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Review

A Review on the Lifecycle Strategies Enhancing Remanufacturing

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Abstract: Remanufacturing is a domain that has increasingly been exploited during recent years due to its numerous advantages and the increasing need for society to promote a circular economy leading to sustainability. Remanufacturing is one of the main end-of-life (EoL) options that can lead to a circular economy. There is therefore a strong need to prioritize this option over other available options at the end-of-life stage of a product because it is the only recovery option that maintains the same quality as that of a new product. This review focuses on the different lifecycle strategies that can help improve remanufacturing; in other words, the various strategies prior to, during or after the end-of-life of a product that can increase the chances of that product being remanufactured rather than being recycled or disposed of after its end-of-use. The emergence of the fourth industrial revolution, also known as industry 4.0 (I4.0), will help enhance data acquisition and sharing between different stages in the supply chain, as well boost smart remanufacturing techniques. This review examines how strategies like design for remanufacturing (DfRem), remaining useful life (RUL), product service system (PSS), closed-loop supply chain (CLSC), smart remanufacturing, EoL product collection and reverse logistics (RL) can enhance remanufacturing. We should bear in mind that not all products can be remanufactured, so other options are also considered. This review mainly focuses on products that can be remanufactured. For this review, we used 181 research papers from three databases; Science Direct, Web of Science and Scopus.

Keywords: remanufacturing; end-of-life (EoL); circular economy (CE); closed-loop supply chain (CLSC); design for remanufacturing (DfRem); remaining useful life (RUL)

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Citation: Fofou, R.F.; Jiang, Z.; Wang, Y. A Review on the Lifecycle Strategies Enhancing Remanufacturing. *Appl. Sci.* **2021**, *11*, 5937. https://doi.org/10.3390/app11135937

Academic Editor: Emanuele Carpanzano

Received: 25 May 2021
Accepted: 22 June 2021
Published: 25 June 2021

1. Introduction

Remanufacturing is an end-of-life (EoL) recovery option whereby returned products are disassembled, cleaned, have all parts inspected, have their repairable parts fixed and the rest replaced with new ones and then are finally reassembled and tested to restore them as good-as-new products [1]. The EoL recovery options are very critical to promoting a circular economy and a sustainable environment. Other recovery options at the EoL stage include reuse, refurbishment, recycling, incineration and landfill. As explained by [2], there is a need to move towards sustainable development and this includes reducing the pollution caused at the EoL stage of products by using any of the above mentioned recovery options. Among these options, remanufacturing is the only recovery option that provides the same quality, performance and warranty as that of the brand new product [3]. For any engineering system to be remanufactured, there needs to be an assessment of the remanufacturability of the system [4]. Research has also been carried out on the assessment of the sustainability of remanufactured products, with a case study on computers [5]. Remanufacturing is the next great opportunity for boosting the circular economy and attaining sustainability [6]. The benefits of remanufacturing with regard to the three pillars of sustainable development—environment, economy and society—have been explained by various authors [7–10]. In reality, most products will eventually end up being recycled, incinerated or landfill, but remanufacturing ensures that the product can have multiple lifecycles before getting to the stage where it has no remaining useful life (RUL) and thereby can be recycled, which is the final recovery option. The environmental and economic assessments in remanufacturing have been well evaluated by [11] and the economic benefits in terms of cost savings have been analyzed by [12]. The environmental benefits of remanufacturing have a great role to play with regard to attaining sustainability [13] and a case study on a truck injector case has been used to demonstrate these benefits. The profit margins of remanufacturing are also very attractive, with final remanufactured products being sold at 40% lower prices than those of new products and making profits of about 20% [14]. This is quite outstanding and shows how beneficial this domain is for all the three pillars of sustainability; namely, they are environmentally friendly, very economic and good for society as well. In terms of social benefits, remanufacturing can create job opportunities as well as new skills due to the flexible nature of its processes, such as disassembling, testing and re-assembling.

Remanufacturing is nowadays more common in the transport sectors, which have capital intensive and durable products with relatively longer product lifecycles ((USITC) [15]. These transport sectors include the automobile, aerospace/aircraft, ship building and railway industries. Hammond et al. [16] pointed out the issues faced during the remanufacture of automobile parts. Due to their longer lifecycles and higher values, remanufacturing is the most economic and reasonable recovery option [17]. In the aerospace industry, original equipment manufacturers (OEMs) are strongly involved in the remanufacturing of their products to avoid competition from third party remanufacturers, as well as to preserve the image of their products (Centre of Remanufacturing and Reuse (CRR)). High performance products, such as caterpillars' heavy duty engines, can be remanufactured as many as six times before they come to be recycled [10]. A roadmap to predict the cost at the EoL stage of a product using the various stages in the supply chain management can be conceived at the early stage of the product to ensure cleaner production [18]. These stages consist of the planning, sourcing, production, delivery and returns of products.

Remanufacturing also encounters various challenges and uncertainties in its various stages, including supply chain management (SCM), disassembly, testing, reassembly and so on [19–21]. Some of the challenges include: a lack of legislation and standards, limited lifecycle design awareness, a lack of a sufficient market and core supply, skill and technology challenges and limited information sharing, variation in the state of the returned products, the need for reverse logistics, uncertainties in the timing and quantities of returned cores, the difficulty of material matching, balancing return cores with demand, the uncertainty of material routings and the disassembly of cores. Moreover, there is concern about consumers' acceptance of remanufactured products due to the fear of purchasing low quality products. A study on the prediction of customer demand for remanufactured products was undertaken by [22]. This limitation can be tackled if the quality of the product is guaranteed by the remanufacturer. Nonetheless, there is more to be happy about the advantages that remanufacturing has in terms of economic, social and environmental impacts towards attaining sustainability. Some of these advantages include: preserving product quality, lower use of energy and raw materials, offering more flexibility and more options in terms of the process planning and market supply, greatly reduced pollution and increased product lifecycle [23]. In addition, remanufacturing usually requires less capital compared to manufacturing and also offers job opportunities and new skills.

Remanufacturing promotes a circular economy and there is a need to find different strategies that will favor remanufacturing at the EoL stage of a product. A multiple lifecycle-based approach to sustainable product configuration design has been explained in detail by [24]. This review points out the various strategies that can facilitate remanufacturing when products arrive at their end-of-life stage. These strategies start from the production planning process and the decisions made at that time have a great effect on the lifecycle of the product. Factors like remaining useful life (RUL), reverse logistics (RL), design for remanufacturing (DfRem), closed-loop supply chain (CLSC), EoL product collection, product service system, data acquisition and sharing and pre-decision remanufacturing timing are explained and analyzed in this review. Recent trends that can also increase the remanufacturability of a product at the end-of-life stage are also discussed.

The main objective of this review paper is to point out the various strategies that can increase the rate of remanufacturing during the product's lifecycle. This is because remanufacturing is gaining more interest all over the world due to its numerous advantages mentioned above. There are certain strategies (existing and non-existing) that can be implemented into the lifecycle of a product so as to increase the remanufacturability of that product at the end-of-life stage. In airplane engine remanufacturing, as an example, the production sector has to apply the design for disassembly and remanufacturing factors in the production planning so as to facilitate the remanufacturing process. As the engine wears out during its lifecycle, it is very crucial to recover the product in time so that it still has some RUL which make its remanufacturing possible. In this example, the factors mentioned are design for disassembling and remanufacturing and in-time recovery.

2. Methodology

In order to better outline the strategies that enhance remanufacturing, a systematic review was conducted. This systematic approach was used to enable the review process to be reproduced, which is a key quality when completing a review of this type [25].The area of investigation did not focus on a specific strategy but was aimed at sorting out the strategies, highlighting the role they play in enhancing remanufacturing and how they have evolved throughout the years. For this review paper, the collection of information was done in several stages with articles selected from databases using keywords. As recommended by Thomé et al. [26], the papers for our review were selected from Science Direct, Web of Science and Scopus, which have all been widely accepted by the likes of [27,28]. This review was done with no filter applied to the publication year and study type so as to avoid bias [29].

