*Review*

# A Review on Remanufacturing Reverse Logistics Network Design and Model Optimization

**Xumei Zhang** [1,2]**, Bo Zou** [1]**, Zhaohui Feng** [1,]*****, Yan Wang** [3] **and Wei Yan** [1]

1. School of Automobile and Traffic Engineering, Wuhan University of Science and Technology, Wuhan 430065, China; zhangxumei@wust.edu.cn (X.Z.); zoubo2602@wust.edu.cn (B.Z.); yanwei81@wust.edu.cn (W.Y.)
2. Hubei Provincial Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan 430081, China
3. School of Computing, Engineering & Maths, University of Brighton, Brighton BN2 4GJ, UK; Y.Wang5@brighton.ac.uk
* Correspondence: zhaohuifeng@wust.edu.cn; Tel.: +86-186-9616-2623

**Abstract:** Remanufacturing has gained great recognition in recent years due to its economic and environmental benefits and effectiveness in the value retention of waste products. Many studies on reverse logistics have considered remanufacturing as a key node for network optimization, but few literature reviews have explicitly mentioned remanufacturing as a main feature in their analysis. The aim of this review is to bridge this gap. In total, 125 papers on remanufacturing reverse logistics network design have been reviewed and conclusions have been drawn from four aspects: (1) in terms of network structure, the functional nodes of new hybrid facilities and the network structure combined with the remanufacturing technologies of products are the key points in the research. (2) In the mathematical model, the multi-objective function considered from different aspects, the uncertainty of recovery time and recovery channel in addition to quantity and quality, and the selection of appropriate algorithms are worth studying. (3) While considering product types, the research of a reverse logistics network of some products is urgently needed but inadequate, such as medical and furniture products. (4) As for cutting-edge technologies, the application of new technologies, such as intelligent remanufacturing technology and big data, will have a huge impact on the remanufacturing of a reverse logistics network and needs to be considered in our research.

**Keywords:** reverse logistics; remanufacturing; review; network design; model

## 1. Introduction

As a result of the accelerated pace of technological development and economic growth, the pace for product replacement keeps increasing, which leads to an exponential surge in the generation of waste products. In order to reduce pollution and promote the reuse of resources, it is paramount to collect and reuse the waste products, for which reverse logistics (RL) is instrumental.

From the return of personal goods to the disposal of urban wastes, reverse logistics has played an indispensable role in these processes. However, the term of reverse logistics was not recognized until the end of the last century.

The concept of RL was proposed by Stock [1], who refers to RL as the collection of waste products or the disposal and management of waste hazards in a narrow sense, and treatment and the reuse of resources in a broad sense. The role of reverse logistics is essentially the process of transporting waste products from the consumer back to the production end for processing. The common treatments of these waste products are recycling, disposal, etc. However, enterprises do not often make considerable profits when implementing these treatments as they are time consuming and laborious. To improve

corporate profits and efficiency in resource reuse, remanufacturing is added as one of the alternatives for the treatment of waste products.

Remanufacturing is an industrial process that turns used products into as-good-as-new conditions (the same quality, functionality and warranty as these for new products) [2] through processes such as disassembly, cleaning, inspection, repair, replacement, and reassembly [3]. Remanufacturing is critical for realizing a resource-efficient manufacturing industry and circular economy [4]. Through remanufacturing, which plays a good role in promoting the extended producer responsibility system, the function of waste products is restored, and new value is created. The products for remanufacturing are usually automobile parts, electrical and electronic equipment, large machinery and office equipment such as printers.

Reverse logistics is closely related to remanufacturing. In many studies of a reverse logistics network of waste products, remanufacturing is an essential research content.

In reverse logistics, the network structure consists mainly of consumers, collection centres, treatment plants and markets [5]. According to the treatment method of products, reverse logistics can be divided into different categories: remanufacturing, recycling, disposal, etc. Compared with the other two reverse logistics categories, remanufacturing reverse logistics (RRL) has a different network structure. Some RRLs utilize hybrid facilities which integrate remanufacturing centres with the manufacturing centres [6], or some are based on the collection centres within the distribution centres [7]. Different structures of RRL have a different utilization efficiency of waste products, which has become a research subject.

So far, there are few literature reviews on the analysis of the state of the art of a remanufacturing reverse logistic network (RRLN). In this review paper, 125 papers on the design and optimization of an RRL network were identified and systematically analysed according to network structure, model, solution method and case studies in order to have a clear understanding of the research status in this field and to define the direction in the future research.

The rest of this article is structured as follows:

Section 2 introduces the previous review papers on reverse logistics and compares them with this paper; Section 3 is the introduction of the screening method; Section 4 analyses the models for RRLN and summarizes several different types of networks; Section 5 reviews the mathematical models and the solution methods employed in the literature; Section 6 analyses the application of the cases in this paper; Section 7 summarizes this paper and puts forward the future research directions.

## 2. Literature Review

There are a few literature reviews in the domain of reverse logistics network. This section analyses the 23 literature review papers on reverse logistics, as shown in Table 1.

Four of the reviews discussed the research status and development of reverse logistics. Pokharel and Mutha [8] argued that research in RL is multifaceted, which distinguishes itself from forward logistics, and concluded that the research on the uncertainty of demands for remanufactured products or the supply of used products and product pricing models is insufficient. By analysing the latest and most advanced research in different scientific journals from 2007 to 2013, Govindan et al. [9] classified 382 papers according to their content and summarise the trends and gaps of different research contents. They present future opportunities for uncertainty, models, and solution methods, and suggested that RRLNs with greener and more sustainable and environmental goals that consider multiple objective issues are becoming a future research direction. Prajapati et al. [10] divided the literature of the reverse logistics into 11 different categories and carried out detailed evaluation and analysis. They also investigated waste product-related legislations, e.g., an expanded producer responsibility system in countries around the world, such as the extended producer responsibility directives (2000) in the European Union, the Brazilian National solid waste policy (2010), and their impacts on RL of used components. In addition,

the paper concluded that consumer behaviour, information management, performance measurement, secondary market perspective, carbon footprint, government regulations, reverse logistics and other research fields have received little attention in the past, which could be research opportunities in the future. Rachih et al. [11] classified the papers according to the meta-heuristic approach and the illustrative context of the reverse supply chain and discussed the effectiveness and flexibility of these approaches in solving RL problems. It showed that the genetic algorithm and taboo search strategy are the most common methods used by researchers due to their applicability to most logistics and reverse logistics problems. In addition, the article also mentioned the potential application of meta-heuristic methods in other areas, such as Dynamic Lot Sizing, Forecasting, and Purchasing problems.

Govindan and Soleimani [12] and Kazemi et al. [13] analysed reverse logistics papers published in the Journal of Cleaner Production (JCP) and the International Journal of Production of Research (IJPR). Both papers indicated the major trends and future areas in the topics of reverse logistics and closed-loop supply chain. The former analysed the deficiencies and related research directions of the JCP papers in the aspects of different products and modelling of the closed-loop supply chain, and the latter discussed the influence of IJPR in the field of RL and closed loop supply chain management (CLSCM), indicating that the future research direction can be oriented to different industries and case applications.

