, we have adopted the viewpoint of design for sustainability (Arnette et al., 2013; Go et al., 2015; Ceschin et al., 2016) and identified antecedents, outcomes, benefits, and challenges. The purpose of adopting DfS theory is to identify which Design for X (DfX) method is applied to a product. These DfX method represents “R” principles of circular economy i.e. reuse, refurbishing, remanufacturing, and recycling. In this review, we focused on products whose recovery solutions are discussed in the literatures. Thus, we have come across the research questions:

Sl.No.	***Authors***	***Area***	***Method***	***Focus***	***Themes/Gaps***	***No. of Literatures Reviewed***	***Database***
1.	Go et al. (2015)	Product Sustainability	Not defined	Design for multiple life cycles	Number of parts, number of materials, level of cleanliness, design cycle, technology cycle,	-	Not mentioned
2.	Ma et al. (2016)	Modular product design (MPD)	Systematic literature review	Relationship between MPD and sustainability	Increased sustainability performance with MPD	65	Compendenx
3.	Go et al. (2011)	Product Sustainability	Technique-based review	Disassembly Method	Integration of the constraints of end-of-life strategies into the design at the early stage	40	-
4.	Rocha et al. (2019)	Design for Sustainability	Literature Review	Corporate Sustainability and Design Management	Integration in business strategy, stakeholder involvement	45	Google Scholar, Web of Science
5.	Mayyas et al. (2013)	Design for Sustainability	Literature Review	life cycle assessment approach, the end-of-life perspective, the design for X, and the light-weight engineering and material selection studies.	Identified shortcomings in the sustainability models of automotive industry.	-	Google Scholar, Web of Science
6.	Ahmad et al. (2018)	Sustainable Design	Technique-based review	Eco-design	Only life cycle perspective is covered.	-	Google Scholar, Web of Science
7.	Sonego et al. (2018)	Product Modularity	Systematic review	Life Cycle Assessment, Design for X	Benefits are claimed in every life cycle phase	81	Web of Science
8.	Peters (2016)	Product Remanufacturing	Content analysis	Life cycle analysis	Extension of existing LCA knowledge to remanufacturing	13	Google Scholar, Web of Science
9.	Pinhero et al. (2018)	Integration of new product development (NPD) and CE	Systematic literature review	Regenerate, share, optimize, loop applied to the NPD study	Circular design, EOL, LCA, PSS are the few important practices to be looked upon.	49	Scopus
10.	Khan et al. (2013)	Product upgradability	Systematic Literature Review	Definition of upgradability, common issues, consumer perspective, design process	Product upgradability helps to retain the product by replacing only a few components that devalue the product over time.	43	Web of Science
11.	Thome et al. (2016)	Sustainable Product Development	Combination of systematic literature review and bibliometric analysis	Cradle-to-grave product design	Life cycle assessment, multi-criteria selection for products and suppliers	167	Springer
12.	Bonvoisin et al. (2016)	Modular Product Design	Systematic literature review	To build a theoretical ground for “Modularization for X”.	Identified drivers of modularization, principles, metrics.	163	Science Direct
13.	Schallehn et al. (2019)	Customer experience creation for after-use products	Content analysis-based literature review	offering characteristics that affect customer response and customer engagement.	Price, confidence, convenience, and delight orientation	69	Scopus and Web of Science
14.	Bangsa and Schlegelmilch (2020)	Sustainable products	Systematic literature review	Relationship between sustainable product attributes and consumer decision-making	Linear and rational consumer decision-making process, focus on environmental sustainability and mostly examine food products	114	ProQuest or EBSCOhost
15.	Arnette et al. (2013)	Design for Sustainability	Systematic literature review	Theoretical framework of DfX in 3R concept	Design with triple bottom line and integrate with supply chain	40	Scopus and Web of Science

Table 1: - Extant Review Studies on Multiple Life Cycle Product

RQ-1 – What are the antecedents that play an important role in designing, manufacturing and delivering a multiple life-cycle product when we take into account the resource circularity in a supply chain?

RQ-2: What are the outcomes based on the antecedents?

RQ-3: What are the challenges that DfS pose for the manufacturers? What are the benefits for the consumer and society when a manufacturer wants to extend the product value?

The paper is structured as follows. Section-2 discusses the existing reviews. Section-3 presents the research design and methodology of the systematic literature review. Section-4 highlights a discussion on the findings and paper relevant to the antecedents. Section-5 posits the Discussion and Section-6 asserts the conclusion.

2. Design for Sustainability for Multiple Life Cycle Product

Design for sustainability has been addressed by many researchers and many presented various aspects of it. We discussed in the previous section about the various corners of DfS and its role in multiple life cycle. We have reviewed and finalized its aspects that enhances the recovery potential of a product after end-of-life. The DfS principles are Design for Environment, Design for Disassembly, Design for Remanufacturing, Design for Recycling, Design for Upgrade, Design for Maintainability, and Design for Component Reuse (Go et al., 2015).

Design for Environment (DfE) can be described as the life cycle thinking that integrates environmental norms and human health and safety factors into the early design phase. The motivation behind using DfE is to improve recyclability and waste reduction. It is basically concentrated on the selection of eco-friendly material which has high recyclability potential at the pre-manufacturing stage and recover it at the end-of-life to improve environmental safety and health. The practices under DfE include waste reduction, material selection and energy efficiency (Arnette et al., 2013). Design for disassembly enables a manufacturer to disengage the threaded fasteners and take the module or sub-assembly out for inspection and cleaning, and testing. Design for upgrade (DfU) aims to extend the life of the product and new component are installed to attract the customer with improved features. DfU recommends to remove critical component from the assembly and rework on it to prolong the functional life of a product. Remanufactured product belongs to a different market and hence supply and demand of EoL staged product depends on the consumer willingness to dispose or return the product. Go et al. (2015) elaborated the product characteristics suitable for remanufacturing, including, product with core, product with functional failure, durable core, disassemblability of core, stable technology of product and process. Design for remanufacturing gives a new life to a product with complete disassembly, inspection and reassembly. Design for remanufacturing (DfRem) requires for a manufacturer to adopt a suitable business model that facilitates in and out of the product and form a closed-loop system. Design for Reuse focuses on recovery of those components or materials or products which don’t get deteriorate with the length of usage. With the component extraction for its use in another product, a manufacturer regenerates the economic opportunities, reduces the material consumption, and improves the environmental health.

Adoption of DfS principles in early product design have implications on supply network and customer relationship. Supply network ensures the smooth flow of new or used component for either refurbishing or remanufacturing by maintaining relationship with distributor or core supplier. Abbey and Guide (2018) proposed a typology of design and strategic focus for remanufacturing, which is characterized by four different regions belonging to multiple life cycle products, durability and reparability, commercial returns and third-party remanufacturing. The authors further described multiple life cycle perspectives as robust design with a profit focus and presented integrated product acquisition perspective and vertical integration of forward and reverse supply chain. Here, a manufacturer implements design for sustainability principles at the early design stage and executes all operation after EoL such as complete disassembly, inspection, cleaning and reassembly. In this review, we have focused on consumer products for which multiple life cycle can be created. We have excluded durable products such as aircraft which is based on the ideologies of sale of long-life cycle with periodic and preventive maintenance.

3. Research Design

A content analysis-based systematic literature review (SLR) was carried out to identify the antecedents of multiple life-cycle products with a procedure similar to Seuring and Müller (2008); Tranfield et al. (2003) for retrieving and selecting the articles. The flow chart of review methodology and steps of content analysis are depicted in **Figure-1 and Figure-2**. The purpose of SLR is to discover the effect and implication across all studies and to analyze the information contained in the various articles. Seuring and Muller (2008) described two levels of content analysis- first deals with obvious content of documents and second identifies the meaning of terms and arguments. We have followed the four steps (Mayring, 2008) of qualitative content analysis that involves the material collection, descriptive analysis, categorization of articles, and material evaluation.

3.1 Material Collection

We collected mainly from Scopus, Science Direct, and Google Scholar research repositories. To search, many keywords are used and applied to fetch the relevant result. At Google Scholar, we used "product sustainability", "design for multiple life-cycle", "Design for Sustainability", "circular supply", "circular product", "remanufactured product", "upgradable product", "design for circularity", "refurbished product". In Scopus, a total of around 305 articles appeared with the "sustainable product design". Product sustainability keyword generated 343 articles, whereas design for sustainability produced 533 articles. The "Cradle-to-Cradle" search in the ScienceDirect website generated 1,672 articles. In the Scopus database, "Product reuse" generated 186 peer-reviewed articles. "Circular Product" produced 153 papers in the web repository of Scopus. Remanufactured product string produced 840 articles. We have considered the cradle-to-cradle products as multiple life cycle products, which are designed in the light of design of sustainability principles and ignored the articles on an eco-designed product that are based only on DfE principles. **Table-2** summarizes the screening and selection process of the article for this review.