To avoid missing important literature due to labeling of the same concept, search terms included "circular economy", "reverse logistics", "closed-loop supply chain", "EoL product collection", "smart remanufacturing" and "pre-determined remanufacturing timing" which were each matched with "remanufacturing". Figure 1 below summarizes the inclusion and exclusion criteria and the processing, cleansing and assessment of the literature. The inclusion of at least one key word in the body of the text was critical to its retention. The articles that contained "remanufacturing" but not the other keywords in the main body of the text were not automatically excluded. This is because certain articles talked about some lifecycle strategies but did not mention them in the keywords. However, articles that did not contain any of the keywords in the abstract and conclusion were excluded. Non-English articles, non-journal articles and conference articles were excluded. After using Endnote X8 to remove duplications, 512 potentially relevant articles were retrieved from between 1995 and May 2021.

A total of 331 of the 512 articles were cleansed for coding in NVivo12 (a qualitative data analysis software) to provide a quantitative assessment of contribution based on the coverage of the database search keywords in addition to the strategies that enhance remanufacturing. The software was used to extract literature affiliated to the various keywords in the 512 selected articles. After full text reading and further screening was done, articles which did not stress any of the keywords were discarded. Finally, 181 relevant articles are retained for this review paper.

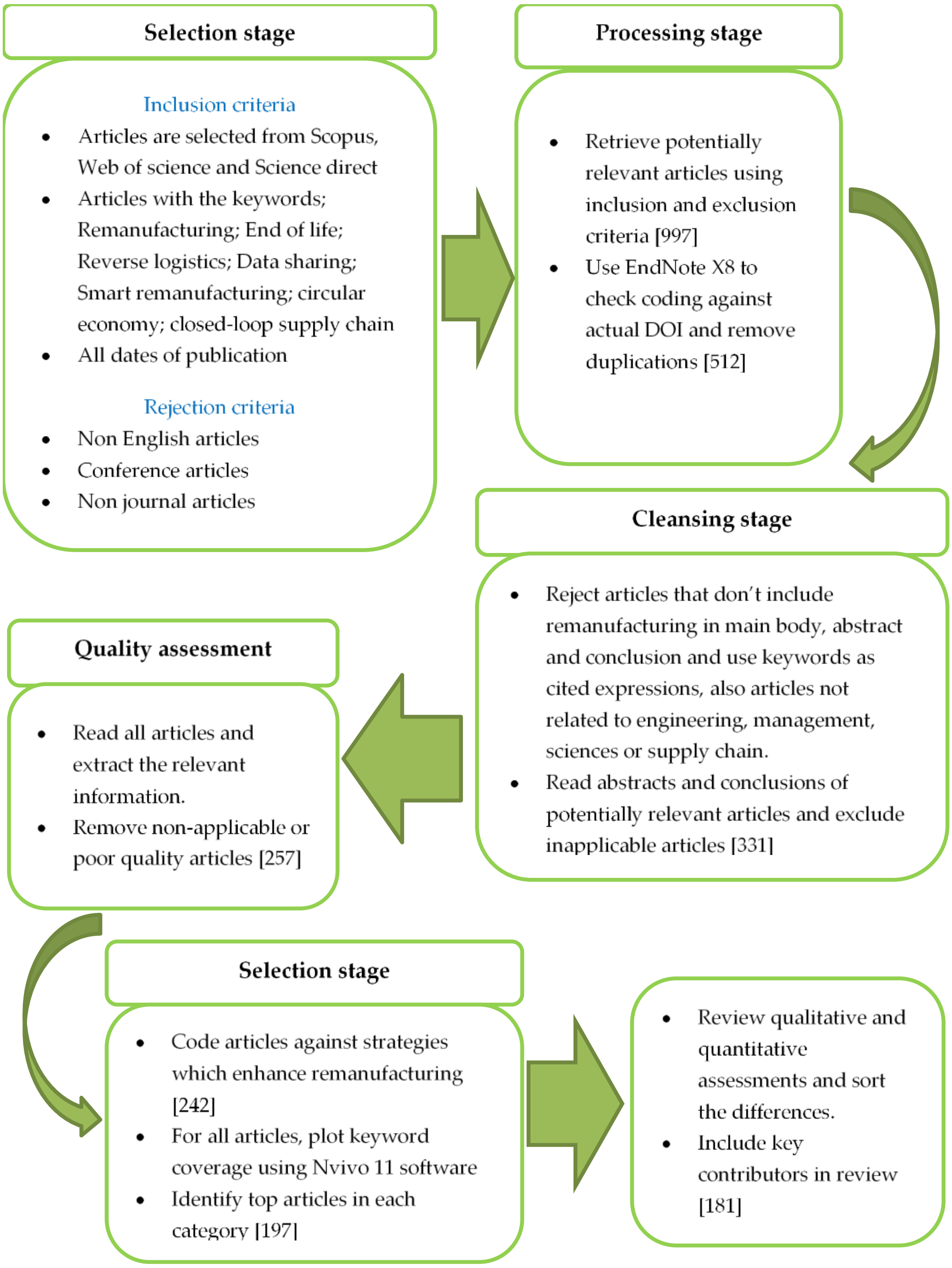

Figure 1. Literature review process.

Figure 2 below shows the distribution of the relevant papers over the past years. It can be observed that most of the relevant papers appeared after 2010. This is due to the fact that remanufacturing has been gaining more attention over the past ten years as a result of the strong need to attain absolute sustainability by 2050 [2]. It could also be due to the increase in the number of remanufacturing conferences held annually that attract the attention of researchers. As seen in the distribution, there was a gradual increase in the number of publications as the years go by. This is due to an increase in the awareness of remanufacturing as a key recovery option for end-of-life products.

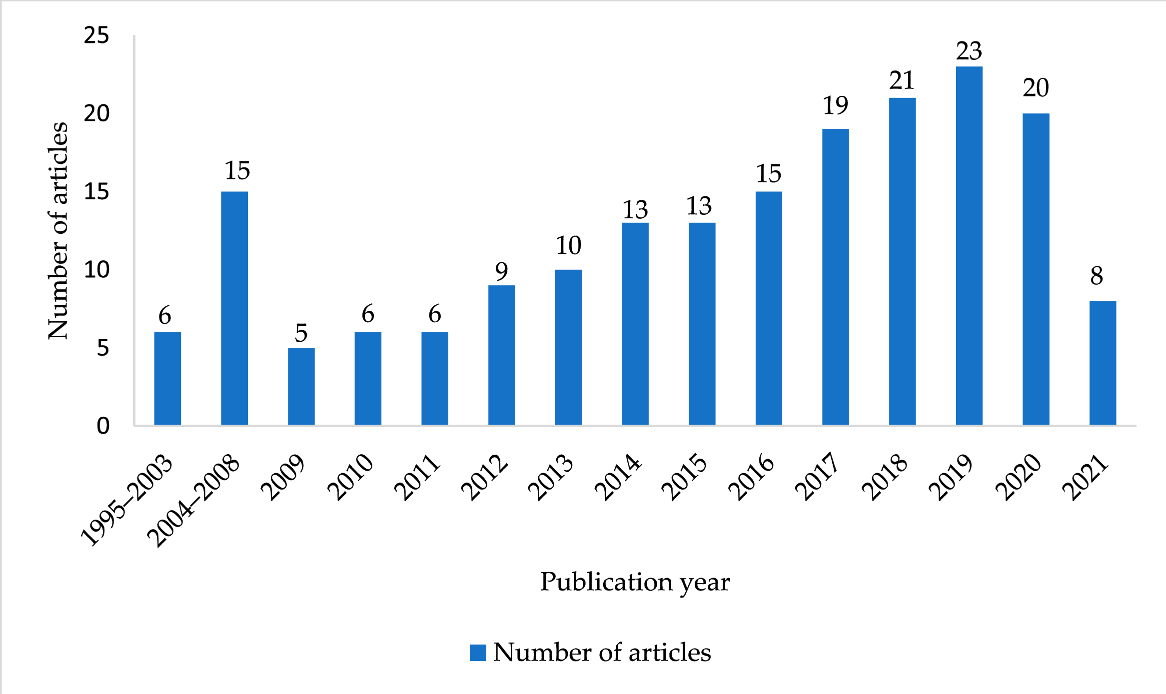

Figure 2. History of relevant publications.

The relevant papers were quantified and coded based on which strategies they had an impact on, the lifecycle stage in which they were applied and the case studies used to demonstrate the theory. Table 1 below shows the case studies used for each strategy.