In terms of product types, there are two papers that reviewed articles on Waste Electrical and Electronic Equipment (WEEE). Islam and Huda [14] used the content analysis method to select and classify 157 papers on WEEE reverse logistics published from 1999 to May 2017. It shows that in RL and closed loop supply chain (CLSC) network design, there is a lack of research considering different modelling objectives, problem formulation and solutions. Doan et al. [15] focused their efforts on e-waste reverse logistics and divided the research of the e-waste reverse supply chain into four categories: implementation factors, performance evaluation and decision making, predictive product recall and network design.

Pushpamali et al. [16] evaluated the research status of reverse logistics practice in the construction industry and highlighted the positive impact of reverse logistics practices on upstream construction activities and suggested that the industry stakeholders' support is vital for the successful implementation of reverse logistics. Therefore, industry decision makers must take the long-term future life cycle into account when making decisions, rather than focusing solely on the current waste problem. Mahmoudi et al. [17] provides a systematic quantitative overview of discarded photovoltaic panels. According to the review results, future studies must focus on the prediction of photovoltaic waste flow, the development of reverse logistics of recovery technology and the policies of individual photovoltaic cells in various countries. Karagoz et al. [18] reviewed the mathematical models of end-of-life vehicle (ELV) management and found that there was insufficient research in social standards. There has been insufficient research carried out on the environmental consequences of introducing or extending ELV logistics networks. More detailed consideration must be given to the recyclability of materials that reduce material waste and innovative molding processes that can recycle materials. In addition, the research also suggested little industry practice in case studies or surveys. There are few papers on risk measurement and uncertainty.

Three papers reviewed articles on models and networks. Agrawal et al. [19] focused their research efforts on the important issues that were unconsidered in previous literature reviews. This review, through a systematic and structured literature review, provides insights into the conceptualization and research on the issues, including adoption and implementation, forecasting product returns, outsourcing, RL networks from a secondary market perspective, and disposition decisions. After the analysis of 242 papers, it as found that there are still research gaps in the selection and deployment, risk assessment network models and the possibility of further research. Bazan et al. [20] reviewed the literature on modelling reverse logistics inventory systems based on economic orders/production

quantities (EOQ/EPQ) and combined economic batches. Van et al. [21] took a comprehensive view of reverse logistics and waste management and analysed the relevant papers on network design in the field of waste reverse supply chain, and explains the importance of factors such as multi-objective and multi-level uncertainty in network design of reverse supply chain.

**Table 1.** Overview of past reviews.

| Author | Year | NS | RL | MM | CLSC | R | PC | Main Focus |
|---|---|---|---|---|---|---|---|---|
| Pokharel and Mutha [8] | 2009 | √ | √ | | | | 164 | The present situation of reverse logistics research and practice is discussed |
| Govindan et al. [9] | 2015 | | √ | √ | √ | | 382 | Research status of reverse logistics and closed loop supply chain |
| Agrawal et al. [19] | 2015 | √ | √ | | | √ | 242 | RL networks and disposal decisions for forecasting product returns, outsourcing, secondary market perspective |
| Bazan et al. [20] | 2016 | | √ | √ | | | - | Literature on modelling reverse logistics inventory systems based on economic order/production quantity (EOQ/EPQ) and joint economic batch |
| Govindan and Soleimani [12] | 2017 | | √ | | √ | | 83 | Literature on reverse logistics and closed loop supply chain in cleaner production |
| Kazemi et al. [13] | 2018 | | √ | | √ | | 94 | Literature on reverse logistics and closed loop supply chain IJPR (International Journal of Production Research) |
| Braz et al. [22] | 2018 | | √ | | | | 56 | Bullwhip effect in a closed loop supply chain |
| Islam and Huda [14] | 2018 | | √ | | √ | | 157 | Waste electrical and electronic equipment/electronic waste reverse logistics and closed loop supply chain |
| Tombido et al. [23] | 2018 | | √ | | | | 134 | 3PL benefits in reverse logistics |
| Pushpamali et al. [16] | 2019 | | √ | | | | 54 | The research status of reverse logistics in construction industry is evaluated |
| Mahmoudi et al. [17] | 2019 | | √ | | | | 70 | The current study systematically investigates global research on EOL photovoltaic modules to identify gaps for further exploration. |
| Prajapati et al. [10] | 2019 | | √ | | | | 449 | According to the structure dimension and content of the paper, the paper is evaluated and classified in detail |
| Rachih et al. [11] | 2019 | | √ | | | | 120 | This paper reviews the previous papers on reverse logistics and classifies them according to the meta-heuristic method and the background of reverse supply chain |
| Doan et al. [15] | 2019 | √ | √ | | | | - | Research on e-waste resource sharing is divided into four categories, namely implementation factor performance assessment and decision forest product return and network design |
| Karagoz et al. [18] | 2019 | | √ | √ | | | - | End-of-life vehicle management |
| Van et al. [21] | 2020 | √ | √ | √ | √ | | 207 | Strategic network design using mathematical optimization models in waste reverse supply chains |
| our work | 2020 | √ | √ | √ | √ | √ | 125 | Network Design and Optimization of remanufacturing reverse logistics |

A "-" in the column indicates it is unclear how many papers are reviewed. NS = Network structure, RL = Reverse Logistics, MM = Mathematical Models, CLSC = Closed-Loop Supply Chain, R = Remanufacturing, PC = Paper Counts.

Braz et al. [22] systematically reviewed the application of the bullwhip effect in a closed-loop supply chain. The results showed that the closed-loop design of the supply chain can reduce the bullwhip effect and have a positive impact on the environmental performance of the supply chain. Tombido et al. [23] focused on the impact of third-party logistics providers (3PLs) on the performance of the existing supply chain. In the analysis, it was found that most of the studies were focused on the third party collecting and reprocessing benefits, while there were few studies on other reverse logistics activities, such as sorting and the distribution of third parties, and there were also few studies on the performance measurement and competition of third parties.

The above analyses indicate that there have been a considerable number of literature reviews in various fields of reverse logistics, but there are few reviews on reverse logistics networks considering remanufacturing. Agrawal et al. [19] divided the reverse logistics network into recycling networks, reuse networks, remanufacturing networks, repairing networks and other categories, and indicated that remanufacturing reverse logistics mainly has the characteristics of high-value products, closed-loop supply chain and uncertainty. According to their analysis, remanufacturing network models have been developed for a wide range of products providing solutions to various propositions of strategic issues. There are many kinds of remanufactured products and a large number of papers on the design and optimization of remanufacturing reverse logistics networks. In order to have a clear understanding of the development and problems of RRL, it is necessary to review the papers in this field.

## 3. Methodology

Literature review helps in determining the research content and comprehending the development trend of current theories. In order to systematically review the gaps and trends in the research of remanufacturing reverse logistics network, the research methodology will be illustrated from three steps: material collection, descriptive analysis and category selection.

### 3.1. Material Collection

Material collection is the first step in a literature review. The unit of analysis is defined as a single study. This step is divided into two parts: collection and screening.

In the first step, a pair of keywords "reverse logistics" and "literature review" are used in the title abstract and keywords to search for review articles. These keywords are used in WOS to select English literature. After reading and analysing the literature review, the term "remanufacturing", "network design", "model optimization" and the key term "reverse logistics" were used to search for articles with options as in first step. In this process, we selected the last 10 years as the time range and collected a total of 387 articles in WOS for further research. The collection of all materials was completed in April 2020.

