Mapping Methodologies and Research Gaps in Remanufacturing Policy: A Bibliometric Insight Toward Circular Sustainability

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Abstract: This research presents a bibliometric analysis of remanufacturing policy research, focusing on key methodologies, thematic clusters, and trends that shape the field. The research explores policy frameworks supporting circular economy principles, resource efficiency, and environmental sustainability. By mapping research methodologies such as Life Cycle Assessment (LCA), simulation modeling, and optimization models, this research highlights their applications in remanufacturing policies and decision-making. The findings indicate that while reverse logistics, closed-loop supply chains, and sustainability policies are central themes, emerging areas like carbon emissions, pricing models, and game theory remain underexplored. The research identifies gaps in policy-focused research, emphasizing the need for interdisciplinary approaches integrating economic, regulatory, and technological dimensions. Recommendations for future research include enhancing policy-driven modeling, incorporating agent-based modeling and simulation (ABMS) and system dynamics (SD), and expanding the role of decision support systems. These insights contribute to advancing sustainable remanufacturing policies aligned with circular sustainability goals.

Keywords: circular sustainability; closed-loop supply chain; decision support systems; environmental policy; optimization modeling; remanufacturing policy; reverse logistics

1. Introduction

Remanufacturing is a crucial component in advancing sustainability and promoting the circular economy by extending product life cycles and minimizing waste[1]. Unlike traditional manufacturing, remanufacturing involves restoring used products to a like-new condition, thereby reducing the demand for raw materials and energy-intensive production processes[2]. This approach significantly contributes to resource and energy conservation, carbon emission reduction, as well as the mitigation of environmental degradation[3,4].

Remanufacturing is an industrial process that restores used products, known as cores, to their original or like-new condition while ensuring they meet the same performance and quality standards[5,6]. As shown in Figure 1, the process begins with collection, where cores are retrieved from customers or other sources. This step is critical to ensure the availability of products that can be remanufactured[7]. After collecting, the cores go through disassembly, where they are carefully taken apart into individual components. This step requires precision to prevent damage and ensure that parts can be reused effectively[8].

Once disassembled, the components are assessed during the inspection and sorting stage. Here, parts are evaluated to determine whether they are functional, repairable, or need to be discarded[9,10]. Components that pass the inspection move to the cleaning phase, where dirt, grease, and other contaminants are removed to prepare the parts for further processing. In the repair stage, damaged components are restored using advanced methods such as welding or machining. If necessary, replacement parts are added to ensure the product's functionality. After repair,

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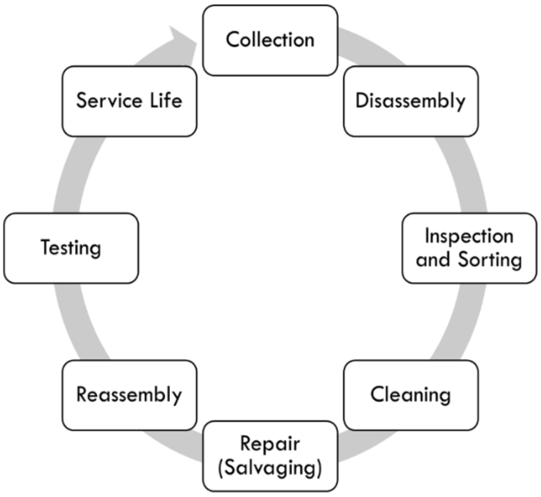

Fig. 1: Remanufacturing Processes (Adaptation from[5,22])

the components are reassembled during the reassembly stage to form the remanufactured product[11]. Finally, the product undergoes rigorous testing to ensure it meets the original performance and quality standards. Products that pass testing are then returned to the market, often with warranties similar to new products[12,13].

In the context of the circular economy, remanufacturing not only facilitates material reuse but also enhances economic resilience by creating new business opportunities and reducing dependency on finite resources[14,15]. Its role has been recognized across various industries, particularly in the automotive[16,17], electronics[18,19], and heavy machinery sectors[20,21], where remanufacturing can substantially lower environmental footprints while maintaining product quality.