A graph has been plotted to show the distribution of the strategies over the years from the relevant papers we identified (see Figure 3). From this graph we can identify which strategies were fading and which strategies were gaining more interest. It should be noted that certain strategies overlapped in some papers. It can be clearly observed that there was a constant increase in the number of publications containing each of the strategies every year. None of the strategies seemed to be fading with time, they were instead gaining more interest but at different frequencies. EoL product collection was number 1 both between 1995 and 2000 and 2016 and 2021, with CLSC as number 2, with 17 papers during the last period, whereas product service system dropped from number 3 to last over time and predetermined remanufacturing time climbed from last position between 1995 and 2000 (0 papers) to third position in the last period (2016–2021) with 16 papers. Reverse logistics came in at the fourth position with 15 papers in the last period, after dropping from first position during the first period. Product lifecycle data climbed from 1995–2000 (0 papers) to fifth position in the last period with 13 papers. RUL publications increased at a much slower rate and remained at number 6 in the last period with 12 papers. DfRem was at number 7, with a slower progress from 2 papers in the first period to 11 papers in the last period.

The recent trends were identified based on the frequency of publication of innovative techniques to enhance remanufacturing, especially for papers which emphasized digitalized strategies to better remanufacturing. Trending terms like "Internet of Things" (IoT), "big data", "artificial intelligence" (AI) and "5G network" were coded with remanufacturing and the publications that used any of the terms in remanufacturing were taken into consideration. Figure 4 below shows the number of papers identified for each trending strategy. We can observe that the frequency was in the following order: industry4.0, COBOTs, upgrading, additive manufacturing, smart remanufacturing and finally SRDM. These trends are discussed in this order in Section 4.

Table 1. Case studies used in various strategies.

Strategies	Relevant Papers	Case Study Used
EoL product collection	[30]	Electronic products
	[31]	Emphasis on remanufacturing
	[32]	Mobile phones
	[33]	WEEE
CLSC	[34]	OEMs
	[35]	Electric vehicle batteries
	[36]	System dynamics analysis
	[37]	Paper recycling
Predetermined remanufacturing timing	[38]	Manufacturing systems
	[39]	Multi-scale PCA
	[40]	Wind turbines
RUL	[41]	Used parts
	[40]	Wind turbines
	[42]	Aircraft engines
	[43]	Railway D-cables
Reverse logistics	[44]	Cell phones
	[45]	Use of algorithm in Taoyuan City
	[46]	Improved genetic algorithm
	[47]	Chinese automobile parts
DfRem	[48]	Disassembly line balancing
	[49]	Analyzing operational factors
	[50]	Analytic network process
Product lifecycle data	[51]	Quality grading and end-of-use recovery
	[52]	IoT scheduling to predict remanufacturing timing
	[53]	Big data in product lifecycle
PSS	[54]	Baby prams
	[55]	Upgradable PSS
Collaborative robots	[56]	Human–robot collaborative disassembly cell
	[57]	Enhanced discrete bee algorithm
	[58]	Maintenance of autonomous train
	[59]	A study on attitude and acceptance in an industrial context
Additive manufacturing	[60]	Metals (silver, iron, etc.)
	[61]	Future outlook for remanufacturing
Industry 4.0	[62]	Inter-country comparative perspective
	[63]	Use of augmented reality
Upgrading products	[64]	EoL tires
	[65]	PSS
SRDM	[66]	Algorithm to optimize disassembly
Smart remanufacturing	[67]	I4.0 and CE

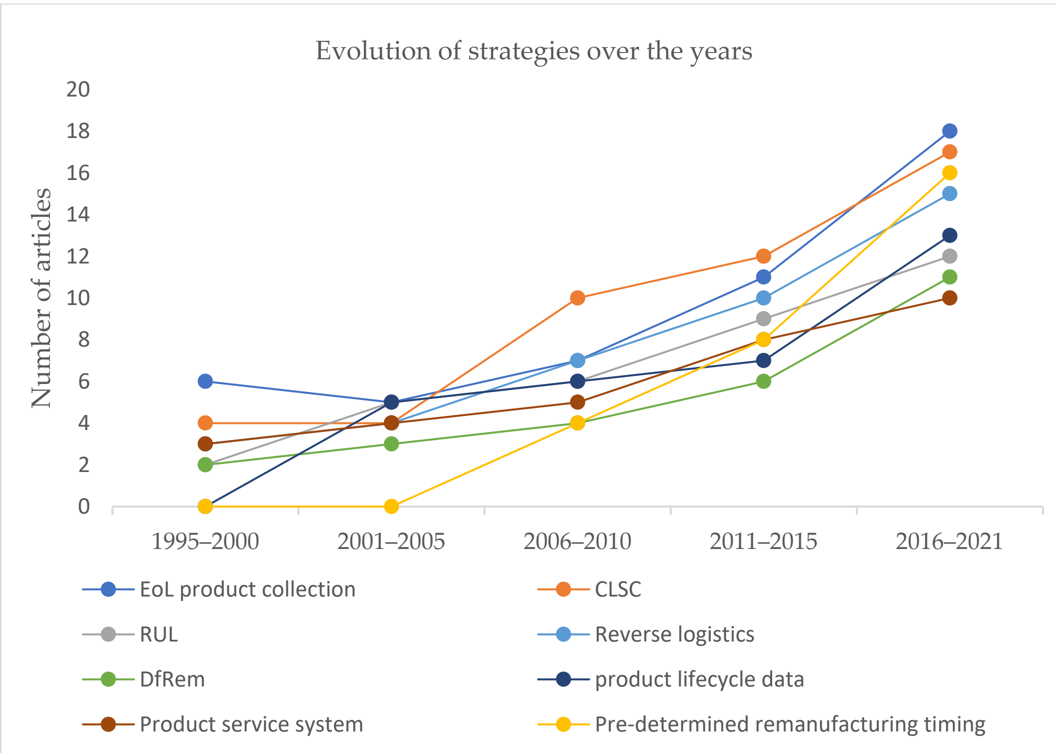

Figure 3. Evolution of strategies over the years.

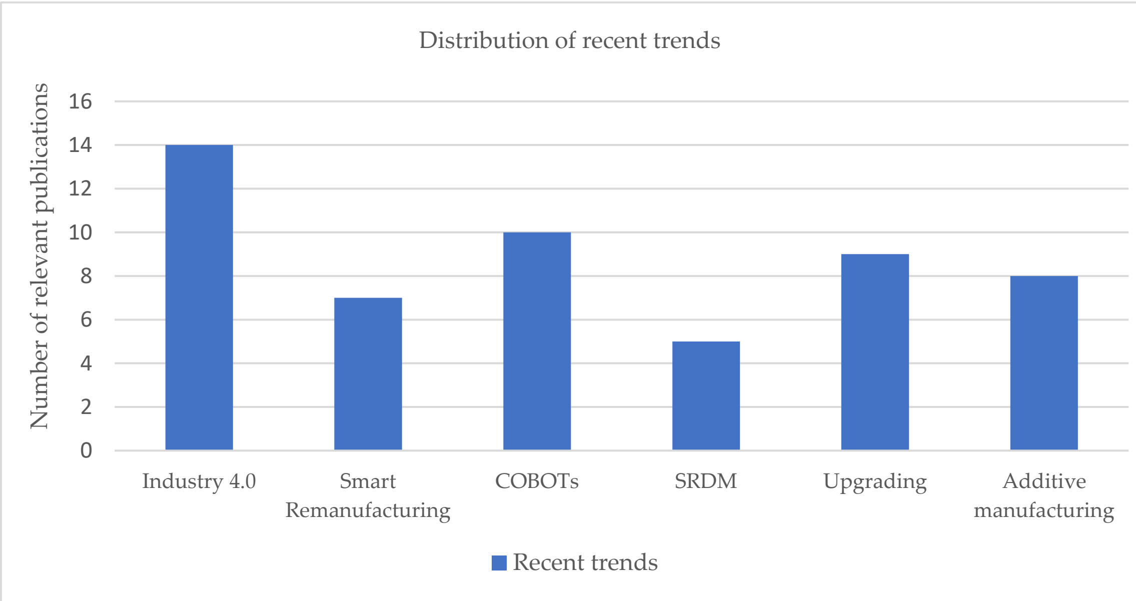

Figure 4. Distribution of recent trends.