Then, we applied the following criteria for further screening:

(1) The network mathematical model or the network structure diagram should be contained in the papers;
(2) The location of remanufacturing facilities is considered in the design and optimization of the network model;
(3) Remanufacturing is the main treatment method for the waste products.

Only those articles which were focused on the above-mentioned criteria were taken into consideration. Finally, a total 125 papers between 2010 and 2020 met these criteria and were used for subsequent research. With a focus on the network design section of remanufacturing reverse logistics, the number of articles analysed for review seems adequate and is consistent with the number of articles analysed in a recent literature review in the RL field.

### 3.2. Descriptive Analysis

To comprehend the multi perspective view of the concepts, articles were sorted out from more than 50 journals. As can be found in the statistical process, most of the articles were published in the Journal of Cleaner Production, Omega, European Journal of the Operational Research and other reputed journals.

Figure 1 shows the annual and the journal distribution of the reference files respectively. As can be seen from the table, most of the articles were published in the last five years. Due to the increasing interest of researchers in the field of remanufacturing reverse logistics, the number of articles has increased significantly in the past few years. The highest number of articles (24) was published in year 2018.
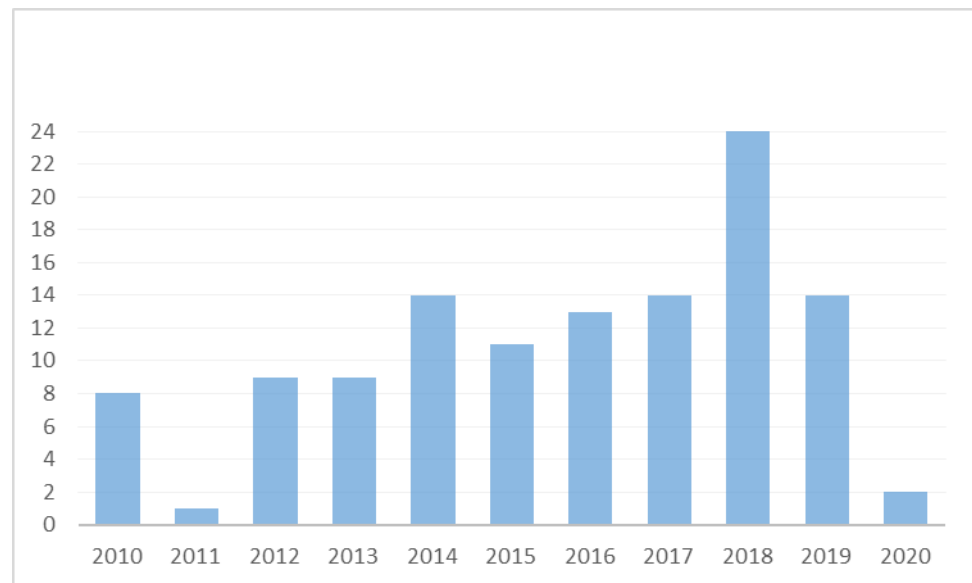
**Figure 1.** Number of publications per year.

### 3.3. Category Selection

The categories and framework of this study are shown in Figure 2. Since the optimization of the RRL network mainly focuses on the study of the network model, this paper adopts modelling steps to analyse the literature: network structure model analyses, solution methods and model validation.
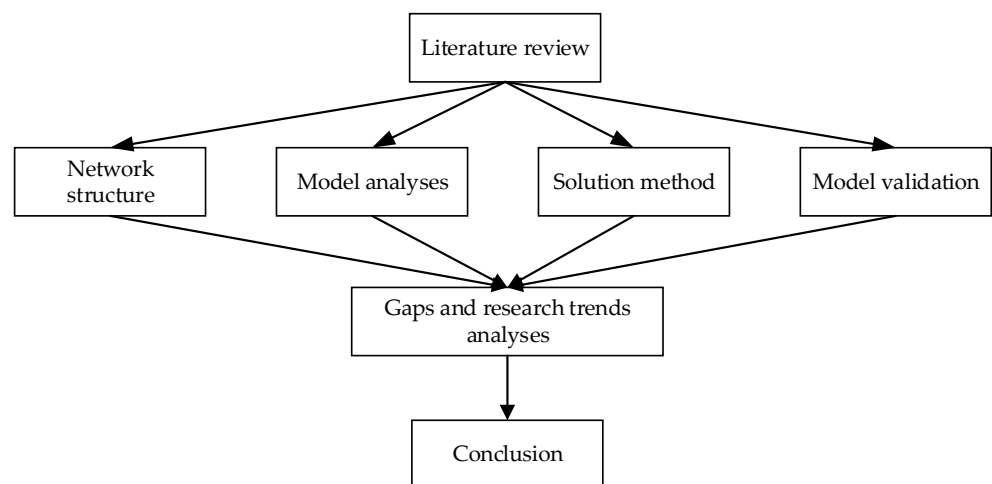


**Figure 2.** Framework for the study.

## 4. Network Structure

To design an RRL network, the first step is to determine the overall structure of the network. This section investigates the structure of the network. We divided the papers into the following three categories according to their different network structure characteristics.

### 4.1. General Network Structure

A reverse logistics network is often comprised of four stages: customers, collection centres, treatment plants and markets. As in Figure 3, the first stage is customer zones, where the used products are generated. The second stage is collection centre, to collect the used products from customer zones, and then the products are inspected and disassembled. After that, components with different values are sent to perform different operations, such

as remanufacturing and disposal. At the final stage, products are sent to different markets for resale.
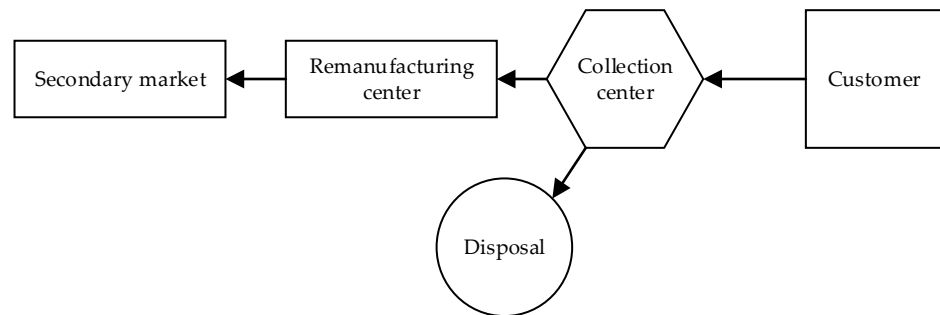


**Figure 3.** Structure of general RRL network.

The following is a basic structure in RRL network design papers. Of all the papers we reviewed, 20 of them used this structure.

*4.2. Network Structure of Closed-Loop Supply Chain*

If the market for remanufactured products differs from that of new products, the network is an open loop. The market for remanufactured products is usually a second-hand market. The networks mentioned in Section 4.1 are typical open loop networks.