Despite its clear advantages, remanufacturing operations face several challenges, including managing reverse logistics[23], ensuring consistent product quality[24], and navigating complex environmental regulations[25]. To overcome these challenges and maximize the benefits of remanufacturing, there is a growing need for robust policies and decision-making frameworks. Such frameworks must balance operational efficiency with environmental sustainability, offering tools for effective planning, execution, and evaluation. By addressing these issues, policymakers and researchers can develop strategies that strengthen the contribution of remanufacturing to sustainability and the circular economy. This underscores the importance of this research, which seeks to map and enhance the methodological landscape in remanufacturing research.

1.1. Problem Statements and Research Objectives

Although remanufacturing research has grown in recent years, there are still important gaps. Many studies focus on general topics like sustainability and the circular economy[2,26,27]. However, there are very few studies that look closely at the methods, scope, objectives, and impacts of remanufacturing policy research. Without this understanding, it is difficult to develop strong frameworks to guide decision-making and improve both operations and environmental outcomes.

Most of the existing research looks at methods individually or focuses on narrow applications. This makes it hard to see how these methods can work together or apply to different goals, like improving efficiency, reducing environmental impacts, or supporting policies. Since remanufacturing happens in many industries, such as automotive, electronics, and machinery, it is important to better understand how methods are used in different contexts.

Therefore, this research aims to address these gaps by exploring how current methods are used in remanufacturing research. It will map these methods to their objectives and impacts, identify what is missing, and suggest future directions to improve remanufacturing policy and research. This paper contributes by providing an overview of methods in remanufacturing research, mapping them to their objectives, scopes, and impacts. It identifies research gaps and proposes future directions for more effective approaches, offering insights to help researchers and policymakers address challenges and improve remanufacturing strategies.

This research contributes to advancing sustainable practices and fostering a carbon-neutral society by addressing critical aspects of remanufacturing policy research. The focus on mapping methodologies in remanufacturing aligns with broader efforts to reduce environmental impacts through circular economy strategies. For instance, studies have shown how adopting circular economy principles can significantly reduce greenhouse gas (GHG) emissions, improve resource efficiency, and support sustainable development[28]. Furthermore, remanufacturing contributes to minimizing waste generation and optimizing material flows, a key pillar of the circular economy[29]. By exploring methodologies that enhance remanufacturing policies, this research supports the development of decision-making frameworks that align with global sustainability goals, including reducing environmental degradation and promoting resource recirculation. Additionally, incorporating innovative methods, such as Life Cycle Assessment (LCA) in policy frameworks strengthens efforts toward achieving environmental sustainability and improving remanufacturing processes[30]. This contribution directly addresses pressing challenges in sustainable resource management and offers actionable insights for policymakers and researchers.

1.2. State of the Art of Bibliometric Analysis on Remanufacturing

Bibliometric analysis is widely used to examine research trends, identify influential works, and highlight gaps in a particular field[31,32]. In remanufacturing research, bibliometric studies help map the evolution of topics, methodologies, and thematic clusters over time. Given the increasing focus on circular economy and sustainable production, analyzing bibliometric studies on remanufacturing provides valuable insights into how research has developed and what areas remain underexplored. To ensure a comprehensive review, an initial search using Publish or Perish 8© with the keywords "remanufactur*" AND "bibliometric" was conducted on the Scopus database, covering the last four years (2020–2024). This search initially generated 84 papers, and after reviewing titles, keywords, and abstracts, 14 papers were identified as closely related to the topic of this research. Table 1 presents a summary of these selected papers which provides an overview of their focus, methodology, database used, and key contributions.