The rest of this review is presented as shown in Figure 5 below. It is organized to clearly show what questions are asked and the proposed solutions. Section 3 highlights the lifecycle strategies that enhance remanufacturing and how they increase the remanufacturability of a product. This review involved a systematic study and shows the progress in the various strategies as well as the current limitations and the possible solutions to address the limitations. Section 4 discusses the trending and more advanced technology and methods that can also improve remanufacturing chances. Section 5 identifies the research gaps and the future work to be done to fill in these gaps and, finally, Section 6 provides the conclusion.

The constructed database of strategies to enhance remanufacturing (Table 2) summarizes the methods described in the literature. All the approaches described in the literature review that conformed to the "strategy" definition given in the Methodology section were included as strategies to enhance remanufacturing.

Table 2. Database of strategies to enhance remanufacturing.

Beginning-of-Life (Design, Manufacture)	
Design for remanufacturing (DfRem)	Design that considers the need to disassemble products for repair, refurbishment or recycling.
Product lifecycle data acquisition	Data collected based on product's design, production process, usage and disposal. Data collected from the middle-of-life stage is shared so as to enhance the production technique, design and usage.
Middle-of-Life (Distribution, Sales, Use)	
Product service system (PSS)	The ownership of the product rests with the producer who provides design, usage, maintenance, repair and recycling throughout the lifetime of the product. The customer pays a rent for the time of its usage.
Smart recovery decision making (SRDM)	Withdrawing products from the supply chain in case of defaults.
Product lifecycle data acquisition	Data collected throughout the product's use stage to detect performance degradation as well as defections.
End-of-life (EoL)	
EoL product collection	Products at the EoL stage are collected and sorted.
Predetermined remanufacturing timing	Decision making for the collection of remanufacturable products and the timing of collection is crucial; the sooner the better.
Remaining useful life (RUL)	Determining how much useful life an EoL product has left, deciding whether it can be remanufactured or recycled.
Reverse logistics	Analyzing various recovery options for collected EoL products.
Product lifecycle data acquisition	Data collected on the state of the collected products for future improvement.
Remanufacturing	
Product lifecycle data sharing	Data collected throughout the product's lifecycle is shared so as to ease the remanufacturing process.
Industry 4.0	The use of inter-connected production processes in the remanufacturing process.
Smart remanufacturing	Using advanced techniques in remanufacturing
Collaborative robots	Human–robot close collaboration to overcome the barriers encountered during remanufacturing.
Additive manufacturing	Using various techniques such as 3D printing to remanufacture complex parts which are difficult to achieve with traditional methods.
Upgrading	Increasing the performance of an EoL product through remanufacturing.
CLSC	CLSC enhances remanufacturing as a recovery option.

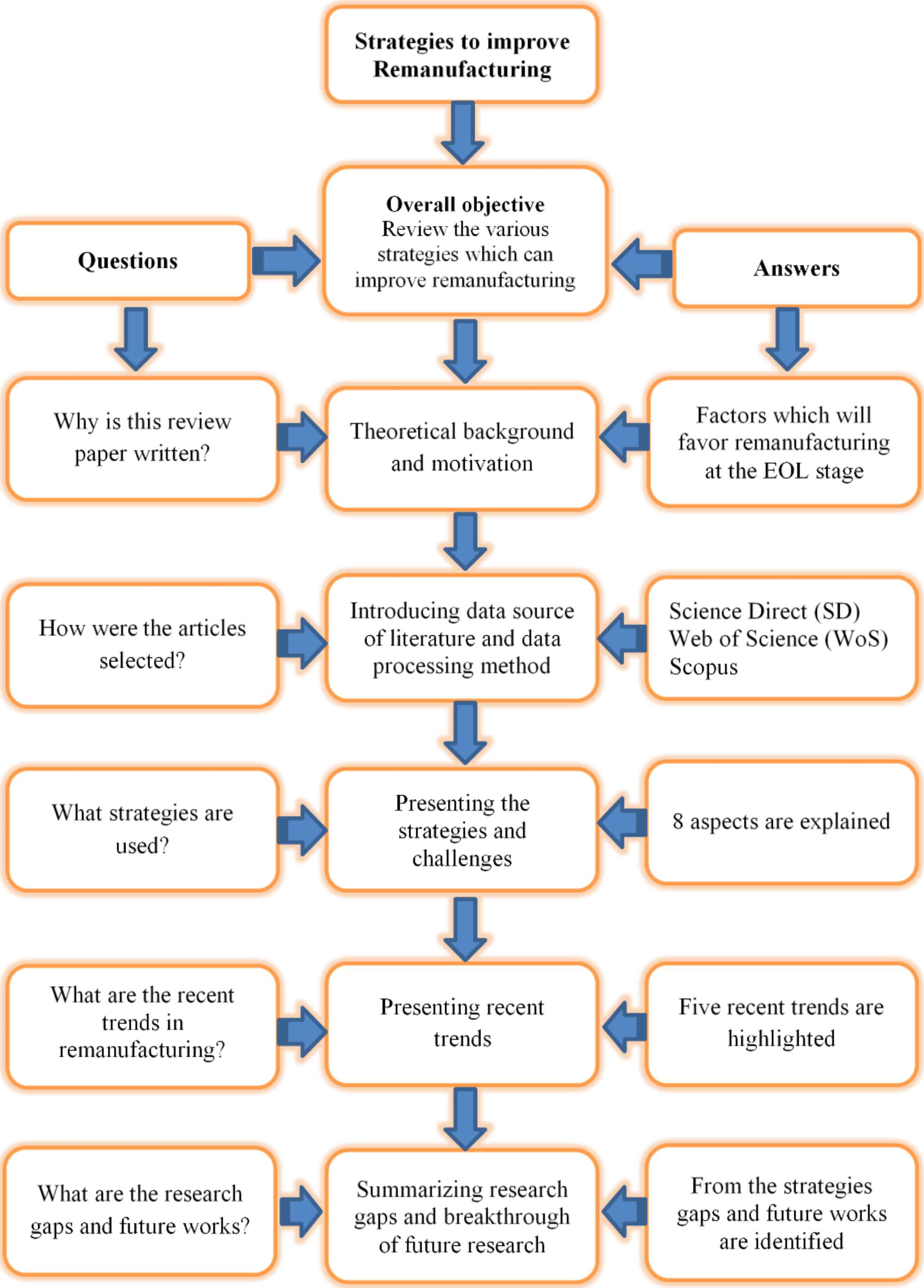

Figure 5. Research framework.

3. Strategies Enhancing Remanufacturing

For an EoL product to be remanufactured, it has to have some remaining useful life in it; for this to be achieved there are many factors which have to be analyzed throughout the lifecycle of the product. Given that remanufacturing forms a closed-loop system, there are certain major decisions that have to be taken at the various stages that can affect remanufacturing directly or indirectly. From a sustainability point of view, the beginning-of-life (BoL) of a product is the first stage of the closed loop and the decisions made at this stage affect the product's entire lifecycle, including its end-of-life scenarios. Even if the right decisions are taken at this stage, there is still the middle-of-life (MoL), which can affect remanufacturing; finally there is the end-of-life itself. The strategies were identified based on the effects they have at the BoL, MoL and EoL stages. The strategies were selected by searching for articles that identified the strategies at the various stages of a product's lifecycle that foster remanufacturing. Highly significant and frequently used strategies were retained while the less used were discarded. Eight relevant strategies were retained and they are discussed in this section. It is important to note here that the strategies do not support every stage of the supply chain but rather the stage which it has a greater influence on. The various strategies which can make remanufacturing processes easier by reducing challenges are discussed below.

3.1. End-of-Life Product Collection

The collection of end-of-life products is one of the most important factors that can determine whether that product will be qualified to be remanufactured or not. Products are generally considered to be at their end-of-life when their end users dispose of them. The timing of the collection of these products is very important because some of them get in even worse shape if they are not recovered in time. Angouria-Tsorochidou et al. [30] discussed how waste electrical and electronic equipment (WEEE) can be effectively recovered at end-of-life using effective collection methods. EoL product collection becomes an end-of-life decision tool when emphasis is laid on remanufacturing [31]. In most cases it is a third party that collects the EoL products. There are often three scenarios for EoL product collection:

Method 1. The drop-off collection system by targeting recycling centers. Here the end-of-life products that still have some useful life are collected whist the rest are recycled. This method usually has a collection efficiency (the quantity of collected EoL products which can be remanufactured compared to the total EoL product collected) of 75% [32].