In cases where the remanufactured products return to the same market as new products, the network is closed loop. A structure of a closed-loop supply chain network (CLSCN) is given in Figure 4. CLSCN integrate forward and reverse logistics. The supplier sent raw materials to the factory, where materials were manufactured into products. Then, the products were sent to the distribution centre for sale to customers. After the end of use, the products were collected by the recycling centre and sent to the remanufacturing centre. After the remanufacturing is completed, the product re-entered the forward logistics. CLSCN occurs when a customer who releases used products is also the consumer for the remanufactured products, such as medical products and industrial products [24]. Due to the concerns about the environment, many countries now advocate "Extended Producer Responsibility", in which manufacturers have to extend the traditional supply chain to include the end-of-life stage of products [7].
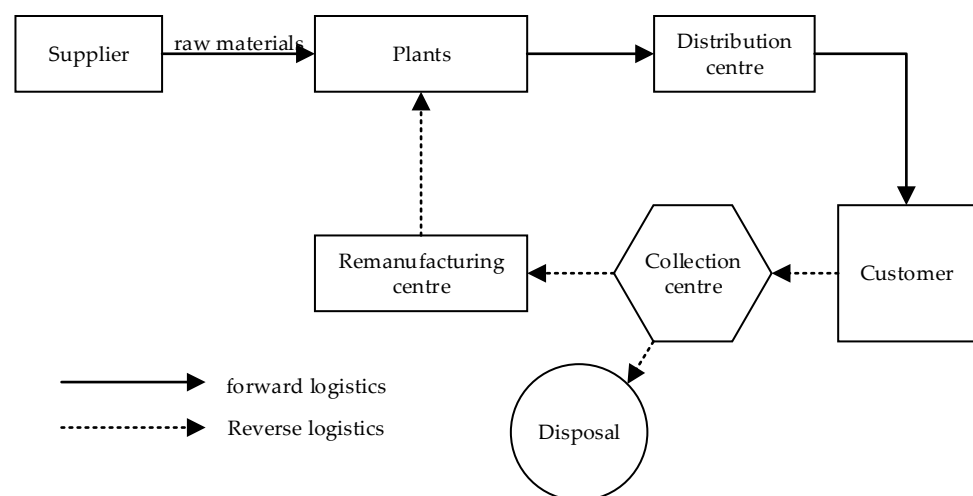


**Figure 4.** Structure of CLSCN.

Seventy-seven papers, more than half of the papers identified, have considered the closed-loop supply chain structures.

*4.3. Special Network Structure*

Some network structures of CLSCN that have some special characteristics are discussed in this section. Some have proposed the concept of hybrid facility. As shown in Figure 5, hybrid facility refers to the remanufacturing/manufacturing facility or collection/distribution centre at the same facility location, which enables the facility to have two different functions and enable the co-existence of forward and reverse logistics at the same time. Some papers considered hybrid manufacturing facilities, where products are manufactured and remanufactured in the same facility and shipped to distribution centres [6,25,26]. In addition to the hybrid manufacturing facility, others also considered the hybrid intermediate facility, e.g., the collection/distribution centre, where the distribution of both new and remanufactured products and the collection of used products are carried out [7,27–37]. The establishment of such hybrid facilities allows the utilization of the nodes of the existing forward logistics network to optimize the design of the reverse logistics network for remanufacturing. Moreover, this method can eliminate the need to establish a new reverse logistics network, thus effectively reducing the costs.
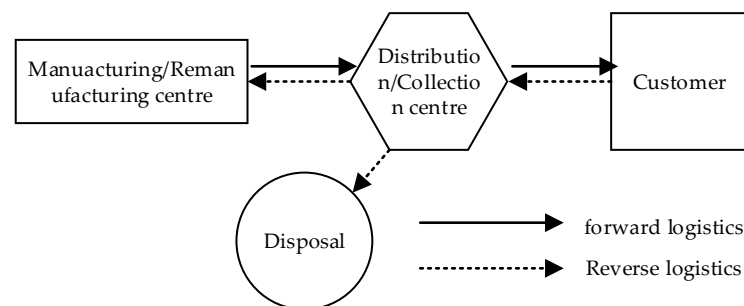


**Figure 5.** Structure of a hybrid facility network.

Regarding the treatment of waste products that could not be remanufactured and recycled, Yu and Solvang [38] and Subulan, Taşan, and Baykasoğlu [39] considered energy recovery to recover energy generated by incineration and biochemical treatment. These products and energy flows should be considered when optimizing the location of thermal treatment plants and are an interesting extension for future models.

Different products are selected for the network design, but few of them considered the product characteristics or remanufacturing processes as a characteristic for the network design. Zarei et al. [40] and Reddy et al. [41] designed a reverse logistics network for the ELV. In these papers the ELVs are disassembled into different components. Depending on the conditions of these components, decisions are made regarding the potential treatment of these components, including remanufacturing, recycling and disposal. Then, these disassembly components and parts are transported to various places, e.g., remanufacturing centres, recycling centres, and landfills, for further treatment. Paydar and Olfati [42] analysed the remanufacturing process of polyethylene terephthalate (PET) bottles. During the whole process, the PET bottles need to go through five different operations, including compression, crushing, cleaning and two granule making techniques before they can be resold into the market. Based on that, workshops with different remanufacturing process capabilities may be constructed. In the established network model, there are material flows of PET bottles between factories, and the PET bottles can only enter the market if specific remanufacturing steps were undertaken on these products. Such a network of various plants with different remanufacturing process capabilities provides a good direction for the further application of reverse logistics in different enterprises.

## 5. Model Analyses

After the network structure is determined, the mathematical models of the networks are discussed. In this section, the mathematical models are analysed regarding these factors, including decision variables, objective functions and constraint conditions.

### 5.1. Decision Variables

Decision variables are the first factor to be determined in a network model. In general, decision variables in a network can be divided into two stages. Table 2 lists several common decision variables at these two different stages.

**Table 2.** Common decision variables.

| Decision-Making Level | Common Decision Variables |
|---|---|
| Strategic level | Facility location<br>Mode of transportation<br>Remanufacturing technology<br>Facility capacity<br>Capacity extension<br>The investment amount of the network |
| Tactical level | Inventory level<br>Production volume<br>Connection between nodes<br>Recovery price of waste products<br>The sales price after remanufacturing |

At the first stage, the model mainly makes decisions at the strategic level. The decision variables at this stage are usually binary variables, which use 0 or 1 to define whether a facility is open, and whether a mode of transportation is selected and the technology is employed for remanufacturing or not. The mode of transportation can be selected by setting different vehicle types [31,39,41,43,44] or different types of transportation [36,45–48]. Remanufacturing technology [30,39,47–50] is related to the cost of the remanufactured products and the remanufacturing processes, rather than the location or capacity of the facility. Different remanufacturing technologies, such as inspection, cleaning, and repair (laser surface cladding, brush plating and thermal spray), require different equipment and incur different costs. In the process of remanufacturing, the selection of different remanufacturing technologies will also have a certain influence on the calculation of the model. Generally, the capacity of facilities is set to a constant value in the model, but some research, e.g., Zarei et al. [40] and Keyvanshokooh, Ryan, and Kabir [51] adds the selection of facility capacity to the decision variables, and Zhen et al. [52] and Üster and Hwang [53] set different capacity extensions. In the multi-period models, the investment value of the network [43,45,54] is also an important decision variable.