Several bibliometric studies have analyzed different aspects of remanufacturing. A bibliometric review of closed-loop supply chains was conducted to identify major research trends and emerging areas[33]. Circular supply chains and mapped key contributions were explored to improve sustainability[34]. Inventory models in sustainable supply chains were investigated to provide an overview of how inventory control contributes to sustainable practices[35]. Another research from[36] examined remanufacturing in product-as-a-service models, while the other analyzed global circular economy trends through bibliometric techniques[37]. These studies provide a broad understanding of remanufacturing research but do not specifically examine how different research methods are applied to various scopes and objectives.

Despite the valuable insights from previous studies, certain gaps remain. Most bibliometric analyses in remanufacturing have focused on general research trends, such as sustainability aspects and supply chain-related topics, but they have not systematically linked research methods with their specific applications and outcomes. For example, studies from[38] and[39] explored circular economy policies and warehouse management, but their studies did not differentiate how particular methodologies, such as mathematical modeling, system dynamics, or multi-criteria decision analysis (MCDA), are used in remanufacturing research. Additionally, while studies like[40] on battery recycling, NEVs discuss policy and technical strategies, but they do not map which methods are best suited for policy evaluation versus operational optimization.

This research addresses these gaps by explicitly examining which research methods are commonly used, what research scope they fit, and what impact they produce in remanufacturing policy research. Unlike previous bibliometric studies that primarily track thematic trends, this research categorizes methods based on their specific applications, such as optimization techniques for operational challenges, system dynamics for policy evaluation, and LCA for environmental impact analysis. By structuring the analysis around methods, scope, objectives, and impacts, this research provides a more systematic and practical framework for understanding how different approaches contribute to remanufacturing research.

By integrating a content-based perspective with bibliometric analysis, this research contributes to a better alignment between research methods and real-world remanufacturing challenges. The findings will help researchers, policymakers, and industry practitioners select appropriate methodologies based on their intended research scope and objectives. In doing so, this research offers a more practical and policy-relevant perspective compared to previous bibliometric studies which ensures that future research in remanufacturing is both methodologically rigorous and practically applicable.

2. Materials and Method

2.1. Research Design

This section explains how the research was designed to explore remanufacturing policy research using bibliometric content analysis. Research design is important to ensure the research follows a clear plan and achieves its goals. This research combines bibliometric techniques to identify methods, themes, and trends in remanufacturing research, focusing specifically on policy. The following parts explain the purpose of the research, why bibliometric analysis was chosen, the main ideas behind the methods, and the scope of the research.

This research places circular economy as an important concept by considering its growing influence to shape remanufacturing policies. The circular economy highlights the need to keep resources in use for as long as possible and reduce waste through remanufacturing. Therefore, the research explores how existing studies address circular economy goals using various methods and policy tools.

2.1.1. Purpose of Research

This research aims to systematically explore remanufacturing research by using bibliometric content analysis, with a focus on remanufacturing policy. The main goal is to investigate the methods, scope, objectives, and impacts within the field. This includes finding out which methods are commonly used in policy-related studies and understanding how these methods contribute to remanufacturing research. The research provides important insights into the structure and themes in this field, which can help both researchers and policymakers.

2.1.2. Choice of Bibliometric Analysis

Bibliometric analysis has several techniques, each useful for different purposes. For example, co-authorship analysis