3.2 Descriptive Analysis

Figure-3, 4, 5, and 6 show the collection of articles on multiple life cycle product. Fig-3 depicts the number of papers published each year. Fig-4 shows the distribution of paper as per the research method. Figure-5 denotes the number of articles clearly mentioned about the product application. To capture a holistic view of the topic, we resorted to reputed journals dealing in the product and services from the design and system thinking aspect. The journals selected are Journal of Cleaner Production, Resources, Conservation and Recycling, Business Strategy and Environment, International Journal of Production Research, International Journal of Production Economics. A total of 87 papers have been screened and finalized. It appears that the Journal of Cleaner Production (JCP) with 18 papers and Resources, Conservation, and Recycling (RCR) with 16 papers has highly contributed to the subject among the screened outlets. Figure-4 illustrates that work has more been acknowledged in the year 2018 and has increased from the previous year. A decrease in the number of publications can also be noticed in the year 2020.

3.3 Categorization

Mayring (2002) discussed two ways to perform categorization of the articles – inductive and deductive. Merli et al. (2018) described the recursive process to concretize structural dimension and analytical category and adopted a deductive-inductive approach. Here, we adopted the same iterative process which starts with the deductive approach to select and filter the material for preliminary analysis, and then analytical categories with the inductive approach are finalized which will be fitted in the scope of review. Five Themes emerged from the analysis – **Recovery Decisions, Product Configuration, Waste utilization, Material Selection, Loop, Reuse Services for Customer**.

Antecedents means as to what factors being causal in nature are involved in various processes such as recovery, product configuration and are influential in developing multiple life cycle. Same procedure was adopted for the outcome, benefits, and challenges.

Procedure for Antecedents Extraction

- Text passages mentioning the antecedents/factors influencing multiple life cycle creation were coded and assigned to the categories.
- The coding contains the set of words corresponding to origin point of factors and reason behind its inclusion.
- The iterative process of coding from the text passage led to the synthesis of antecedents.

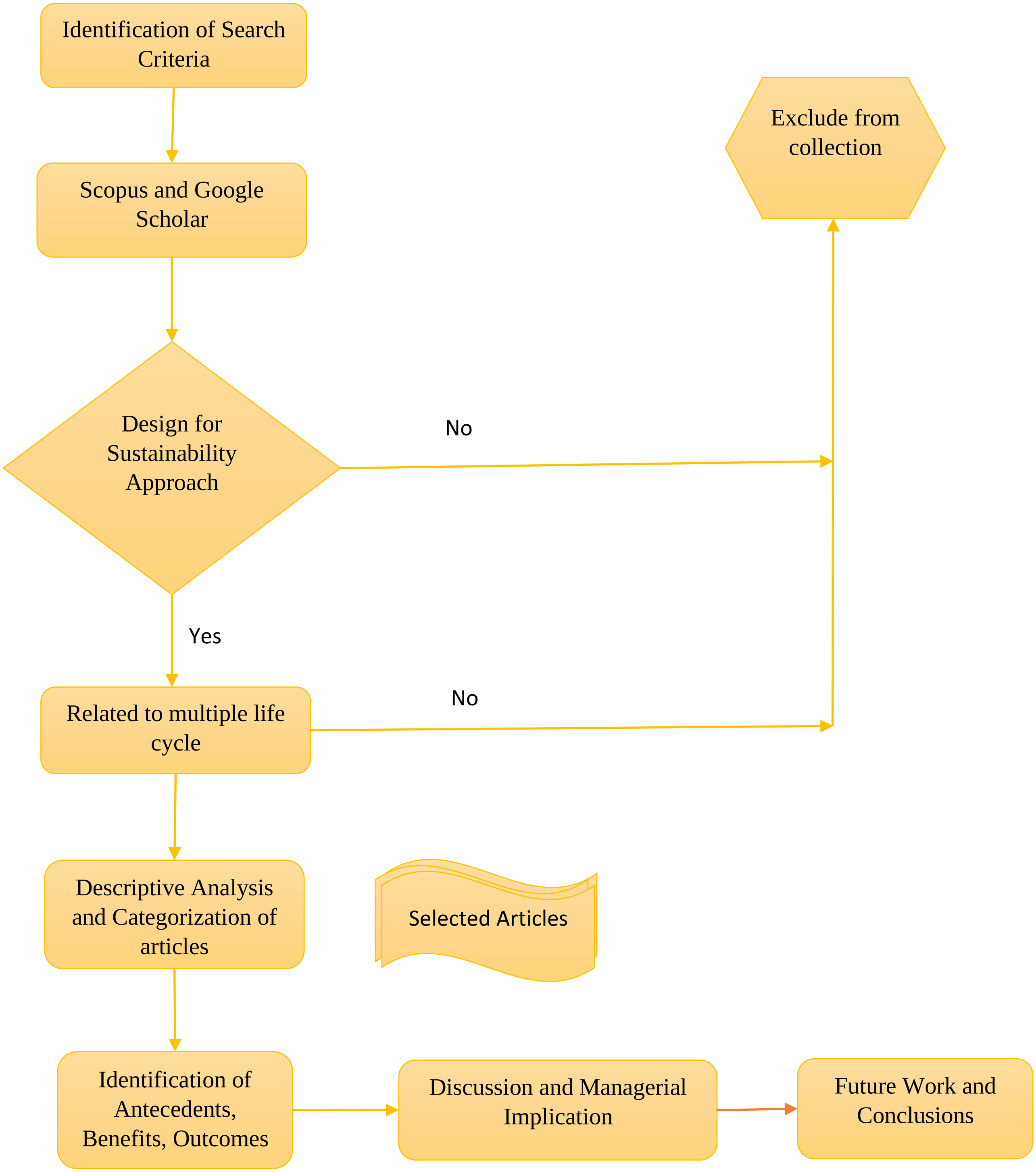


Figure-1: Flow Chart of Review Methodology

3.4 Material Evaluation

To ensure the reliability of the evaluation, three authors have separately analyzed the entire material and performed the coding. The first-cut classification was carried out by one researcher and later, a consensus has arrived with repetitive discussion on the classification, thus both intra-evaluator and inter-evaluator cross-checking is performed. All the researchers used MS excel software to enter the observations and the views were matched and in case of any deviation, we all discussed. In MS-excel, a tree diagram was made based on the paper theme and outcome. After this, we performed a validity test to ensure rigor in our approach. The researchers adopted firstly deductive approached and refine the papers based on keywords. After careful study of the abstract and introduction, we then adopted an inductive approach for further improvement. Thus, the closeness of the category is achieved by utilizing multiple classifiers, and the mutually agreed view of the researcher upon definition of the category establishes the validity.