Method 2. The existing drop-off collection system which involves collecting products from the various little drop-off points. This is a longer process but it has a higher collection efficiency of 80% [32].

Method 3. This system involves door-to-door collection of EoL products from different households. This is the most tedious of all the collection methods because it requires many more personnel and takes more time. The good thing about this method of collection is that it has a collection efficiency of 90% and the products can be recovered in better shape than the two other methods. This is because the products are collected directly from the consumer and they have not been contaminated by other products. In Denmark, after collection of the WEEE, 10% the value of the remarketed product was given to the owners who disposed of the products to further encourage the return of EoL electronic products [33].

The chances of a product being remanufactured gradually reduce if the product is not quickly collected for reuse after its disposal. There are some uncertainties in the recovery of EoL products, like the state of the returned product, the quantity of returns, etc. A multi-objective decision-making approach aimed at dealing with these uncertainties has been explained by [68]. In order to beat the odds and increase the remanufacturability of a product at its end-of-life stage, the products have to be collected in the right way and in time. The strategies which can help improve the quality and quantity of EoL products have been outlined by [69].

3.2. Closed-Loop Supply Chain (CLSC)

The supply chain in its classical form (forward supply chain) is a combination of processes that meet customer requirements, including all possible entities such as suppliers, manufacturers, transporters, warehouses, retailers, and the customers themselves [70]. Reverse supply chains, on the other hand, usually begin from the collection of end-of-life products, which are later reintegrated into the supply chain or disposed appropriately [71]. End-of-life products can be returned to the supply chain through value retention processes such as re-use, repair, refurbishment, recycling or remanufacturing, and our main focus here is the domain of remanufacturing. If both forward and reverse supply chains are considered with the aim of creating value throughout the product's lifecycle, the resulting network leads to a CLSC. The "design for sustainability" concept shows the various connections between supply chain management and the environment [72]. The general form of a CLSC is shown in Figure 6. Khor & Udin [73] have described how the various members of a supply chain can work together to ensure the smooth functioning of the supply chain. The evolution of the supply chain has been described by [25].

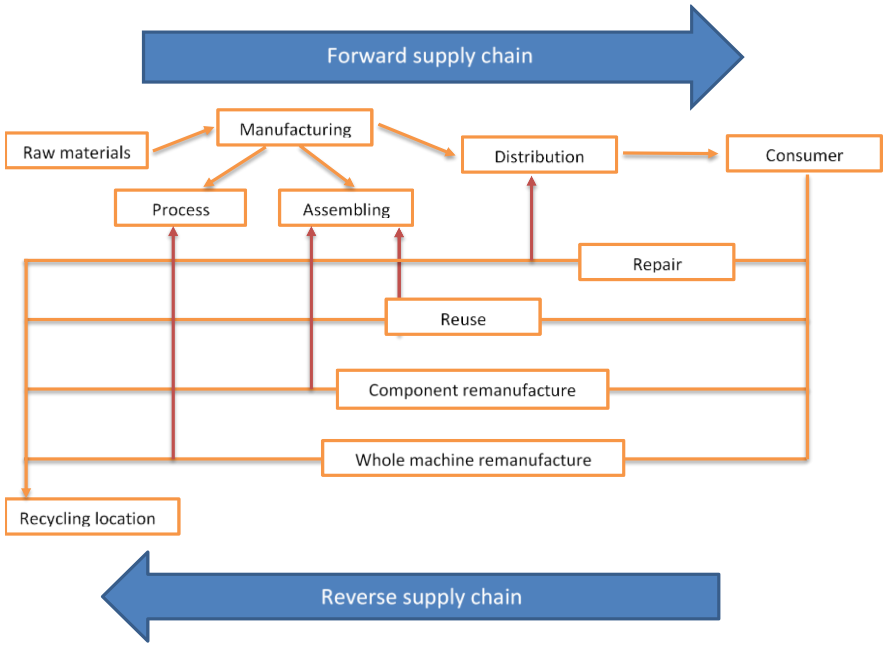

Figure 6. Structure of a CLSC.

A study on the modeling of a reverse supply chain through system dynamics for realization of the transition towards a circular economy has been undertaken by [35]. Electric vehicle batteries were used as a case study, and the study showed how electric vehicles can be moved within a reverse supply chain after reaching their end-of-life, thereby creating a closed-loop supply chain and promoting a circular economy. The environmental and economic sustainability in a closed-loop supply chain have been explained by [36]. There are often uncertainties about the returns for remanufacturing, like the timing, quality and quantity of the returns. The aforementioned uncertainties encountered during remanufacturing can be solved with the CLSC through the collaboration between the forward supply chain and the reverse supply chain. In this case, there is a constant flow of material and the quality, quantity and time of returns are highly improved with the help of good collaboration between the EoL product collectors and the remanufacturers. According to [74], there are certain uncertainties that hinder the fluidity of a CLSC, and literatures reviews on closed-loop and sustainable supply chain management have indicated the need for additional uncertainty factors of the CLSC to be systematically studied [75]. There is also a financial problem within the CLSC, whereby some OEMs are unable to meet financial demands, which can then help them form a CLSC, such as by collecting their own products at the end-of-life or by getting involved in remanufacturing. Zhang & Chen [33] discussed a way to optimize production by capital-constraint OEMs and the various strategies that can be used to boost their capacities. Proposed solutions to these uncertainties have been well-explained by [76] and could be a breakthrough to ensure the proper functioning of CLSCs, which could in turn solve the uncertainties encountered in remanufacturing.

3.3. Predetermined Remanufacturing Timing

The remanufacturing timing of an EoL product is very crucial because, if the product stays in service for too long in its MoL stage, it may be impossible to remanufacture that product. This is where the notion of predetermined remanufacturing timing comes into play. As seen in Figure 3 above, this strategy has seen the greatest rise in the number of relevant publications, from 0 papers in the period 1995–2000 to 17 papers in the period 2016–2021. This just shows the importance of this strategy in the lifecycle of a product. It is normally difficult to determine when a product has reached its end-of-life stage just by observing, and there are certain factors that have to be analyzed before decisions can be made.

Industrial research carried out by [77,78] has shown that a high percentage of waste products cannot be remanufactured and thereby have to be recycled as industrial solid waste. Considering the product lifecycle, these EoL products cannot be used as the cores for remanufacturing processes. Such a situation can be remedied by using predetermined timing, which consists of evaluating the operating performance of a product such that it does not get to a stage where the product can no longer be remanufactured.

Remanufacturing is often offered to customers as a restoring procedure with improved performance and reduced total cost [38]. Therefore, remanufacturing should be seen as a maintenance option which should be considered in time when product performance degrades. Product performance degrades with a small ratio at first and a higher ratio after a certain time. This is because the performance of a brand new product is at its peak at the beginning of use and with time the key components start degrading, leading to faster overall product degradation [79]. When product performance is too low to meet the operating requirements, the entire product is wasted at its end-of-life. Product performance is expressed as a decreasing function of operating time [80].

There are three factors considered in decision making regarding remanufacturing timing, namely economic, environmental and technical aspects [81]. Component performances are taken into consideration when dealing with remanufacturing timing; the main options are:

(a) *Variable performance of key components:* A product is made up of various components and some components are considered "key components" due to their importance. Therefore, their performance is observed during their lifecycles so as to determine the exact period it needs to be remanufactured.
(b) *Remanufacturing timing with key components:* Given that the structural failure of each component is totally different according to the individual operation environment, identifying the influence on product performance from each key component is important. Moreover, the components are the main cores to be disassembled, inspected and restored. The utilization values in the use phase and the costs in the remanufacturing phase of different key components should not be similar. Accordingly, the specific remanufacturing timing of individual components should be analyzed as the foundation of a product's remanufacturing timing.

Methods to estimate the performances of these products mainly involve online monitoring for structure failure with the use of sensors or related methods [40,82,83].