After selecting the appropriate sites, the second stage requires a tactical decision. At this stage, the decision variables mainly make decisions on the specific details in the network. The surplus inventory in the network [24,55–58] and the inventory level [30,39,41,51,59–63] are related to the production capacity of the factory, so it is of great benefit to select the appropriate inventory for the operation of the company. The transport between nodes can be represented by continuous variables, or whether two nodes are connected or not can be determined by binary variables [29,56]. In addition, the tactical decision of the network includes the production volume [62,64,65], the recovery price of waste products [41,64] and the sales price of remanufactured products [66]. As described above, in the process of determining decision variables, many scholars tend to analyse remanufacturing technology. Under the circumstances that multiple remanufacturing technologies are suitable for the same product, the cost of different technologies and their influence on the model are worth considering.

### 5.2. Objective Function

It is very important to determine the objective function in the design of RRL network. A network model cannot be solved without an optimization objective. In papers on network model, objective function is mainly divided into two categories, including single objective and multi objectives.

Common objectives in single objective models are the maximal total revenue or minimal costs. Two objective models are often employed to analyse network operations from two perspectives, including profits and losses avoidance. Other uncommon objectives are maximum sustainability [67], minimum carbon emissions [68], and maximum expected net present value [69]. This kind of single-object problem can be solved with different mathematical models, such as commercial solvers and heuristic algorithms, according to the size, characteristics and complexity of the model.

Of the 125 papers, 40 adopted multi-objective functions, as can be seen in Figure 6. The economic benefit of the network has always been the focus of network design papers. In addition to the minimum cost and maximum benefit used in the above single-objective models, the multi-objective models also take into accounts other factors affecting network economic benefits, such as service level [29], customer satisfaction [30], number of equipment [70] and network coverage and flexibility [71]. Ramezani, Kimiagari, and Karimi [72] apply the change in equity as the objective function to be optimized. Some papers consider the recovery rate of waste products [73,74], product return [75] and network fault [76,77], which have a certain influence on the network. Vahdani and Mohammadi [7] added the concept of queuing for two-way facility processing to the network, and its target includes minimum queuing time of remanufacturing products. For remanufactured products, the timeliness of distribution and the defect rate of the products are crucial. There are seven articles considering the on-time delivery target [26,75,78–82]; however, only four papers considered defect rate of products [26,29,78,83]. Social benefit targets in RRL networks are also very common, such as the maximal social welfare [35,36,48,49,84–87] and maximal job opportunities [49]. Due to increasing concerns of environmental problems recent years, the environmental benefits of RRL networks have been increasingly recognized. However, like any manufacturing activity, there are also some environmental problems associated with the RRL network, such as the construction of facilities and the transportation of products. Taking into consideration environmental objectives in the process of the network design optimization can minimize environmental problems associated with remanufacturing. In the reviewed papers, environmental objectives are mainly achieved by minimizing environmental impacts or maximizing environmental benefits, such as the minimization of carbon emissions [24,25,30,31,35,47,66,70,76,84,88–91], the maximization of green performances [78,87,92,93], minimum pollution emissions [66], minimum environmental problems [94], minimum environmental impacts of facilities and treatment processes [48,85], transportation [86] and transportation channels [81], maximising the environmental benefits of clean technology and recyclable materials [95] and the environmental benefits of recycled products [87].
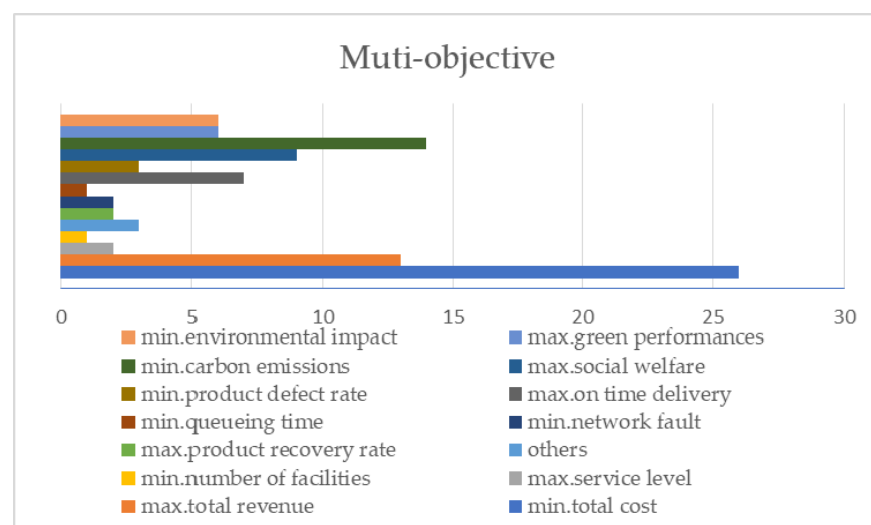


**Figure 6.** Different multi-objective functions.

In the selection of objective function, it is common to choose cost and profit, as well as green objective, e.g., carbon emission and environmental impact. In addition, the queuing time of remanufactured products and the rate of product defects are seldom considered in the remanufacturing reverse logistics network.

## 5.3. Constraints

It is very important to determine the constraints of the model, which is vital to whether the solution of the model can be proceed normally to gain the correct result.

In RRL network models, the most common constraints are flow conservation, processing and storage capacity constraints, demand satisfaction and allocation constraints between nodes for products. Other constraints are maximum number of facilities refs. [5,6,24,29,31,44,54,56,57,71,83,89,96–101], distance constraints between facilities refs. [43,45,47,54,63,71,96], capacity constraints of the transport routes [5,54,66,102–105], facility expansion constraints [43,45,52,54,106,107], remanufacturing technology selection constraints [30,49,50], network inventory constraints [30,39,51,59–62,70,92–94,104] and minimum throughput constraints of facilities [39,43,45,76,106,108].

There are constraints on proportion in some of the reviewed papers, including, e.g., the proportions of waste products in the recovery process [38,83,97,109–113], disposal [34,42,50,61,78,83,92,93,95,114–117], remanufacturing [62,65,82,110] and other procedures [56,63,64,90,118–123]. When multiple products are concerned, there are also constraints of demand proportion of each product [53,113] and the distribution proportion of each part after disassembly [55]. The model can be simplified by using the proportional constraint, but the proportional constraint method cannot reflect the actual situation well.

There are a few special constraints to be noted. In the papers considering the closed-loop supply chain, closed-loop constraints are included to ensure the closed-loop structure of the supply chain [46,60,124,125]. This constraint makes the network a closed loop by ensuring that each remanufactured product is returned to the same actors who undertake the forward flow in a reversed sequence. Some papers considered the price discount of raw materials ordered in large quantities and proposed the quantity discount constraints [26,30]. Four papers considered the constraints of carbon emissions [38,71,108,126]. Differently from the objective functions, the carbon constraints force the network to emit less than a certain amount. Yu and Solvang [90] suggested a flexible constraint of capacity, e.g., the capacity of facilities can be adjusted within a certain range. Hatefi et al. [27,127] added facility reliability constraints in their papers. In some multi-period papers, investment value and investment allocation constraints are utilized for each period [31,33,40,45,54,128].

In the determination of constraints, the constraints on the selection of remanufacturing technology need to be noted, which puts forward restrictions on the selection of remanufacturing technology, e.g., no more than one technology can be selected at a time, and the remanufacturing technology cannot be changed in multiple periods.