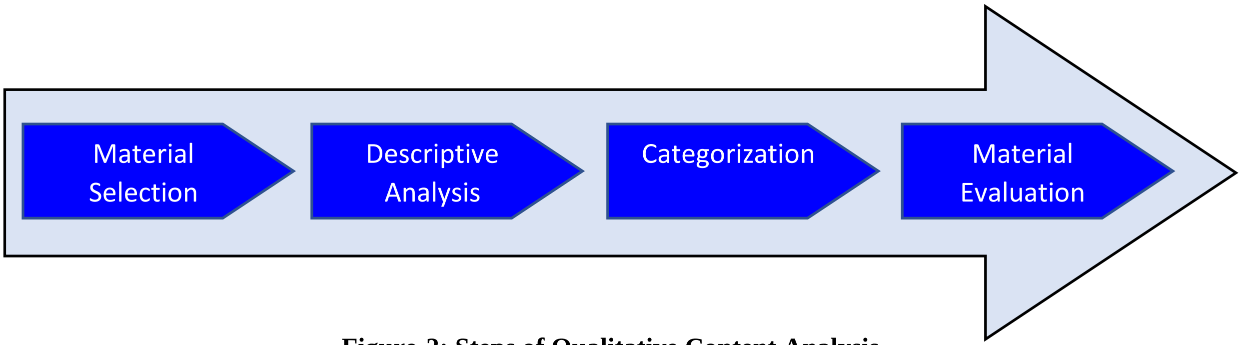


Figure-2: Steps of Qualitative Content Analysis

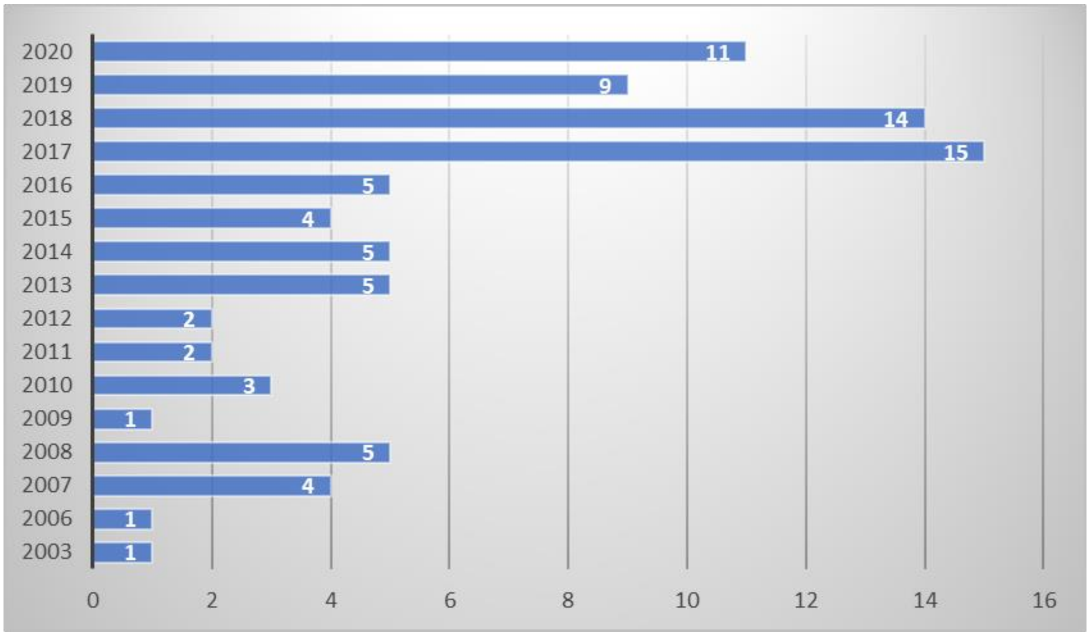


Figure-3: Distribution of Papers by Year

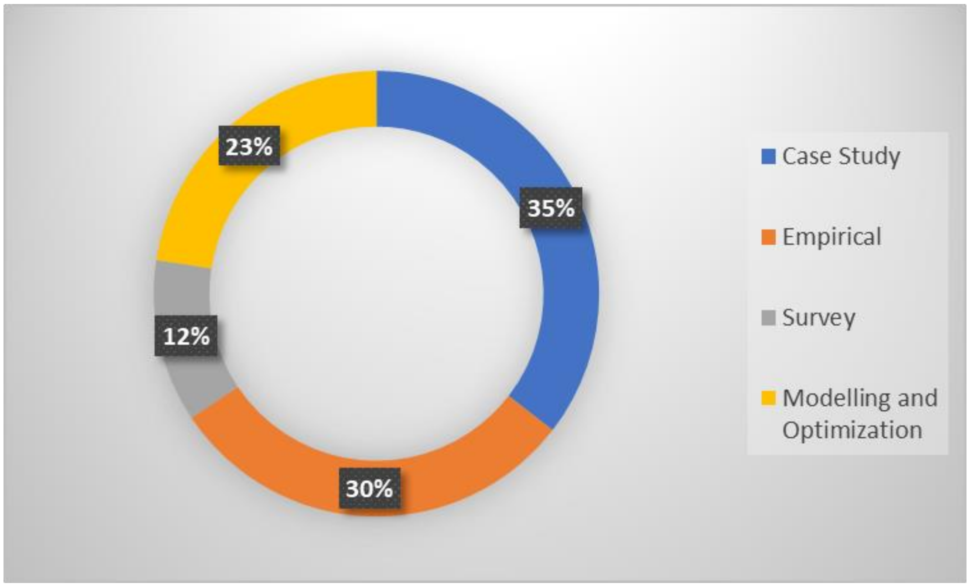


Figure-4: Distribution of Papers by Research Method

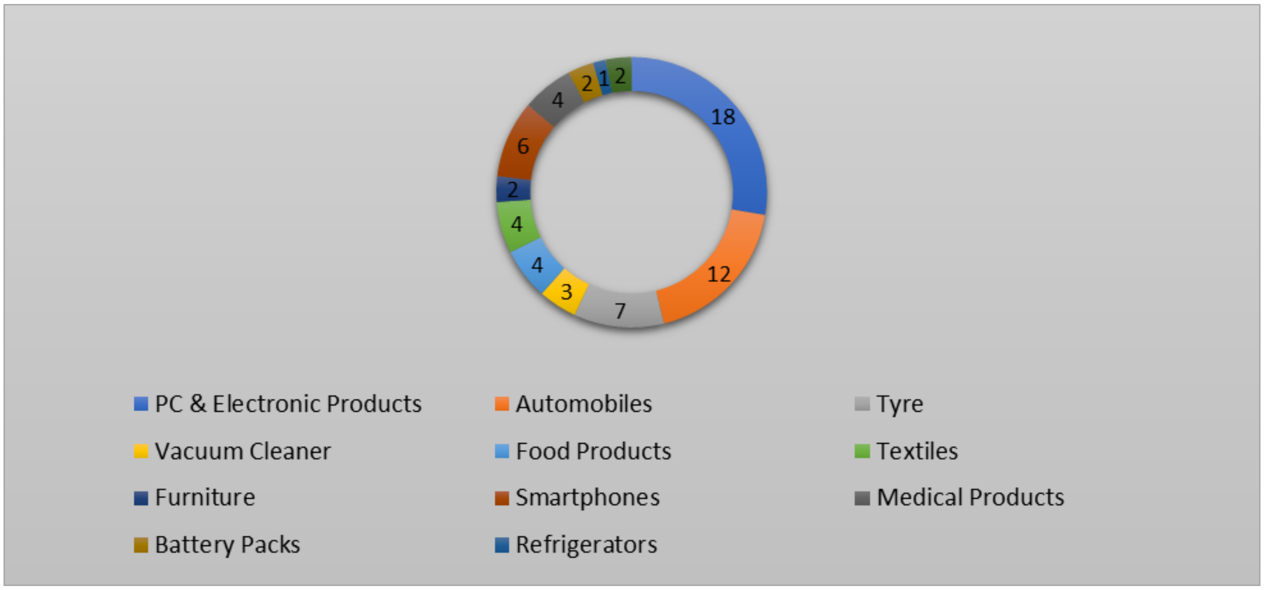


Figure-5: Distribution of Papers by Product

Step	Description	Number of Papers
Keyword search	“Product Sustainability”, “Upgradable Product”, “Sustainable Product design”, “Circular Supply”, “Circular Value”, “Design for Sustainability”, “Remanufactured Product”, “Design for multiple life cycles”, “Design for Circularity”, “Refurbished product”	3932
1st stage filtering	1. Article duplication 2. Relevance to the multi-life cycle product 3. Abstract analysis	852
2nd stage filtering	1. Product and Services 2. Sustainability and Product life Cycle 3. Reuse, Remanufacture, Recycle	271
Final screening	Full paper analysis	87

Table-2: Screening process of the article

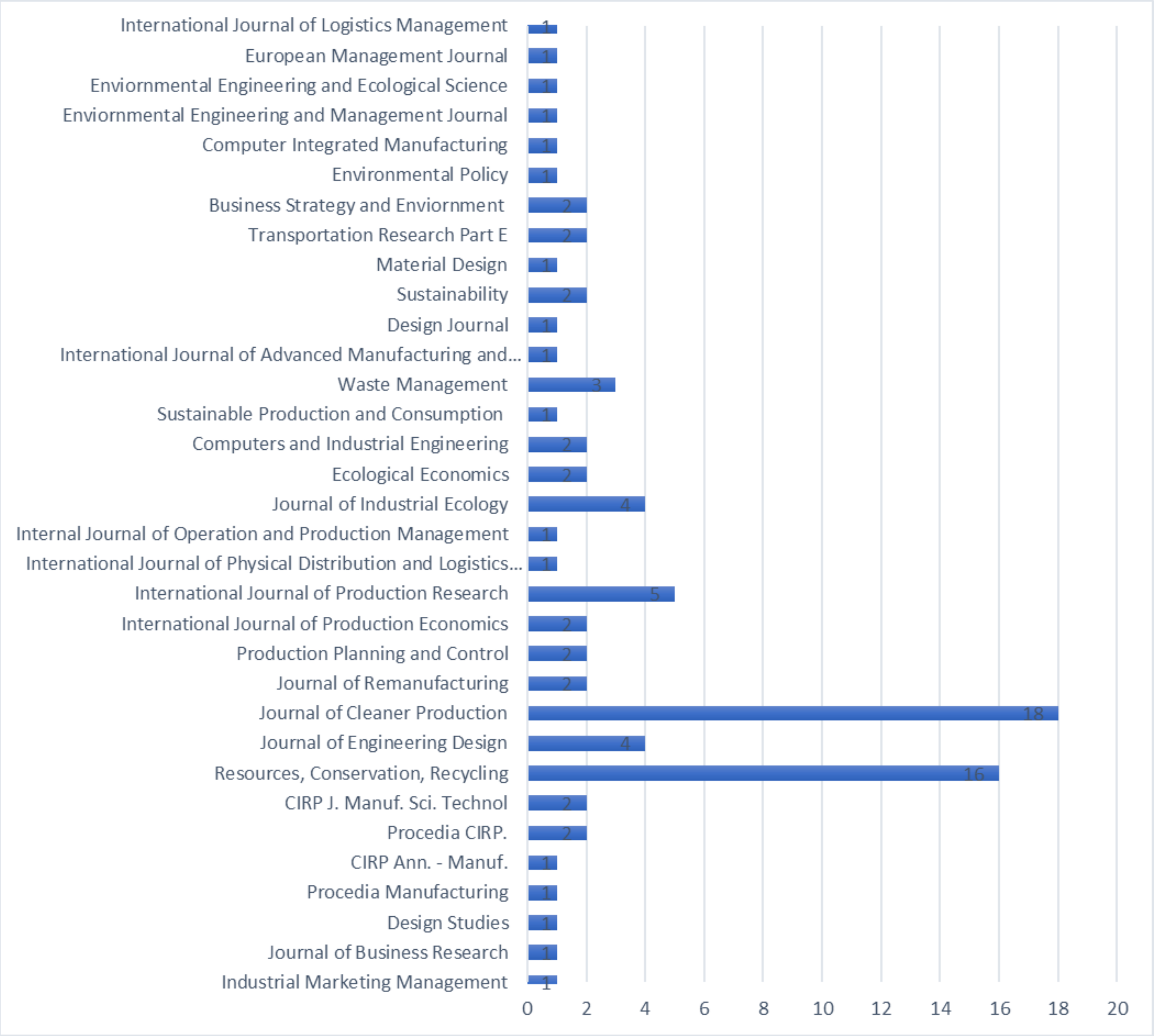


Figure-6: Distribution of Papers by Journal

4.0 Analysis

This section covers those literatures that considered various types of antecedents in achieving an outcome and a benefit. The antecedents are derived from several types of studies and mainly include factors considered for a specific area of multiple life cycle such as recovery estimation, product characteristics, material, waste utilization, circular loop, and consumer involvement.