3.4. Reverse Logistics (RL)

According to the American Reverse Logistics Executive Council, reverse logistics is defined as "The process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" [84]. Due to environmental concerns, reverse logistics is now becoming an important strategy to increase customer satisfaction. RL originates from a waste management standpoint. It is complicated due to the presence of driving forces, return reasons, product types and uncertainty around the reverse flow. Also, how the material is recovered and who will execute and manage the various reverse operations are important issues [85,86]. Since reverse logistics includes a series of processes involving product return, repair, dismantling, refurbishing, recycling, remanufacturing and disposal of used or end-of-life products, the implementation of a reverse logistics network is a strategic decision. This decision seeks a single objective or multiple objectives of cost minimization, profit maximization, customer satisfaction and environmental benefit [46,47,86,87]. It includes the determination of locations, the number and capacity of facilities and the flow quantity sent from one facility to another. It is severely complicated by many uncertain factors, as explained by [88]; therefore, several papers have focused on the design of reverse logistics networks [37,48,89–91].

A classification scheme for different types of reverse logistics networks has been identified by [92]. Reverse logistics networks range from simple echelons to complex echelons composed of forward and reverse supply chain networks, as explained by [71,93,94]. According to Curvelo et al. [44], refurbishing and recycling of cell phones can be sustainable for the circular economy. Due to the complexity and economic effect of reverse logistics, a common mathematical model has been developed to solve the network problem [93–96]. Bazan et al. [87] reviewed mathematical inventory models for reverse logistics from an environmental perspective. A more comprehensive survey of reverse logistics was undertaken by [71,93,97].

The diverse research carried out on reverse logistics shows just how important it is in the promotion of a circular economy. It can greatly reduce the problems encountered in remanufacturing, especially in terms of the arrival, quality and quantity of returns at the EoL stage. Liao, T.Y. [45] described an algorithm that can be used to gather information based on locations of companies, manufacturers, retailers and different elements of the supply chain, with this information then synchronized so as to ensure a smooth flow of resources. This algorithm is used in real-life recycling of bulk waste in Taoyuan City, Taiwan, which is a very big step toward the creation of more algorithms.

3.5. Product Lifecycle Data Acquisition and Sharing

One of the challenges at the remanufacturing stage is the lack of product lifecycle information. With inadequate information on a product, it is very challenging to come up with a process plan for that product. Data are stored at different levels of a product's lifecycle by different stakeholders, whether for its manufacturing production planning system or the distribution and usage stages [81]. These data are often not shared by manufacturing companies due to fears of competition from their direct OEM rivals or even from third party remanufacturing companies. However, the synchronization of such data acquired from the entire lifecycle of the product can benefit remanufacturing in so many ways [51]. IoT scheduling can be used to predict when a product can be remanufactured based on lifecycle data [52]. With the emergence of 5G networks and very sophisticated cloud technology, product information can be stored in the cloud and later accessed when needed; this greatly helps in providing access to a product's information at any stage [98]. A demonstration of the flow of information in a supply chain is shown in Figure 7. The figure clearly shows how information flows in both directions from the cloud to different stages in a supply chain and vice versa. This information flow needs to be secured and well defined.

Due to the security concerns of OEMs and other key members of the supply chain, a solution has to be found to tackle this problem of companies copying data from others with the access they have to other companies' data. One proposed solution is to create a well-secured cloud with limited access only for those who have the green code to access the information [99]. There also has to be an agreement put in place that prohibits them sharing the information with non-authorized personnel or even for their personal interest. It would be in the interests of all the parties involved. This project to create a universal, well-secured cloud, which could be used on a worldwide basis, is still in process and it could be a breakthrough for the full integration of the fourth industrial revolution [100].

This will have a great impact on the functioning of CLSCs and will benefit remanufacturing as well.

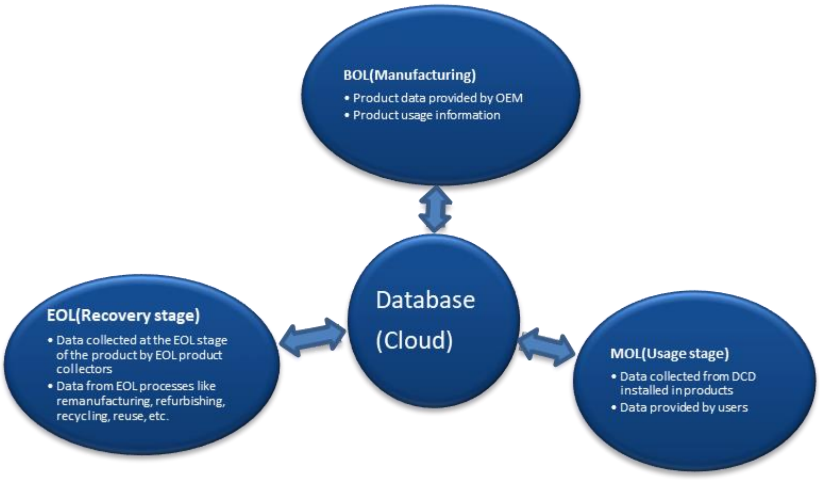

Figure 7. Lifecycle data flow.

3.6. Remaining Useful Life (RUL)

The remaining useful life of a product is an estimation of how much useful life the used part or product still has and for how long it can still be used. It can be used to determine whether or not a used part can still withstand another lifecycle [101]. As explained by [41], there are three main factors which need to be checked:

(a) *The physical remaining useful life:* This is based on the actual state of the product, usually visible by simple observation. Questions which can be raised here include: Can the product still withstand the stress which it has to go through to satisfy its users? Is it safe for the user to keep using that product [102]?
(b) *The technical remaining useful life:* For the technical aspect of RUL, the aspect to take into consideration is whether the main parts of the product are still functioning properly; in order words, whether the product is still able to carry out its assigned function.
(c) *The economic remaining useful life:* This option has to do with profit margins and is special for products that normally generate revenue when they are being used, for example, a food processing machine. The main question asked here is whether the product can still generate its allocated revenue.

These three factors can be determined through calculations, as shown in detail by [41]. Further predictions using embedded systems have been undertaken by [42,43,103].

3.7. Design for Remanufacturing (DfRem)

Design for remanufacturing is a concept that has developed into a research hotspot due to the problems that are encountered during the remanufacturing stage. These problems arise due to poor product design which makes it difficult for the various stages of remanufacturing to be carried out, especially with regard to disassembling. According to [104], design for remanufacturing (DfRem) is a means of supporting sustainable manufacturing goals within a firm. Remanufacturing is preferable to recycling from an environmental perspective as it returns a product to working condition rather than reducing it to raw materials. In a review on DfRem, Hatcher et al. [105] recognized several key problems with design for remanufacturing in practice; firstly, there is a lack of knowledge and understanding amongst designers. Secondly, even if the idea is understood, there are few products being remanufactured and even fewer designed for remanufacturing. Finally, there are few tools for DfRem.

One of the main reasons why many products are not designed to be remanufactured is because the original equipment manufacturers (OEMs) are not heavily involved in remanufacturing. Due to this limitation, the product encounters disassembly issues during remanufacturing. OEMs getting involved in remanufacturing would further improve the design of products since they would want to reduce the problems encountered during the remanufacturing stage. Disassembly is the first stage of remanufacturing and it is definitely the most important stage because if the product is not well-disassembled, then the cores can be further damaged. The reasons cited for remanufacturing are mostly environmentally focused, such as recovery of components at the end of a product's useful life based on take-back and end-of-life legislation in countries like Germany [106] and increased environmental awareness among businesses. Hatcher et al. [49] studied three OEMs from the UK mechanical industrial sector to determine what internal and external factors affect the integration of DfRem into the design process. It was discovered that many of the factors are similar to those that influence design for environment decisions, but DfRem was not primarily identified as one of the factors which influence environmental degradation. The objective is to design a product that can be disassembled to facilitate salvage of recyclable material and to safely dispose of unrecyclable material. This is because only a few components are remanufacturable for some products, while the rest of the components are recycled, so the manufacturer has to take all of this into consideration. Remanufacturing is an environmentally focused driver for disassembly, although economic factors, such as service and maintenance, are also heavily dependent on disassembly [50].