## 5.4. Solution Method

After establishing the mathematical model of the network, it is necessary to find a suitable method to solve the model. The method for solving a proposed model to (near) optimality depends on several of the characteristics discussed above. Depending on different factors, such as the problem complexity, size and the available computation time, priority can be given to exact or heuristic approaches.

If models are rather limited in size and complexity, such as single-objective or deterministic models, commercial software packages are able to find an exact solution in a reasonable computation time. CPLEX and LINGO are the most common commercial solvers used to solve mathematical models. Of the 125 papers reviewed, 31 used CPLEX [30,34,36,37,41,43,60,62,64,69,80,95,101,103,106,108–110,117,127,129–132] or LINGO [67,74,96,133–136] as a solution tool. Often, it is used with GAMS (or AMPL, AIMMS, IBM ILOG Optimi-zation Studio) as a higher-level programming environment.

In addition, there are solvers such as XpressSP [57], Knitro [75], Gurobi [91], etc. that are employed in the reviewed papers.

When the problem becomes large and complex, common methods cannot obtain the optimal result, so approximation methods (heuristics/meta-heuristics) need to be used. In recent years, numerous heuristics have been used to find a reasonably good solution in a limited computation time. In contrast to the exact solution methods, heuristics do not guarantee an optimal solution. However, as problem dimensions increase and models become more complex, these techniques become inevitable. The meta-heuristic algorithm is an improvement of the heuristic algorithm, which is the combination of the random algorithm and local search algorithm. Meta-heuristic is an iterative generation process. Through the intelligent combination of different concepts, this process realizes the exploration and development of search space with the heuristic algorithm. In this process, learning strategies are used to obtain and grasp the critical information to effectively find the approximate optimal solution. The meta-heuristic algorithm is mainly used to prevent the search from falling into the local optimal prematurely. The papers adopting the (meta-) heuristic algorithm include: the genetic algorithm (GA) [35,40,42,47,54,55,66,76,81,86,98,118,122,137,138], imperialist competition algorithm (ICA) [2,7], cuckoo optimization algorithm (COA) [48], tabu search [52,102], league championship algorithm (LCA) [114], seeker optimization algorithm (SOA) [111,120], artificial bee colony algorithm (ABCA), the ant colony optimization (ACO) approach [89], particle swarm optimization (PSO) algorithm [73], complex evolution algorithm (CEA) [139], simulated annealing (SA) algorithm [140] and artificial immune system (AIS) algorithm [58].

These algorithms have their own advantages and disadvantages. For the same model, different algorithms usually obtain different results. To bring the solution closer to the real value, some models adopt a hybrid algorithm [24,28,49,50,63,77,85,105], that is, a mixture of different algorithms for solving a problem, which can discard the defects of some algorithms and obtain better solutions.

As there have been many heuristics developed so far and since problem formulations do not differ substantially, it would be worthwhile to compare the performance of the proposed heuristic with existing ones. In some papers [49,53,85,87], the performance of algorithms is compared, among which, Fathollahi-Fard, Hajiaghaei-Keshteli, and Mirjalili [49] proposed three new hybrid metaheuristic approaches, each made up of three algorithms divided by a different order. The comparison between solvers and algorithms is shown in Hajipour et al. [141], Zarei et al. [40], Soleimani, Seyyed-Esfahani, and Shirazi [55], Paydar and Olfati [42], Alimoradi et al. [122], Zohal and Soleimani [89] and Sadjadi, Soltani, and Eskandarpour [142].

The combination of multiple algorithms has become a trend. The research of Fathollahi-Fard, Hajiaghaei-Keshteli, and Mirjalili [49] shows that different combinations of algorithms will produce different results. This confers certain inspiration for the future algorithm selection and how to better combine different algorithms.

### 5.5. Model Validation

Once the mathematical model of the network is established and the solution method is developed, cases are required to verify and apply the proposed model.

According to the different data sources of the cases, we divided them into three categories. The first category is the numerical experiment, in which the data used is fabricated within a certain range by the computer. The main purpose of such cases is to verify the validity of the model or the computational advantage of the algorithm. The second type is the reference cases, which uses the data obtained by referring to other papers or a reference dataset that combines data from the literature along with certain assumptions for some parameters [110], and whose function is the same as the first type of paper. The last category is the actual cases, which is the real case in life. The data are usually provided by some companies and enterprises. The purpose is to apply it to real life. In the reviewed papers, there were 65 numerical experiments, 12 reference cases and 44 actual cases.

In actual cases, the analysis of the network is often accompanied by information about geographical locations and product types.

Figure 7 shows the regional distribution of actual cases around the world. It can be intuitively seen from the figure that before 2014 and 2015, the cases of the RRL network were mainly applied in Portugal [36,69,117,143], the Netherlands [68], Greece [60], Germany [106], Italy [91] and other European countries. After that, there are some cases in America [53,88,144], but more cases are beginning to be developed in developing countries, such as Iran [4,24,42,70,85,86,126,132], India [41,44,56,67,71,75,96,135,136,145], China [63,76,118,133,137,139] and the United Arab Emirates (UAE) [43,54,84]. This is closely related to the increasing environmental awareness of the general public in these areas and the government's attention to environmental issues.
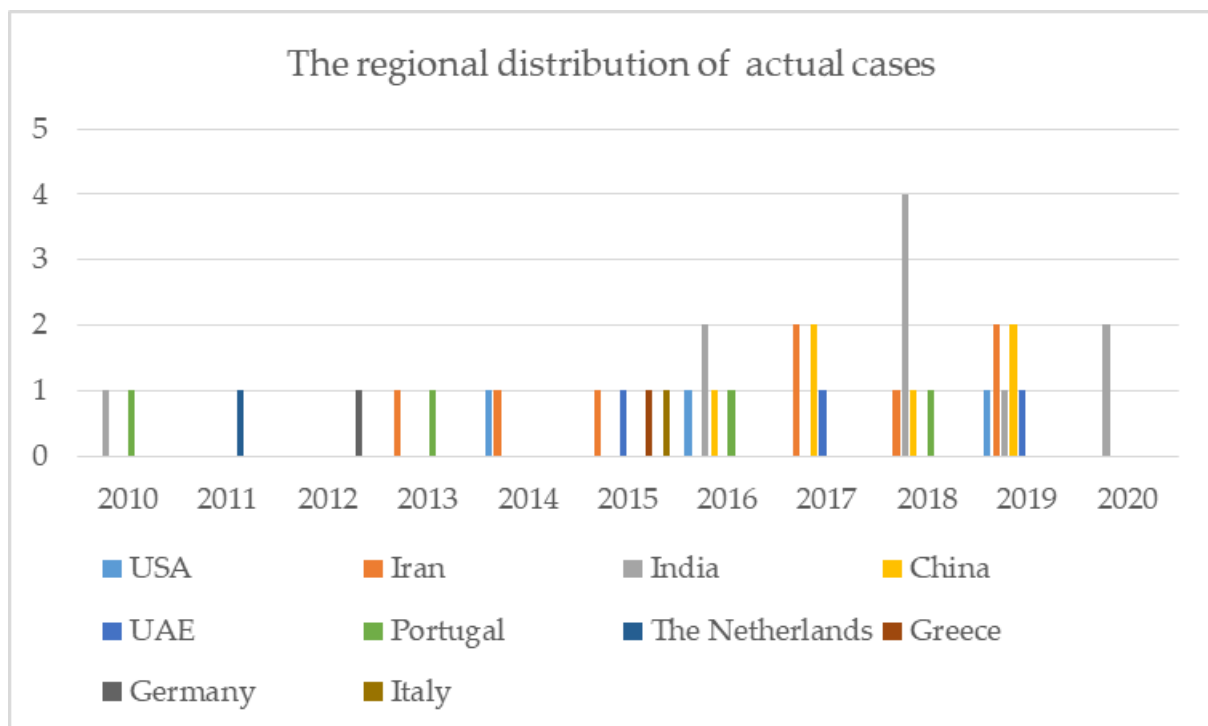