4.1 Antecedents

- **Recovery-based Antecedents:** The decision for a firm to reutilize the usable resources at the end-of-the life and end-of-the-use rests on the *residual value* of a product and its component and is further influenced by the *cost associated with the recovery process* and *quality and quantity of the recovered portion* for remanufacturing. Coates and Rahimifard (2008) proposed a vehicle costing framework based on the current direct and indirect costs and revenues affecting vehicle retirement, to facilitate increased value recovery to an array of EoL operators. Meng et al. (2019) worked on hybrid recovery system to handle a batch of EoL products to select the best alternatives between remanufacturing and complete dismantling and included the cost of inventory, dismantling, disassembly in achieving the objective of minimizing total life cycle etc. Anthony and Cheung (2017) calculated refurbishing, recycling and remanufacturing cost with other factors such as *disassembly and assembly time*, *cost of the part and component failure* in case of remanufacturing, part removal cost in recycling case, and cost of refurbishing if a part is in a good condition or a part with complete failure. Tonnelier et al. (2006) proposed a qualitative tool to evaluate the recovery potential earlier in the product design process of the front bumper of a car and considered two criteria - materials and the disassembly potential.

  Du et al. (2012) evaluated the economic and environmental feasibility of used machine tool, where the economic feasibility is connected to remanufacturing cost and the environmental benefits of machine tool remanufacturing are evaluated in terms of energy saving, material saving and pollution reduction. *Product classification for EoL acquisition* is defined with product characteristics such as *length of usage of products, residual value, and the marginal value of time*. A longer lifetime of usage reduces the predictability of the product return and hence, it is difficult to plan for recycling. Farel et al. (2013) adopted studied ELV glazing recycling and investigated the cost and benefit towards secondary use in the different value chains. The factor considered in the study includes *collection cost, dismantling cost, transportation cost, treatment and recycling cost*. Steeneck and Sarin (2018) explained extended durability with *new product production cost, part replacement cost, part salvage value and the proportion of good parts* obtained from disassembly. Hatcher et al. (2013) examined the influence of internal and external factor on design for remanufacturing. Internal factors considered are related to *business, design process, manufacturer-remanufacturer relationship, and socio-psychological*. External factors are *profit, customer demand, competitiveness, sustainability, products naturally suited to remanufacture*. Ferrão and Amaral (2006) presented a design for recycling strategies for the automobile seat and evaluated the economics of recovery.

- **Product-based Antecedents:** Design variant, function, attributes, and architecture are the four important aspects of a product that have been discussed in the literature. *Material composition, design features, and ease of disassembly* are essential attributes that determine the fate of the product after its use and investigation is executed for the products including, robotic vacuum cleaner, computers, tire (Parajuly et al., 2017; Feriha et al., 2014). For toner cartridges, Badurdeen et al. (2018) considered *% of new components, component variants, and % of reuse components* as product characteristics for multiple life cycle-based optimization model *to minimize total life cycle cost, total global warming potential and total water usage* that includes cost incurred over all life-cycle stages, including pre-manufacturing, manufacturing, use and post-use. Aydin et al. (2019) considered *number of product return* as the basis to formulate multiple life cycle design considering life cycle cost, average energy usage per product, and average water usage per product.

  The product family and criticality are adopted as a different approach to design sustainable product configuration and it is seen to influence the sustainable performance as the family contains similar function and product architecture (Parajuly et al., 2017). Kim and Moon (2017) considered *quality of module instances, part-worth utility, process cost, market size*, demand for new and manufactured product to achieve the objective of maximizing profits from both new and EoL products. Mesa et al. (2018) defined product families for prosthetic fingers with *modularity, commonality, and functional variety* and adopted design for slowing and closing loop. Parajuly and Wenzel (2017) adopted product family design for electronic products to embrace the commonality, compatibility, standardization, or modularization to counter the barriers in the transition to sustainable design. The factor considered relates to product attributes such as *functionality, material composition, product design and expected life span*.

  Ardente et al. (2015) identified product criticalities with indicators including, *large dimensions of appliances, presence of refrigeration and oils, parts with valuable materials, presence of insulation foams*. These criticalities have been addressed under design for disassembly (DfD) for battery packs (Talens Peiró et al., 2017). Vanegas et al. (2018) calculated disassembly time of LCD monitor with factors such as number of connections, number of product manipulations, and the order of the disassembly. Kane et al. (2018) studied circular design for medical products and considered factors such as *economic viability of the recovery process, hygienic criticality, location of device, support structures, product criticality and product value* for the selection of design strategies. Sundin and Bras (2005) investigated remanufacturing facilities for household appliances and automotive parts on technical, economic aspects. Ijomah et al. (2007) explored product characteristics facilitating remanufacturing, which includes longer product lie, services, clean core, non-adhesive surfaces, threaded fasteners or shape memory fasteners. disassembly complexity, fastener accessibility, disassemblability, and recoverability. Fang et al. (2015) proposed design feature-based metrics for remanufacturability assessment, including *disassembly complexity, fastener accessibility, disassemblability, and recoverability*. Ijomah et al. (2007) worked on design for remanufacturability and studied various technical and not technical aspects influencing it. Design features in that study included product complexity, assembly type, design cycles, materials. Key technical barriers include fewer durable materials and poor disassemblability. Operational and technological aspect of remanufacturing is also seen to be influenced by the *returned product quality* and the contextual investigation is performed for the alternators and hedge trimmer (Yang et al., 2015). Zwolinski and Brissaud (2008) extracted internal and external factors affecting successful remanufacturing of 11 remanufactured product profiles.

- **Material-based Antecedents:** Yang et al. (2017) examined material condition for product design for remanufacturing. The authors included criteria such as *durability, cleanability, upgradability, cost, density, air emission, reliability of the reconditioned part, recyclability, wear and fatigue resistance* and considered five materials such as grey cast iron, Aluminum A356-t6, CGI ASTM A482 Grade 450 etc. Gaustad et al. (2018) discussed the role of circular economy strategies such as reuse, remanufacture, collection, lean principles, recycling and dematerialization to handle the critical material issues. The authors also explored firm-level strategies to handle it and these are *supplier diversification, more research and development, product re-design, strategic alliances with the supplier*. Mesa et al. (2020) developed an indicator named as material durability indicator that combines the advantages of mechanical durability and environmental foot print and applied it to prosthetic finger. Moorhouse et al. (2017) emphasized on the various brands that use *biodegradable and recycled plastic*. Mestre and Cooper (2017) highlighted the use of *recycled PET, hemp and cotton* for the fabrics and laces applied to Nike shoes.
- **Waste Utilization-based Antecedents**: It details as to how far the component and sub-assemblies from previous life-cycle or recycled content can be applied to a product. EoL products contain valuables in the form of material, component, function, and embodied energy. These values can be lost if the process adopted is not suited to the purpose of recovery. Ostlin et al. (2009) discussed supply and demand issues in three remanufacturing scenario – product remanufacturing, component remanufacturing, and component cannibalization. Factors such as the *mean product lifetime, rate of technical innovation, and failure rate of components* are seen to influence the return rate of products from end-of-use and end-of-life stage. In the case of EoL tire management, regrooving, and retreading extends the product usability and the introduction of recycled content improves the material circularity (Lonca et al., 2018). Recycled material for new tire production was received from two sources- recovered material from scrap tires generated by the production process and tires in their ultimate EoL phase and the authors applied material

circularity indicator (MCI). Few evaluation methods such as material flow analysis and simplified LCA has been applied to calculate the downstream material flow that went out for recovery operation, including remanufacturing and recycling of steel components (Diener and Tillman, 2015). Feriha et al. (2014) determined the best proportion of reclaimed rubber and crumb rubber as a part of the constituents used in the manufacturing of three different tire parts (tread, side wall, and inner liner). Simões et al. (2013) assessed the environmental advantages of substituting aluminum for a polymer composite in the manufacturing of a supporting structure for solar panels. Indicators such as material circularity indicator (MCI), longevity indicator give information on the material being reused or recycled and hence, it can be used to measure the sustainable resource use at the product level (Figge et al., 2018).