3.8. Product Service System (PSS)

The product service system is a system by which OEMs market the services provided by their products, instead of selling the product itself [107–109]. This system comes with many advantages, including the fact that the usage mode of the product can be set and closely monitored. The disadvantage is that users might be careless with the way they handle the products because it does not belong to them. This method is very effective because the inspection of the products at any time will be very easy since OEMs rather than end users are responsible for the recovery options for EoL products [54]. This opens the door for remanufacturing being the main route at the EoL stage. With this system, predictive remanufacturing can also be used if the products are equipped with data carrying devices (DCDs) which signal when the product is suitable for repair or remanufacturing [110]. One example is the bike-sharing system used in China and some other countries all over the world. The users use the bikes but they do not own them; they instead pay a certain amount every time they use them and after use they park them properly. This makes collection a lot easier when they arrive at their end-of-life stage, and it also provides for the possibility of the product being upgraded [111]. There are many more examples currently in use, like public power banks, electric sharing vehicles and others.

4. Recent Trends in Remanufacturing

There has been new research recently aimed at improving remanufacturing techniques and trying to solve the various problems encountered in EoL strategies and the remanufacturing process itself. The gradual increase in the number of companies getting involved in remanufacturing has led to the emergence of new techniques to tackle the setbacks encountered in remanufacturing. The rapid growth in technologies and the never ending work of researchers have advanced methods to solve problems encountered during remanufacturing, thereby increasing the chances of a product being remanufactured after its end of use. The trends described here were selected based on the advanced technologies used as well as the advantages they have over the strategies mentioned in Section 3 above. A more digitalized strategy can solve a problem much more efficiently than the aforementioned strategies. Some of the methods are listed below.

4.1. Industry 4.0 (I4.0)

Industry 4.0 is a term used to refer to the fourth industrial revolution, which has brought advancements in digital technologies that will completely change traditional manufacturing architecture [112,113]. It can be efficiently used to aid digital transformations of an organization to achieve sustainable development goals, and it can also help manufacturers enhance advanced manufacturing capabilities and further meet their sustainable development goals [114]. However, I4.0 technologies pose a challenge because they are relatively new and manufacturing companies face difficulties such as skill gaps, financial constraints and operational complexities in I4.0 projects [62,99]. The key impact of I4.0 is its ability to produce and access real-time information to allow increased visibility and to mitigate risks in the supply chain network [112].

Globally, firms are focusing on developing sustainable production and consumption strategies to reduce their negative environmental and social impacts. This thereby helps them to carry out manufacturing and remanufacturing activities in an environmentally friendly manner. Yang et al. [115] discussed the opportunities for I4.0 to support remanufacturing and the three main factors they describe are smart lifecycle data, smart factories and smart services. There are a lot of factors that must come into action to ensure that I4.0 can be appropriately used in remanufacturing, and since it is a new domain, research institutes and universities are playing an important role and are constantly working to find the methods that can be used to make the running of I4.0 successful. The use of big data to collect information so as to improve I4.0 has been closely studied by [53,83,98,116]. Moreover, the IoT has also been listed as a key factor for I4.0 with regard to scheduling of various I4.0 processes [52,99,100]. For remanufacturers to fully integrate into I4.0, the remanufacturing companies will have to upgrade their technology to modern day technology, such as by establishing a digital technology link between manufacturers and users [117].

4.2. Collaborative Robots (COBOTs)

Robots are very common in almost all manufacturing companies as well as some companies that deal with highly intensive labor. They are highly efficient compared to humans but are to a certain extent limited as far as intelligence is concerned, and they also pose safety issues. The emergence of industrial COBOTs is a huge step forward for industries as it remedies the limitations of robots [118]. Here, robots and humans work in close collaboration with each other to ensure smooth work flow without any concerns over the safety of the human operator [119]. The robot carries out the tasks that humans cannot do (labor-intensive and precision work) and the human worker carries out the tasks that the robot cannot do (those that require human intelligence) [58]. The use of these COBOTs in remanufacturing is a big boost for remanufacturing companies given the complexities of the various remanufacturing processes, like disassembly, inspection and reassembly [120]. An experimental demonstration has been published by [56]. COBOTs mostly carry out jobs that are considered dull, dirty, dangerous or monotonous, and they can be deployed pretty much everywhere. In remanufacturing COBOTs could be used in the various processes and they could work closely with humans, meaning humans could also do the same work [121]. Disassembling is often the most challenging work since the EoL products are in different conditions upon arrival. Liu et al. [57] came up with a bee algorithm for robotic assembly. Augmented reality (AR) has also been used to further increase the efficiency of COBOTs by [63,122]. This addition will see certain EoL products that would have normally been recycled being remanufactured and this will have a great impact on the environment as well. There was an increase of 23% in the number of COBOTs deployed between 2017 and 2018 and the number keeps increasing [59].

4.3. Upgrading Products

Remanufacturing, as mentioned earlier, is a recovery process that helps transform a used product into a good-as-new product. Under normal circumstances, the remanufactured product carries out the same functions as the original product and often has the same appearance. There has been a recent trend in remanufacturing whereby the EoL product is upgraded such that the final remanufactured product does not necessarily look like the original product and has higher performances than the original product [55]. This trend has emerged due to the fact that certain EoL returns are still in good shape to be remanufactured but cannot perform the same functions as the original products [64]. Upgrading products at their end-of-life adds more options in remanufacturing, making it more flexible and thereby increasing the chances of EoL returns being be remanufactured [110]. Products can be customized by remanufacturing to meet the demands of customers due to the fact that remanufactured products are often way cheaper than the original product and OEMs often avoid getting involved in remanufacturing because they might lose customers [123]. This is because if the remanufactured product has higher performances and lower prices, then the demand for new products will drop. Upgrading these products enables them to be sold at higher prices than the normal remanufactured products [111]. For example, a 50cc motorcycle can be upgraded into a 100cc model through remanufacturing. According to [65], upgrading through remanufacturing can benefit the PSS.

4.4. Additive Manufacturing for Remanufacturing

Additive manufacturing (AM) is a manufacturing technique whereby material is continuously added onto another to form a product. There have been advancements in this domain with laser additive manufacturing being used, which offers much more precision and better results [124,125]. Some EoL products are in such bad shape upon collection that normal techniques cannot be used to replace them. This is when AM steps into remanufacturing, as it is one of the most advanced manufacturing techniques and can be used to remanufacture complicated parts [126]. There have been a lot of improvements in this manufacturing technique, notably the fact that it is no longer limited and can be used in various domains. The inclusion of this technology in remanufacturing is boosting remanufacturing companies, especially for products which pose complications [127]. For example, in the remanufacturing of car engines, there are certain parts of the interior of the piston that are difficult to replace but they can be repaired with the use of AM. Direct energy deposition (DED) and powder bed fusion (PBF) are the main AM methods for metals that are used in refurbishing, repair and remanufacturing of metal parts [59]. DED- and PBF-based technologies are quickly rising and they are playing a significant role in the circular economy. An algorithm for remanufacturing has been developed by [128] to identify products that need to be repaired or remanufactured by 3D deposition.

One of the greatest benefits of AM, especially laser AM, is that the gas emission percentage is much lower than other manufacturing techniques like milling, drilling, grinding and others [129]. Also, it can be used in different processes, like repair, refurbishment and maintenance, not just for manufacturing or remanufacturing. Aziz et al. [60] have described how an EoL component can be optimized based on AI in support of AM for remanufacturing and repair. This will be very helpful in building a circular economy and it will be a great bonus in remanufacturing.

4.5. Smart Remanufacturing

With the emergence of industry 4.0, new techniques are being used to improve manufacturing methods. This will be very beneficial to remanufacturing given that a design for remanufacturing perspective is kept in mind during the manufacturing stage, thereby also directly affecting remanufacturing. Smart remanufacturing with the help of industry 4.0 has to follow the norms of sustainable development, which consist in balanced economic, social and environmental performance, also referred to as the triple bottom line [130]. Kerin & Pham [131] have pointed out the ways in which smart remanufacturing meets up with the requirements of these three pillars of sustainability. In terms of the social needs, people need to engage in sustainable manufacturing entrepreneurship and collaborative working [132]. There is also a need for a collaborative environment, like personnel being trained using virtual or augmented reality and additive manufactured parts. The design philosophy needs to be understood, whether it be design for disassembly, service, remanufacture or sustainability [67]. In a factory equipped with smart remanufacturing technologies, factory equipment is managed using real-time collaborative, intelligent, distributed decision making and control [133]. The facilities need to be flexible, scalable, reconfigurable, customizable, enterable, modular and diagnosable. These factors are very important given that the systems will need to understand their environment to ensure the safety of the operators before accepting remotely controlled signals [134].