**Figure 7.** The regional distribution of actual cases.

The waste products that are to be remanufactured need to have the value for reuse and the technology is available to achieve remanufacturing. According to the papers reviewed, the general products to be remanufactured are electronic products, such as laptop [46,83,97,119], cell phones [61,136], cameras [136] and other electrical and electronic equipment (WEEE) [36,78,82,86,99], household appliances [37,43,67,106,112,115,135], batteries [41,44,84,92], vehicles [40,103,109,132,139], and tires [39,65,71,96,123]. Figure 8 shows the number of different product types. In addition to the above common remanufacturing products, there are also large construction machinery [118], hospital equipment [24], furniture [91], glass [85,117], LEDs [74] and PET bottles [42]. The temporal distribution of product types can be seen in Figure 8.
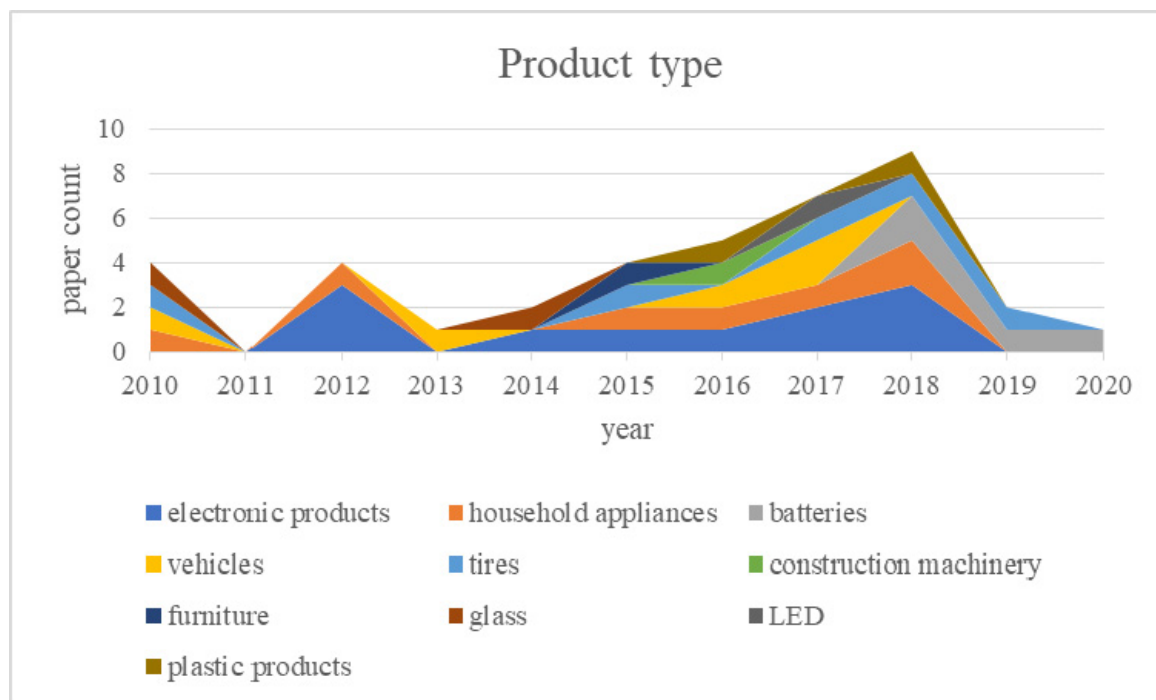
**Figure 8.** Different product types.

## 6. Gaps and Research Trends Analyses

Based on the different sections above, research gaps were identified and analysed by the researchers. A summary of the findings and research trends is discussed in the following sub-sections.

### 6.1. Novel Structures in Networks

Figure 1 in Section 3 illustrates a significant increase in research interests in RRL network design from 2010 to 2020. This indicates that RRL is gaining increasing attention from scholars. In their studies, the CLSCN is often adopted as it can facilitate the remanufacture and resale of waste products. As can be seen in Figure 9, papers on CLSCN are gradually increasing. Of all these papers, 10 considered hybrid facilities. As we mentioned in Section 4, such a network structure provides a good method for the establishment of reverse logistics network with lower cost and shorter time, which is a trend in the field for enterprises and researchers. However, there are still deficiencies in existing studies on hybrid facilities. The hybrid facilities proposed in the papers mostly exist in manufacturing/remanufacturing centres, and recycling/distribution centres, without considering the potential of sharing other logistics facilities in CLSCN, which is a point that needs to be improved in the utilization of hybrid facilities.

In the process of combining with practice, few papers considered the possible impact of remanufacturing technology on the reverse logistics network structure. The remanufacturing technologies of products are different; when designing the network structure, in addition to analysing the recycling process of waste products, the difference of its processing process also needs to be further analysed, so as to establish the RRL network structures that conform to the reality. This can be seen in the papers of Paydar and Olfati [42], Zarei et al. [40] and Reddy et al. [41], who designed different networks by analysing the remanufacturing processes of PET bottles and vehicles. The combination of other products and network structures is what we need to consider.
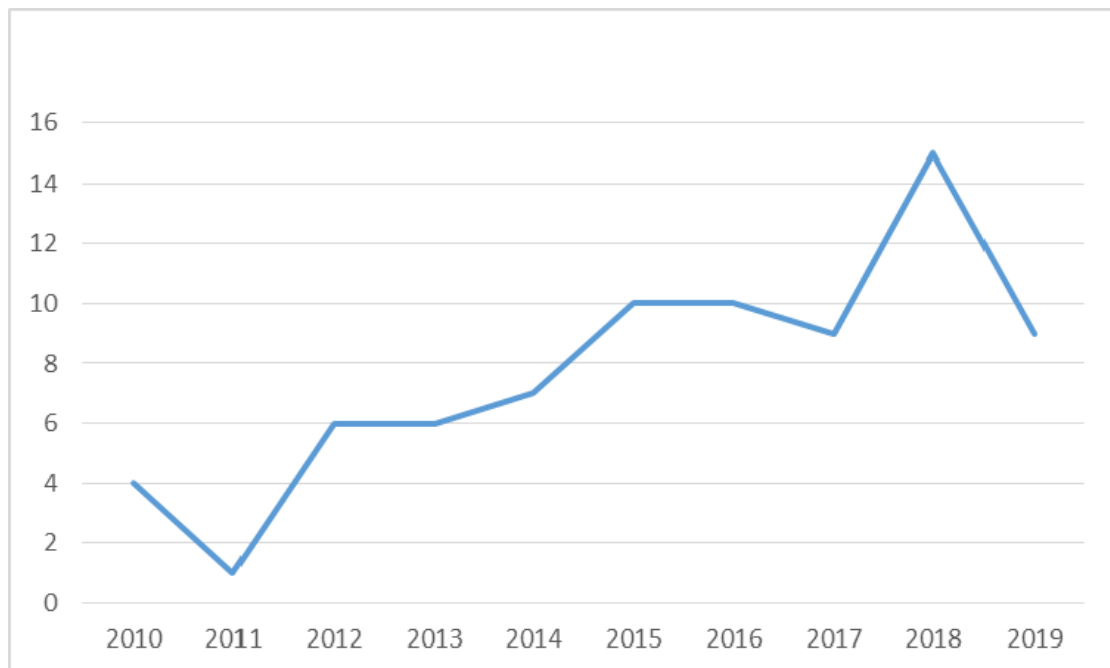
**Figure 9.** Number of papers in CLSCN per year.