- **Loop-based Antecedents**: There are three forms of loop – reuse-based loop, remanufacture-based loop and recycle-based loop comes under circular services. The formation of circular loop is governed by several factors such as *material composition, service partners capability, collaborative innovation, product design complexity, extended producer responsibility (EPR), reprocessing technology, and infrastructural readiness* (Franco, 2017). Hansen and Revellio (2020) proposed circular loop architecture under four scenario – make, ally, outsourcing. The analysis suggests vertical integration with internal capacity building for *make-based circular coordination*; *alliance and strategic partnership for ally-based circular coordination*; *market-based coordination with several partners* for outsourcing-based circular coordination. For food products, *reuse and remanufacturing-based circular loops* can supply the waste material into the secondary market and recycling-based can generate fresh material for consumption (Vlajic et al., 2018). Household appliances and personal electronics face technological obsolescence quickly and few have shorter life spans and thus suitable material efficiency strategies are essential to be adopted and Dominish et al. (2018), in this regard, analyzed the strategies that create slow or narrow loop for metal containing products and focused on the distribution, sale, and use of the product as this phase is vital for sustainable consumption. Bridgens et al. (2019) considered *appropriate component lifetimes, role of the citizen in the circular economy, customer interaction, environmental life cycle assessment, and social impacts* to design close loop system. The effort is to capture value in the form of functional components and metals from mobile phone circuit boards. Sinha et al. (2016) applied two indicators, namely, loop leakage and loop efficiency to investigate the drivers for closing metal flow loop for global mobile phone product system. The factors considered were *mass of metal per phone, recovery rate, demand, price elasticity, cost of metal recovery, manufacturing cost, price of metals, phone use time* etc.
- **Supply Relationship-based Antecedents:** Close-loop formation entails the continuous supply of EoL component or sub-assembly for either refurbished/remanufactured product. Product life extension or resource recovery calls for a *collaborative approach* among the companies for the diverse product chain. Design variants for multiple life cycle change the product attributes and architecture, which may

influence the supply chain relation and structure. This influences the lead firm to rethink of its relationship with suppliers, recovery agencies, reverse logistics partner etc. The literature provides ample evidence of circular material flow (Batista et al., 2018) which is planned and organized by the focal firm that manufactures the product and reaches out to the customer with product uniqueness. The focal firm depends on its *value network* that is part of *pre-sales and post-sales strategy* and creates and delivers value to the customer (Koh et al., 2017). Ostlin et al. (2008) described supply chain relationship for the remanufacturing operation and these are *ownership-based, service-contract, direct-order, deposit-based, credit-based, buy-back and voluntary-based.* Remanufacturing entails the continuous flow of cores and critical components that necessitates supply chain cooperation from the original equipment manufacturer (OEMs) or core broker or local workshops or distributors of used products and Lind et al. (2014) observed a special contract named as reman-contract initiated by the OEMs.

Supply chain relationship has also been explored for the reverse flow of material. Field and Sroufe (2007) explored the implications of using recycled versus virgin materials for supply chain structure and supplier relationships and the broader effects on operations strategy in an evolving sustainable environment. *Supply chain integration* for circular resource flow has emerged as an important resource efficiency strategy for multiple products (Elia et al., 2020) to comply with environmental regulations and fulfill CE objectives. *Internal coordination and communication, collaboration with suppliers, logistics partner, workshops, and recovery agency, and distribution channel for collection and sorting* can meet the reverse flow objectives and complement the circular design of a product e.g; fast-moving consumer goods, computers, etc. (Simpson, 2010; Mishra et al., 2018; Insanic and Gadde, 2017). The literature discusses *operational and resource efficiencies, adaptability to new technology and process, and capability development* for environmental supply chain cooperation (Zhu et al. 2010). Supply chain partners are encouraged to get involved with a focal firm to improve their operational metrics and sustainability performances. The scholars have weighed the importance of adaptation in buyer-supplier relationships (Murfield and Esper, 2016; Mukherji and Francis, 2008). Miemczyk et al. (2016) concluded that *green raw materials, lower life cycle cost, market orientation can drive product stewardship for textile products*. The adaptation under customer pressure or self-developmental program can generate a positive impact on sustainability performance and its management is governed by relational conditions and the management behavior in response.

- **Reuse Services and Customer-based Antecedents**

The circular design and services are not enough to generate orientation for circular value without capturing the customer's preferences of product use, disposal and reuse. Wastling et al. (2018) coined a term known as circular behavior and proposed a model wherein provider ownership and user ownership are discussed in relation with use and post-use phase. The major activities governing the circular behavior when a consumer owns the product at the use phase are related to *product care, relationship, repair, engagement with product life extension services*. Whereas, in the post-use phase, *prolong replacement, correct disposal or recycling and reuse, product return* are the governing factors.

Literature has been prolific in product re-use studies. The reusability of a product depends on many factors including, *appearances, features, upgrading, take-back agreement* with the user at the point of sales, and environmental performance at the use phase. Kissling et al. (2012) discussed reuse services that cover *technical support, warranty, service fee if customer wants EoL services, user training, less distribution charges, safe recycling and disposal, collection and certification for compliant preparation for re-use or recycling to suppliers*. In another study related to disposal tendency, *consumer's environmental attitudes, product characteristics, and congruence between product and personality* influence the adoption (Sarigöllü et al., 2020). Several other actors such as *consumer experience with the product, consumer willingness to return the product, awareness of socio-economic and socio-environmental benefits of resource recovery, perceived quality, and perceived functional risk of the refurbished product with content of earlier life-cycle* are important determinants. The findings related to household electrical and electronics products suggest that users are oriented towards using those products which exhibit attractive features and reuse emerged as the best EoL scenario (Atlason et al., 2017). Agrawal and Singh (2019) considered internal and external factors that influence product disposition such as *consumer behavior, business environment, existing practices, environmental conditions, supply chain integration, government rules and regulations, product value, reverse logistics costs, quantity of retuned products, quality of returned products*. Mugge et al. (2017) focused on the *design for upgrade* to convince the customer of the refurbished smartphones such as *upgraded battery, updated appearance, upgraded performance, upgraded screen, upgraded camera* etc. Vanweelden et al. (2016) also considered *design for upgrade* for circular consumption of refurbished phones and identified product-related factors such as *product aesthetic durability, long life time, updated software, good battery* etc. Borrello et al. (2020) studied circular food propositioning strategies and focused on the retailer-consumer relationship. This work also examined the consumer knowledge, experience and attitude towards food recycling. Duan and Aloysius (2019) explored the effect of transparency about supply chain sustainability on consumers and investigated the effectiveness of message characteristics. The antecedent considered were *perceived quality, willingness-to-pay-premium*.

4.2 **Outcomes:** Based on the antecedents identified from the literature, there are outcomes highlighted in the literature. Here, we have categorized the findings into two parts – reuse and manufacturing economics, and design impact on value recreation. The figure-6 describes the various outcomes.

- **Reuse and Remanufacturing Economics:** EoL usage and its economics is vital for multiple life-cycle generation. Anthony and Cheung (2017) concluded that the recycling will be the preferred scenario for the brake pad of a car but it doesn't add benefit to the EoL product. Steeneck and Sarin (2017) found that cost was dependent on the numbers of core, part selected to be remanufactured, and the demand for remanufactured products. The outcome includes the mapping of product configuration with the policy structure, which are of types – Salvage, Remanufacture and Salvage, Remanufacture, and No Collection. Another outcome was related to the end-of-life vehicle (ELV) costing framework of Coates and Rahimifard (2008), who suggested that the movement of waste material for re-use, recovery of high value metals, and evaluation of dismantling scenario are important in ELV. Similar outcome was found in the case of end-of-life Tyre (ELT) recycling study by Landi et al. (2018) with decent economic advantage calculated with economic net present value (ENPV), economic rate of return (ERR) and benefit/cost ratio. Meng et al. (2019) concluded that recovery decision and sustainable performance are subject to market demand of secondary product. The authors concluded that tire textile fibres can be a substitute to the reinforcement cellulose commonly used in asphalts and performed a cost-benefit analysis. In a scenario of certain demand for remanufactured product, economic and environmental benefits increase due to increase in component demand. Du et al. (2012) concluded that machine tool remanufacturing is technologically and economically feasible. The technology feasibility is evaluated in terms of the feasibility of disassembly, cleaning, inspection and sorting, part reconditioning, machine upgrading and reassembly operation, whereas, the economic feasibility is evaluated from aspect of remanufacturing cost.
- **Design Impact on Value Recreation:** From the analysis, it is revealed that adoption of design variant such as design for component reuse, refurbishment, and remanufacturing has impact on circular value. Vlajic et al. (2016) proposed that circular flow takes place under any residual value and suitable measures will be chosen accordingly if the residual value is high. Parajuly and Wenzel (2017) concluded that the reuse of e-waste components such as cables, switches, displays, electromotors and transformers can improve the material efficiency and commonalities between various robotic vacuum cleaners in terms of brushes, wires, casing bins can be utilized to segregate and sort the components before processing. Thus, an efficient presorting and testing system, organized collection system, and family centric processing of e-waste can improve EoL management. Vanegas et al. (2018) calculated disassemblability index and argued that it can be utilized for eco-design improvements. Franco (2019) concluded that short-lived products, compared to long-lived ones, are highly disposed of and collected due to faster replacement time. Another finding was related to long-life products, wherein product returns are fewer in quantity because they are distributed over a longer time period.