There are various data that are shared in such factories; the data are a combination of all the data collected during the entire lifecycle of the product. These data include product data, which consist of the data collected during the use stage of a product and the remanufacturing data shared to service providers or OEMs, process data, logistics data and business data [135]. The combination of these data could be used in remanufacturing with all the systems interconnected. At the beginning-of-life of a product, OEMs need to make product nominal data available and during the use stage the product performance and status data need to be monitored against nominal data. At the end-of-life stage, product nominal performance and status data are used to feed remanufacturing product data. The synchronization of this data is what makes smart remanufacturing so efficient, thereby solving a lot of problems encountered in remanufacturing, such as product identification, original production planning and the products' lifecycle history and ratings from users.

4.6. Smart Recovery Decision Making (SRDM)

This system concerns the withdrawal of a product from any stage of its lifecycle with the help of decision making [136]. A product can have defects right from its manufacturing stage and rather than letting that product go through an entire lifecycle where it could possibly not function well at use stage, it is better to withdraw that product from the supply chain and fix the error. This same procedure can be applied at any stage of the product's lifecycle, be it the design, manufacturing, distribution, usage or collection stages. This plays a critical role in the CLSC. Figure 8 shows the flow of information and data in a SRDM.

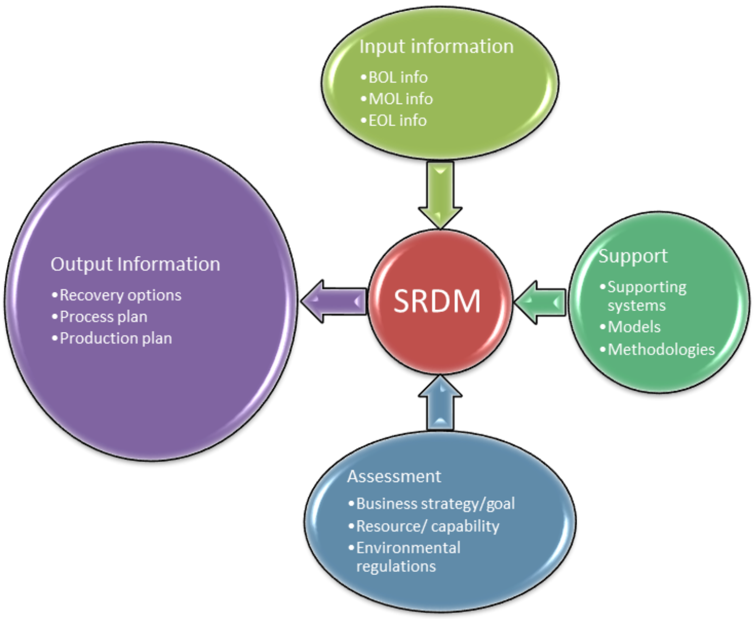

Figure 8. Information flow in an operational SRDM.

SRDM uses advanced technologies like AI, IoT, big data and machine vision to detect the products that can be withdrawn from the supply chain either for repair, refurbishing, remanufacture or recycling, with remanufacturing and repair being the most preferable routes [22,52,53]. This can be done with the help of DCDs, which detect the defects in the products and transmit them to the monitoring sector that then identifies and withdraws the products from the supply chain. Tseng et al. [66] described an algorithm that can be used for disassembly based on data collected from the SRDM. The main aim of this concept was to make sure that products remain in a closed loop which would greatly reduce environmental pollution and also promote sustainability.

5. Research Gaps and Future Work

5.1. Research Gaps

Despite the fact that the domain of remanufacturing is increasingly gaining more popularity and attracting more companies nowadays, there are still various uncertainties encountered with few or no concrete solutions proposed. Some of the gaps are listed below:

(a) There have been improvements in design for remanufacturing concepts and implementations in the supply chain. However, there are still limitations since there are no standards put in place so that manufacturers of the same product worldwide can apply the same DfRem principles. This causes a lot of discrepancies.
(b) Online monitoring is being used mostly for high value products and it is limited for lower value products. Even for the high value products with online monitoring systems in place, using the data is still problematic as there is no mechanism to share information across stakeholders.
(c) For EoL collection methods, there are methods of collection that have been used for a very long time now, e.g., from dumping sites. With emerging technologies such as smart lifecycle data and I4.0, there needs to be an upgrade in collection methods that matches the high level of technology. A more improved method for waste collection would greatly reduce the challenges faced in collecting and sorting EoL products.
(d) Another gap concerns the product lifecycle data collected. Data collection is done for certain products and it is very useful for I4.0.There are two issues here: (a) there are no tools for the information sharing for remanufacturing, and (b) even if the tools are available, the stakeholders are reluctant to share the information. This gap causes a lot of difficulties in remanufacturing since product information determines the production process which the product will follow during its remanufacturing stage.
(e) With new technologies being used in remanufacturing activities, there are quite a few case studies that show how these new technologies are being used in real time on products. Most of the work is still in the theoretical stage and for the practical stages there is much work to be done to improve the situation. The more researchers there are using case studies to explain their discoveries, the greater the chances of them being realized are.
(f) The RUL of a product is a very important element that can help the remanufacturing timing. There are still research gaps with regard to how exactly the RUL of a product can be calculated at any particular stage in its lifecycle. Various calculations have been made for certain products but they have not really been implemented because they are not all coherent.

5.2. Future Work

Remanufacturing, as earlier mentioned, has been gaining a lot of popularity due to the urgent need to attain sustainable development. There is still a lot of work that needs to be done to ensure that the ideas that scholars and research institutes come up with can be realized. Some of the future work includes the following:

(a) DfRem standards should be set for companies that manufacture the same products; this would improve the uniformity of the products during remanufacturing.
(b) There needs to be a mechanism set in place that can ensure the safe sharing of data between stakeholders without the fear of information leakage.
(c) An online monitoring system for lower value products could be established that would expand online monitoring beyond high value products.
(d) More research needs to be done on how the RUL of a product can be calculated at any given time in its lifecycle.
(e) More case studies should be used to demonstrate how emerging technologies like smart remanufacturing, I4.0 and SRDM can be applied in real circumstances.

The bigger picture is to obtain a balance between the three aspects of the triple bottom line, namely social, economic and environmental needs. In the domain of remanufacturing, there needs to be more awareness and willingness from companies and nations to adopt remanufacturing as a main recovery option. More work needs to be done on the various actions that can be taken to ensure that a product can be recovered at its end-of-life stage. This worldwide awareness will definitely lead to sustainable development and a great decrease in the environmental pollution.

6. Conclusions

This review clearly outlined the various strategies that can increase the chances of a product being remanufactured at its end-of-life stage; in other words, how remanufacturing can be prioritized over other EoL recovery options. The strategies were systematically quantified, coded and analyzed and their implementations were explained, as well as the shortcomings and proposed solutions. The review also provided insights on the latest happenings in the domain of remanufacturing and how upcoming sophisticated technologies are being directly or indirectly implemented in remanufacturing activities. The research gaps and the future work that could be done to further improve the process were also discussed.

We can conclude this review by stating that every member of the supply chain has to play their role to ensure the smooth running of the closed-loop supply chain. Awareness has to be created at various levels of the product lifecycle and emphasis should be laid on the importance of implementing the various norms at each of the stages. It is the combination of these levels that will help create a solid system and an environment that is conscious of the needs of attaining sustainable development.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research paper was supported by the National Natural Science Foundation of China (Grant No. 52075396, Grant No. 51905392). These financial contributions are gratefully acknowledged.

Conflicts of Interest: No potential conflicts of interest were reported by the authors or the stakeholders.

Nomenclature

EoL	End-of-life
OEMs	Original equipment manufacturers
BoL	Beginning-of-life
MoL	Middle-of-life
WEEE	Waste electrical and electronic equipment
CSLC	Closed-loop supply chain
RL	Reverse logistics
RUL	Remaining useful life
DfRem	Design for remanufacturing
I4.0	Industry 4.0
IoT	Internet of Things
COBOTs	Collaborative robots
SRDM	Smart recovery decision making
AI	Artificial intelligence
SCM	Supply chain management
DCD	Data carrying devices
PSS	Product service system
CE	Circular economy

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