*6.2. Different Elements in the Model*

Mathematical modelling plays an important role in the process of network design. Different model parameters and solving methods in the papers will be analysed below.

As mentioned in Section 4, most of their models adopted multiple objective functions. Most of these models is to minimize costs or maximize benefits combined with another objective, such as environmental, social benefits, and product quality. However, there are some more specific objectives that need to be noted. Vahdani and Mohammadi [7] proposed the concept of two-way facility processing queuing in the network, with the purpose of reducing the processing time of remanufactured products. Vahdani et al. [77] developed a bi-objective mathematical programming formulation which minimizes the total costs and the expected transportation costs after failures of facilities of a logistics network. Rajak, Parthiban, and Dhanalakshmi [81] considered the impact of different transportation channels on the environment. These papers explain the key factors in the RRL network model from different aspects and analyse the relationship between different factors and their influence on the model, which provide a good method in model constructing.

The RRL network has a high degree of uncertainty. The establishment of an RRL mathematical model needs to solve this problem. The time, quantity and quality of waste products in the collecting process are uncertain. Some products have multiple collecting channels, so the channel selection in the collecting process is also uncertain. These features make it difficult to establish the RRL model. Most of the papers considering uncertainty focused on the quantity and quality and did not carry out in-depth analysis of other aspects. The uncertainty of collecting time and collecting channel of waste products is worth studying.

In the analysis of Section 5, we find that there are constraints on the recycling ratio and remanufacturing ratio in many papers. This method simplifies the model and makes it easier to obtain results, but it suffers from a lack of accuracy. The common methods to deal with uncertainty are stochastic programming [146], while scenario-based methods are used to analyse uncertainty factors and calculate the optimal expectation to obtain the optimal scheme of RRL network under an uncertain environment. Other ways to deal with uncertainty are mathematical models based on triangular fuzzy number or robust design.

*6.3. Product Type*

There are many types of products that have been applied in the papers. As shown in Section 6, the most common remanufactured products are electronic products, because they have a relatively perfect recovery mechanism, and the network structure can be optimized according to the existing mechanism when establishing the reverse logistics network. Other types, such as hospital equipment and furniture products, have fewer analyses. The remanufacturing technology of some products has been applied in practice. However, the recovery system is still not complete, which makes it difficult to establish reverse logistics. It is a good direction to analyse the network structure of these products and discuss the establishment of the product recovery system in this paper.

*6.4. Research Trends*

The development of modern society has promoted the emergence of many new technologies, which are applied to all aspects of industry, and have a great impact on RRL. With the development of intelligent technology, intelligent remanufacturing will become a realizable technology complex and will continue to develop in the future [147]. It is worth studying how intelligent remanufacturing and other technologies will affect the existing RRL network.

Industry 4.0 (I4.0) emphasizes intelligent production, and the application of intelligent technologies can have a great impact on logistics networks. According to the analysis of [148,149], I4.0 mainly includes emerging technologies such as the internet of things (IoT), cloud technologies, artificial intelligence, big data analytics, etc. As we mentioned in Section 5, remanufacturing technology has a great influence on the model, and the decision of different technologies has a great impact on the network. As the fusion of remanufacturing technologies and intelligent technologies, intelligent remanufacturing technology is based on the whole life cycle data of products which enables automatic remanufacturing processes and seamless information flow and interactions between remanufacturing processes and RRL. Reference [150] provides us with a technology, additive remanufacturing, also known as three-dimensional (3D) printing. This technology creates parts by adding materials in layers, providing a beneficial ability to construct parts with geometric and material complexity, while contributing to the reuse of materials and reducing environmental problems. This paper describes the application of additive technology in the field of remanufacturing and provides different additive remanufacturing technology, which provides a new factor for the research of the RRL network model.

As can be seen from the analysis of [148], the development of technology requires corresponding infrastructure, which presents new challenges to RRL's network. While applying new technologies, the establishment of new facilities are required, which thus incurs more costs. It is necessary to analyse and balance the benefits brought by technology and the cost of facilities. In the analysis of [149], it is worth noting that the semi-automation of trucks can improve efficiency and reduced labour costs in the process of logistics transportation, and reduced fuel consumption and carbon emissions.

Industry 5.0 adds people-oriented theory to industry 4.0, emphasizing the more sustainable people-oriented transformation in the process of intelligent production. Future research is thus needed to understand how human-centric smart transformation can be achieved in logistics sectors. I5.0 could revolutionaries remanufacturing, and a promising future research area could be the integration of I5.0 and RRL.

## 7. Conclusions

In this paper, a comprehensive review of a remanufacturing reverse logistics and closed-loop supply chain network design is presented. A total of 125 online papers published until 2020 are selected, reviewed, and categorized based on the proposed criteria of this study. The review has shown that there is a significant increase in the number of studies after the year 2011. These studies focus on many different network structures, mathematical models, and product types, which developed the RRL research.

It was found that the Journal of Cleaner Production, Applied Mathematical Modelling, and European Journal of Operational Research represent primary publication outlets for the investigated research area. The results can help researchers interested in remanufacturing reverse logistics networks to understand the research content of published papers and future research opportunities. The mainly findings and opportunities are shown below:

(1) The research on RRL networks has been focused on closed-loop supply chain structure. Some papers adopted a hybrid facility network structure, in which enterprises can establish reverse logistics networks on the basis of existing logistics networks. This network structure provides a method for the establishment of reverse logistics network with lower cost and shorter time, which provides a good direction for researchers.

(2) Among various mathematical models, the constraints of remanufacturing technology and products have been the concern of many scholars and provide a reference for model building. Considering remanufacturing techniques for different products can make the networks more specific and more applicable to real life. In addition, we found that in terms of uncertainty, factors such as the uncertainty of collecting time and collecting channel are worth studying.

(3) We conducted a descriptive analysis of existing new technologies in order to bring new opinions to existing RRL networks. These new technologies will change the structure of existing networks and have impacts on mathematical models, which is worth further study.

However, this review has its own limits. The search and screening of papers is subjective, and the characteristics of papers are not well analysed in the statistical process. Some opinions in this paper are relatively simple and lack of in-depth analysis, which needs to be improved in the future.

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