  Few different terminologies have been observed in the multiple life cycle design such as design for circularity, design for product longevity, and design for dismantling and its influence on value creation.

Vanweelden et al. (2016) stressed on the design for circularity in the original product design to create multiple life cycle and highlighted the role of enhanced features with requisition features and functionality in making a strong refurbished product basis. The author contended that product related factors are of huge importance in convincing the consumer to buy a refurbished product. Dominish et al. (2018) established that product longevity are the most significant strategies for material efficiency of metal-containing products in Australia. Remanufacturing and component reuse are of limited reuse as they are only suitable for durable product types and standardized components. Kane et al. (2018) concluded with a diagram to show the relationship between product criticality and value. The authors showed that in case of low value and low critical products, the suitable circular design strategies are design for separation, design for recycling and design for waste management. For high value and low product criticality, the strategies are design for refurbishment and design for remanufacturing. Ardente et al. (2015) recommended that design for dismantling of some key components, restricted use of some blowing agents, and provision of information with the labelling of the insulation foams to increase the recovery potential. To support the above life cycle extension exercises for value recreation, Hansen and Revello (2019) found that circular loop architectures with high degree of vertical integration are more beneficial and in absence of circular design, the full value creation cannot be achieved, particularly for repair and refurbishing activities. Laurenti et al. (2015) advised that information technology should adapt to render help to designers consider parameters for effective circularity, end-of-waste, and limiting hibernation of resources in the use phase.

- **Environmental Impact**: Product life extension is seen to have an impact on environment. The study can be characterized into three parts – consumer use pattern, remanufacturing operation, and tack-back scenario. Pérez-Belis et al. (2017) took vacuum cleaner as case study and observed that consumer use behavior mostly affects the environmental sustainability. The analysis further recommended that the consumers can use vacuum cleaners occasionally, using and repairing them until the end of their life span to have an energy efficient vacuum cleaner. Van Loon and Van Wassenhove (2017) estimated environmental impact of remanufacturing of chassis product and concluded that remanufacturing, where components are reused and their lifespan extended, has a positive effect on the environment. Krystofik and Gaustad (2018) assessed the environmental impact of tying product (printer and cartridges) under three tack back scenario (no collection, collective take-back, individual take-back) and found that individual take-back with 90% environmental savings has the least environmental damage in terms of dollars.

To summarize this section, reuse and remanufacturing economics, design impact on circular value, and environmental impact are the outcomes of product recovery efforts. These convey about how cost, material input into another product, design selection, product criticality, and usage intensity and operational impact on environment are the final choices of decision makers.

4.3 Challenges

Besides clear influence of antecedents on the various outcomes, cyclicity of product, components and materials face some challenges. Following are three challenges that we identified from the literature.

- **Product Standardization and Circularity:** The design of consumer, luxury, and special products changes rapidly and is driven by market demand. Fashion products stay for quite a short time in the market and there are many traditional practices of fashion design, cutting, assembly and finishing in the developing countries. There are many consumer products such as handcrafts, utensils, fashion clothes etc. whose features and functionality are not standardized. Material of such products might be recoverable at the end-of-life, but sometimes, they fail to adhere to the regulations. On another hand, mobile phones design and its EoL fate are strictly regulated under the waste of electrical and electronics equipment (WEEE) to minimize the environmental degeneration (Parajuly and Wenzel, 2017). Lack of standardization can restrict the part and component rom reuse as they mayn't be compatible with the refurbished or remanufactured product for the same application (Dominish et al., 2018). Parida et al. (2019) discussed standardization mechanism to implement circular economy and opined that firms need to co-develop technology standard to acquire eco-friendly materials with the key partners and strive for formal certification. Organizations need to adopt standardization process (BS 8001:2017) to create a regenerative system of parts and components. Few standard i.e. design for disassembly (DfD) proposed by European Commission is aimed for easy maintenance, repair, reuse, and recovery of components and materials by small adjustment in assembly and joining process (Talens Peiro et al., 2017). Adoption of DfD process can be a vital step towards material efficiency and can facilitate the design standardization. Parajuly et al. (2016) expressed the challenges in terms of improper product design, use of connectors, placement of key components, and material compatibility. Laurenti et al. (2015) discussed challenges to sustainability in electronic products in terms of (i) product and consumption redundancies; (ii) embodied environmental and social impacts occurring distant in time and space from the point of consumption; and (iii) production and consumption dynamics. Sinha et al. (2016) found in the analysis that longer life-span of mobile phones (i.e., phone use time) decreases loop leakage and increases loop efficiency. Sinha et al. (2016) observed in the analysis of global mobile phone that the informal recycling in developing countries resulted in lower resource recovery and higher systems leakage. Other drivers, such as manufacturing cost, export cost, and utility of a refurbished phone didn't add much to loop leakage or loop efficiency.

- **Product Obsolescence**: Chouinard et al. (2019) in their study of mechatronic products, observed that prolonged use of product with regular updates is not easy to happen. They reasoned that certain component is not supplied on time and hence, the products are either withdrawn or discontinued. Other finding is related to stable norms and regulations for the product. These regulations are strict and manufacturers can't redesign these products with certain changes to the standard. The product manufacturing process is time-consuming and it's difficult to introduce the product in a short time into the market. Pal and Gander (2018) found that for environmental value with efficiency-based narrowing logic are not realized as traditional design thinking creates hinderances for scalability for fashion products. These products are of short life-span and prone to changes in cultural and social landscape with the time. Thus, life extension or prolonged use logic doesn't work here for the fashion products due to conflicting scenario of customer value and producer benefits. Bridgens et al. (2019) summarized that technological obsolescence is mitigated by upgradation of the functional components, whereas cosmetic or stylistic obsolescence is controlled by stimulating emotional attachment between the owner and the exterior of the device.
- **Business Model Innovation** – Multiple life cycle is not easy to achieve as it requires system thinking which integrates all stakeholders to create and deliver value in terms of product and service. Customer involvement in design exercise and design improvement, if not organized well, can't produce the desired outcome. Thus, customer interface and value network are crucial for product circularity. Consumer needs and behavioral change are other tensions that must be given attention before proposing and creating value. Geissdoerfer et al. (2018) defined business model innovation as the "conceptualization and implementation of new business models" and raised the problem of failure of business model innovation in his review. Today, the value propositions are not indicated in clear words to the customer in terms of features, material and services and they fail to perform in a specific market segment. Consumers feel difficulty to attach to the product and doesn't recognize direct and indirect benefits from a specific product and related service. Baldassarre et al. (2017) depicted value proposition framework with three elements – stakeholder network, sustainability problem, and product/service. Here, the authors raised the importance of user-driven innovation to create business opportunities and linked it to business model innovation. Currently, multiple life cycle-oriented specific business model hardly exists in the literature. Kissling et al. (2012) observed challenges in reuse-oriented business model and these are related to market where they acquire the EoL and redistribute the product, size of the supply, and the finance requirement.

To summarize this section, lack of standardization is the biggest challenge in achieving the multiple life cycle as restricts the designer to include design for disassembly and reassembly in the product. In order to extend the life cycle, adoption of suitable business model is important, which acquires new resources and develop relationship with key partners to execute key activities. Product obsolescence depends on current technological trend, scalability, and policies toward selling of upgraded product and thus it hinders the multiple life cycle generation.

4.4 Benefits

The major benefits that literature highlights are *used or recycled material as input, customer relation, long lasting products, social and environmental benefits*. Manninen et al. (2018) mentioned *reduced import dependence on natural resources, efficient use of natural resources, minimized overall energy and water use, closure of material loops, sustainably sourced raw materials, reduced emissions, and less pollution*. Steeneck and Sarin (2018) focused on the environmental and economic benefits while minimizing life cycle cost. Campbell-Johnston et al. (2020) studied tire recycling in the Netherlands and evaluated the system's circularity and advised for the improvement of recovery and sustainability targets that goes beyond the limits of a single product life-cycle. Blomsma and Tennant (2020) described intra-state and inter-state cycling for electronic products. The major benefits are reduced burden on virgin material and intensifying loop creation etc. Hopkinson et al. (2020) identified sustainable values with diverse case studies that include *design for durability, improved repairability and maintainability, recyclable content, dedicated partner network* for EoL acquisition and treatment. Vlajic et al. (2018) recommended that loop creation provides social benefits by redistributing the food surplus and environmental benefits by reducing the food waste. Atlason et al. (2018) mentioned social and environmental benefits when a user shows willingness to dispose the electrical and electronics product at the end-of-life. Du et al. (2012) indicated environmental benefits of machine tool remanufacturing in terms of energy saving, material saving and pollution reduction. Bridgens et al. (2019) highlighted environmental and economic benefits in mobile phone upgrading. Socio-economic enterprises have significant contribution towards loop operation, product cyclicity and life cycle extension of mobile phone (Sinha et al., 2016). Re-use of consumer products generate numerous social and environmental advantages including, employment and training opportunities for people with disabilities or the long-term unemployed (Kissling et al. 2013). It can be inferred from the above highlights of the contribution that multiple life cycle offers several benefits including reduced environmental impact, socio-economic value, and increased resource usage.

5.0 Discussion

Reduced product life time is one of the problems in the current production and consumption pattern. This has resulted in the flood of waste product and component at the EoL, leading to more burden on natural resources and environment. Fast changing technology cycles such smart phones, computers, washing machines, are giving plenty of option to consumers to purchase the product on the basis of price, brand,

and features. Consumer demand for innovative products have also been a cause of worry and tensions as it cannibalizes other products. It is also seen that consumers quickly get bored with the rapid entry of innovative products in the same segment. This results in making a product less usable and short life-cycled. In such scenario, these products find the scrap yard easily. To overcome the problem of short life-cycle and quick obsolescence, multiple life cycle design provides opportunity to either extend the life or recover the usable portion for another life cycle. Design for sustainability combines several DfX principles catering to both forward and reverse supply chain activity and provides solution to problem of material waste and quick product obsolescence. We observed that EoL planning at design stage is crucial for a product as recovery decision has influences on cost, quantity and homogeneity in product return. Scholars have improved the product design to imbibe the features that enable the firm to recover the expended resources after end-of-use and end-of-life. Noted strategies discussed in the literature are modularization and easy disassembling, recyclable materials, increased product use, cascaded use of recovered materials, longer product life, and product life extension with upgrade and remanufacturing. Laptops, notebooks, desktop, mobile phones have short life cycle and this, refurbishment/upgradation and remanufacturing are the most viable life extension strategy. On another hand, sustainability integration in product portfolio requires the involvement of various internal and external stakeholders in the early stages of product development to translate the customer requirements into the features and services. We have observed that few articles have explicitly mentioned them and explained its facets. Others were focused on the value that these principles create. For instance, Atasu and Souza (2013) mentioned about durable products but didn’t mention the particular DfS principles. Articles belonging to recovery decisions didn’t explicitly mention about DfS rather they discussed benefits in terms of cost and energy savings if a manufacturer opts for that alternative. Recovery decisions and product design seem to be interconnected from the literature synthesis and it appears that parameters and configuration selected in the design stage can become a determinant for a particular outcome. Thus, a proper EoL strategy that estimates the cost, a quantity of material recovery and suggests the most suitable recovery alternatives among recycling, refurbishment, and remanufacturing has to be formalized. It is observed that product standardization sets the stage of product recovery and holds potential to create values for the customer – standard type value creation, customized type value creation, solution co-creation-type value creation, and solution option-type value creation (Oh et al., 2015). But few literatures emphasize its relevance. Bocken et al. (2015) advocated the design for standardization and compatibility to create parts that fit with the product easily and disassembly operation can be performed. This can be regarded as strategy to ensure the smooth flow of materials and components for reuse. Vanegas et al. (2018) adopted design for disassembly for flat panel displays and explained the same. Franco (2019) connected DfS principles such as design for long-life, design for ease and maintenance, design for disassembly and reassembly to circular design of slowing and closing resource loops for household appliances. Product criticalities and value is very vital and it has been examined for medical products. There are few challenges in terms of reuse content or recyclable content in the upgraded product and it has to be tested under different scenario. Critical components identification in refrigerators, microwave, and washing machines may help the designers to compare the cost of recovery alternatives and cost of maintenance. Other products' design needs to be reviewed and more exploration in terms of application of DfX principles is necessary.

Loop formation for value recreation depends upon the type of product and residual value that it retains after use or after life. Large household appliances have high residual value after use; hence it has good potential to contribute to repair and upgrade circular based loop (Kissling et al., 2013). Literature has shown the influences of institutional policy that pave the way for the firm to expand the value network. Countries like China, US, UK, Germany have designed the waste policy for different product segments and innovated models of value recreating processes. But there are few works that connect policy to product design. Apart from that, literature doesn't show up the policy implication of improvement in product design. This is a major lacuna in the knowledge about the multiple life cycle products. Ardente et al. (2015) adopted design for disassembly and design for recycling for commercial refrigerators and the main aim is to bring synergies between product design and waste policies to improve the recyclability potential of the product. Some products deserve unique treatments post-consumption, and thus design must address those concerns as per norms. For instance, design for disassembly and design for recycling is important for glass products, insulating material, and elastomer products, and thus product design should be per the regulations. Medical products have special elements such as MRI scanners, CT scans, Biopsy devices, and hence, there is a need to develop a waste policy uniquely for such critical elements.

Product repair and maintenance has also been supported by IT, big data, IoT based devices and digital twin. The data generated in the use phase are shared with the service provider and manufacturer over a cloud technology platform. This technology is meant to integrate production resources and capability to support service pool for maintenance of production resources of waste electrical and electronics (Wang and Wang, 2017) and allows service engineers to reconfigure or upgrade the product or applications in case of smart car utilizing the concept of virtual product twins and IoT platform (Abramovici et al., 2019). Digital twin (Wang and Wang, 2019) has been adopted to recycle, recover, and remanufacture the waste electrical and electronic equipment (WEEE). Life cycle information collection is feasible for the point of care devices (Glucometers) with the IoT devices and it helps improve the level of servitization and extend the usability of the product (Adeogun et al., 2010). In the case of aircraft, the maintenance, repair, and overhaul (MRO) service model (Zhu et al., 2012) has been proposed to integrate product development with maintenance and service operation. Apart from sensor embedment, big data played a major role in achieving the current servitization capability (Zhang et al., 2017). Information technology is applied to improve product traceability is important in the supply chain and in this regard, a process-based reference model and information system have been applied to better manage and control the quantity and quality of the supply network of the Motorcycle (Kuo et al., 2012).

5.1 Managerial Insights

The review analysis revealed that recovery planning is spurred by the managerial capability for the choice of a suitable recovery method. The firms can develop resource and network partners to organize the take-back with collection agencies and independent remanufacturers. Managers need to carefully select the appropriate model for the price of new and remanufactured products keeping in mind return uncertainty, quality, and volume of used products. The recovery planning hinted towards the measurement of the circular potentiality of a product. The various design for recovery strategies identified from the literature can guide the managers in designing the product shapes, inter-connection between components, and features. The market for a new and remanufactured product depends on the consumer knowledge and orientation towards sustainability apart from the pricing and quality of refurbished/remanufactured product that influences their decision. Some forces exist and compete in the market for recoverable products. OEMs have to carefully design the supply chain and collaborate with the collection and distribution channels for the returned product.

Supply-based antecedents denotes how to decouple from resource consumption and it allows the waste or used product to reinter into the system as a fresh input, reducing the supply uncertainty of virgin material. Component or metal which are not corroded or worn out can be extracted and its circulation improves resource efficiency. To support the circulation, managers must think about the economic advantage and socio-cultural impact that the product re-use creates. Product designers can go for the design for multiple cycles with secondary raw material and components as a new source of value creation if the institution sets up the business environment for sellers of the secondary products. It is also the responsibility of a firm to increase awareness about the circular features of a product and the firm should adopt either top-down or bottom-up approaches to co-create value with customers. Firms are largely influenced by the customer dispositions towards the EoL treatment of used products. Thus, a proper EoL strategy that estimates the cost, carbon footprint, and quantity of material recovery suggests the most suitable recovery alternatives among recycling, refurbishment, and remanufacturing.

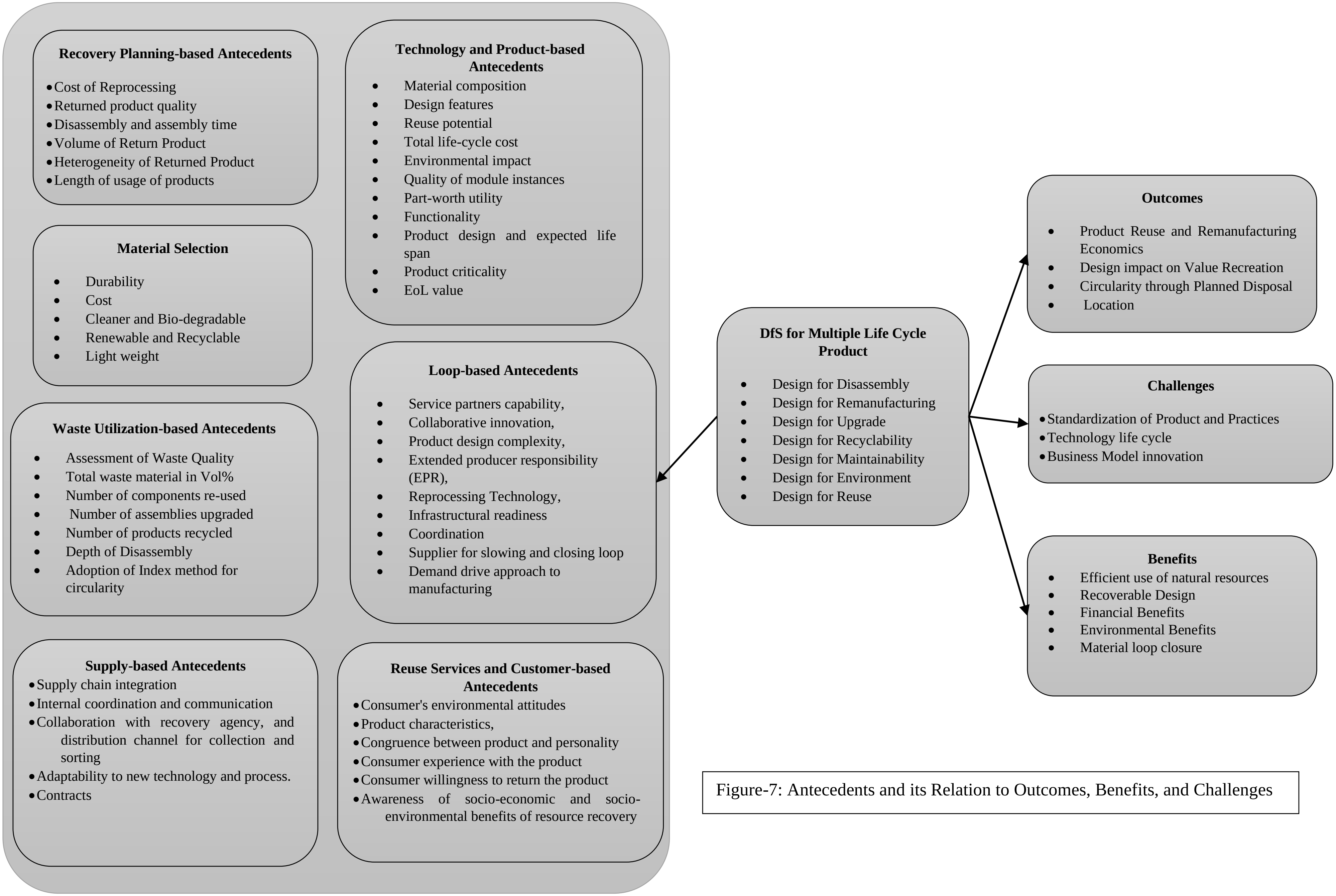
6.0 Future Work

This review revealed that product reuse and remanufacturing economics is inherently connected to product design and disassembly complexity. Product design in circular economy includes design for disassembly and reassembly, design for component reuse, design for upgrade, design for remanufacturing. These are deemed to be EoL path that a retired product is expected to follow. Though, disassembly planning, sequencing, and yield uncertainty has been covered (Ma et al., 2011; Sodhi et al., 2004; Wang et al., 2017) in depth in the literature, but consumer knowledge about the disassembly operation, inclusion criteria of specific component from the previous life cycle, and the conflict between disassembly and reassembly operation is yet to be explored. Moreover, disassembly complexity has bearing upon the type of component to be recovered and its current state of quality and how it has been designed with the perspective of environmental impact. The study can be directed at the interface of design for disassembly and design for reassembly with the design for modularity and design for reliability. For example, a refrigerator which is mature in terms of technology now and have long life cycle, remanufacturing can't be applicable in this case. The most viable EoL alternative is upgradation of the technology or replacement of condenser which has 10 years of life cycle. Bakker et al. (2014) pointed out that design for recycling is good for the refrigerator as this product become less energy-efficient with the use and as they age, the frequent change of coolant pipes and condenser occurs. The future study needs to consider these energy consumption cycle of refrigerators, washing machine during the design stage.

Literature have produced insights related to circularity assessment or resource efficiency indicator to estimate how much a resource is still in use for a length of time (longevity) and how much resources move in same or other loop different to the original one (circularity). While the many consumer products have been analyzed for profitable EoL solutions, we feel that circularity assessment is not dealt together with the reuse and remanufacturing implications. We still have inadequate knowledge as to how much a resource is used for another life cycle and what technological and economic criteria is applied to calculate the overall economics. The above problem scenario becomes more complex when we have a large equipment that utilizes different material and whose disassembly sequence involves large number of small components. For instance, 4-wheeler, which has approximately 30,000 parts made of different material grades. The partial or full destructive disassembly planning are supposed to entail the simultaneous consideration of parts or components which are designed for either component reuse and or design for upgrades, which the current study hasn't considered yet. Many parts are still designed without giving proper thought of its recovery method. It is also observed that DfX method is less applied at the beginning and selection of proper assembly method is still immature. We have few numbers of articles that capture this angle. The work should focus on the selection of design variant and modularization method to attain multiple life cycle (Ma and Kremer, 2016).

Second frontier is related to supply relationship and supplier participation in multiple life cycle. The analysis highlighted that remanufacturing is adequately considered with respect to supplier involvement after EoL stage. According to topology of remanufacturing proposed by Abbey and Guide Jr. (2018), multiple life cycle products require vertical integration of forward and reverse supply chain with integrated product acquisition management. This nature of supply chain configuration is seldom studied except Hansen and Revello (2020) analysis of circular loop architecture. More studied is needed to explore the antecedents and outcomes for different product in a scenario of integrated supply chain. Many companies such as Xerox make a contractual agreement with the third-party remanufacturer to acquire, inspect and reprocess the EoL product. Such studies are rare in literature and we need to see bright and dark side of product life cycle extension through third-party remanufacturing. When we use a recyclable content in a product, it has to be supplied by a firm in a contractual agreement or a vertically integrated. The analysis couldn’t find a solution when a vertically integrated firms use recyclable content for a product.

Thirdly, waste reutilization is challenging and its reuse scenario is not fully captured. Tire and textile recycling is studied in detail and impact of reuse on environment is well established. But, risk identification and analysis for waste reuse is still not considered for many household products. This has to be carefully evaluated keeping in mind the economic impact. In this context, circularity indicator also has limitations. The employment of indicators for slowing loops and closing loops are not clearly established. In the refurbished product cases, these indicators will need to be modified as many materials and components will be scraped due to malfunctioning will go to open-loop for cascaded use. Hence, these indicators will need to be adaptive for various products as they vary in characteristics of exhibiting recyclablecontent.



Recovery Planning-based Antecedents

- Cost of Reprocessing
- Returned product quality
- Disassembly and assembly time
- Volume of Return Product
- Heterogeneity of Returned Product
- Length of usage of products

Material Selection

- Durability
- Cost
- Cleaner and Bio-degradable
- Renewable and Recyclable
- Light weight

Waste Utilization-based Antecedents

- Assessment of Waste Quality
- Total waste material in Vol%
- Number of components re-used
- Number of assemblies upgraded
- Number of products recycled
- Depth of Disassembly
- Adoption of Index method for circularity

Supply-based Antecedents

- Supply chain integration
- Internal coordination and communication
- Collaboration with recovery agency, and distribution channel for collection and sorting
- Adaptability to new technology and process.
- Contracts

Technology and Product-based Antecedents

- Material composition
- Design features
- Reuse potential
- Total life-cycle cost
- Environmental impact
- Quality of module instances
- Part-worth utility
- Functionality
- Product design and expected life span
- Product criticality
- EoL value

Loop-based Antecedents

- Service partners capability,
- Collaborative innovation,
- Product design complexity,
- Extended producer responsibility (EPR),
- Reprocessing Technology,
- Infrastructural readiness
- Coordination
- Supplier for slowing and closing loop
- Demand drive approach to manufacturing

Reuse Services and Customer-based Antecedents

- Consumer's environmental attitudes
- Product characteristics,
- Congruence between product and personality
- Consumer experience with the product
- Consumer willingness to return the product
- Awareness of socio-economic and socio-environmental benefits of resource recovery

DfS for Multiple Life Cycle Product

- Design for Disassembly
- Design for Remanufacturing
- Design for Upgrade
- Design for Recyclability
- Design for Maintainability
- Design for Environment
- Design for Reuse

Outcomes

- Product Reuse and Remanufacturing Economics
- Design impact on Value Recreation
- Circularity through Planned Disposal
- Location

Challenges

- Standardization of Product and Practices
- Technology life cycle
- Business Model innovation

Benefits

- Efficient use of natural resources
- Recoverable Design
- Financial Benefits
- Environmental Benefits
- Material loop closure

Figure-7: Antecedents and its Relation to Outcomes, Benefits, and Challenges

7. Conclusions

This paper sets out to explore the antecedents, outcomes, benefits, and challenges in multiple life cycle product. In total, we examined 87 papers between 2003-2020 descriptively and thematically. In the descriptive analysis, the articles were analyzed according to publication trend over time, number of products, and the research methodology perspective. We have studied those products which have been designed with the thinking of reusing, refurbishing and remanufacturing after EoU or EoL and its economic and environmental impact. This study contributes to multiple life cycle or circular product literature in two ways. Firstly, this review identifies and categorizes the antecedents, outcomes, benefits and challenges of multiple life cycle product. In this regard, we have observed that design for sustainability plays an integrative role in the generation of multiple life cycle and connects antecedents to outcomes and benefits. DfS also poses challenges that has to be kept in mind while designing and conceptualizing a product. The integrative role of DfS turns waste into resources when it is applied as early design attributes. Second contribution is related to challenges at the both product and firm level. At the product level, we highlighted the product standardization and circularity and product obsolescence. At the firm level, we stressed on business model innovation for multiple life cycle products. Finally, we discussed current research gaps and future work directions based on synthesis of literature. Here, it is important to highlight that product design strategies need to be expanded to cover consumer behavior and scholars must explore the perspective of distributor-retailer-user triad in closing the loop by adopting design for sustainable behavior (Bhamra et al., 2011). It is also observed that studies on multiple life-cycle product and corresponding business model needs to be expanded to cover both economic and environmental impact.

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