Table 1: Previous Studies Related to Bibliometric Analysis on Remanufacturing

Reference	Year	Research Scope/Focus	Review Method	Database Used	Key Findings/Contribution
33)	2020	Closed-Loop Supply Chain	Bibliometric Review	Web of Science	Trends in closed-loop supply chains and emerging research areas
34)	2024	Circular Supply Chains	Bibliometric & Network Analysis	Scopus & Web of Science	Strategic framework for circular supply chain integration
35)	2022	Inventory Models in Sustainable Supply Chains	Bibliometric Analysis	Scopus	Identified trends in inventory models for sustainability, analyzed most cited papers
36)	2023	Remanufacturing in Product-as-a-Service	Systematic Literature Review	Scopus	Challenges & opportunities for remanufacturing in PaaS models
37)	2021	Circular Economy Development	Bibliometric Analysis	Scopus	Global analysis of circular economy trends and future research agenda
38)	2024	Circular Economy & Communities	Systematic Literature Review	Scopus	Stakeholder engagement in CE transition and participative dynamics
39)	2023	Warehouse Management & Sustainability	Systematic Literature Review & Bibliometric Analysis	Scopus & Web of Science	Sustainability impacts of warehouse management systems
40)	2024	Battery Recycling in NEVs	Bibliometric Analysis	Web of Science	Policy & technical strategies for battery recycling in NEVs
41)	2022	Internet of Things (IoT) in Circular Economy	Systematic Literature Review	Scopus & Web of Science	Framework on IoT in CE, identifying enablers and barriers
42)	2023	Green Manufacturing	Perspective Review	Scopus	Future research directions in green manufacturing
43)	2023	X-Reality & Lean in Aircraft Remanufacturing	Critical Review	Various Industry Sources	Integration of XR and lean methodologies in aircraft disassembly
44)	2022	Circular Economy Measurement & Multi-Criteria Decision Making (MCDM)	Systematic Literature Review	Scopus & Web of Science	Mapped MCDM techniques for CE assessment, summarized 22 MCDM techniques
45)	2021	Dual & Multi-channel Closed-loop Supply Chains	Content-Based Analysis	Web of Science & Google Scholar	Analysed multi-channel strategies in CLSCs, proposed future research directions
46)	2024	Reverse Logistics & Sustainability	Bibliometric Analysis	Scopus	Mapped research trends in reverse logistics, identified key authors & collaborations

looks at collaborations between researchers, citation analysis identifies important papers, and co-citation analysis examines relationships between frequently cited publications. In this research, co-occurrence analysis was chosen because it focuses on the relationships between keywords. This method identifies patterns and themes by mapping how keywords are connected in the dataset. Co-occurrence analysis is widely used to explore themes and methods in research fields, making it suitable for exploring remanufacturing policy[47,48]. It also highlights how methods and policies are related, helping to show the main approaches in the field.

2.1.3. Conceptual Framework

As shown in Figure 2, this research uses the concept of science mapping to better understand remanufacturing policy research. Science mapping studies the relationships between keywords, themes, and clusters in the dataset. Science mapping helps reveal the structure of a research field[32], while it also uncovers trends and emerging topics[31]. In this research, science mapping is used to find which methods are most common in remanufacturing policy research and how they are related to key policy themes. This approach ensures that the research captures both the main ideas and the connections between them. Therefore, performance analysis was not conducted in this research because the primary focus is on identifying and mapping methodologies and thematic connections within remanufacturing policy research, rather than evaluating contributors such as authors, institutions, or journals.

2.1.4. Scope of Research

The scope of this research focuses on the intersection of remanufacturing, policy, and methodologies. The research looks at publications discussing remanufacturing policies, such as industrial regulations, strategic policies, and frameworks. It excludes unrelated topics like recycling, waste management, or construction. This ensures that the dataset is directly relevant to remanufacturing policy. Co-occurrence analysis is used to identify patterns and trends in the selected publications[49]. The results provide clear insights into the methods and themes that are most important in this field, helping researchers and policymakers better understand the landscape of remanufacturing policy research[48,49].

2.2. Research Methods

The methodology in this research is adapted from the frameworks of[32,35]. By combining their approaches, a detailed seven-step process was developed to systematically explore remanufacturing policy research using bibliometric analysis as shown in Figure 3. The method is specifically tailored to analyze the methodologies used in this research domain and employs co-occurrence analysis as the primary technique.

The bibliometric data for this research was collected from the Scopus database, which was selected as the primary source due to its broad coverage of peer-reviewed research, structured metadata, and comprehensive citation indexing. Scopus is widely used in bibliometric studies because it provides detailed citation tracking, keyword co-occurrence information, and author affiliation data, which are essential for conducting co-occurrence analysis and network visualization. The structured indexing in Scopus also facilitates a systematic and reproducible data extraction process, ensuring that only high-quality academic sources are included in the analysis.

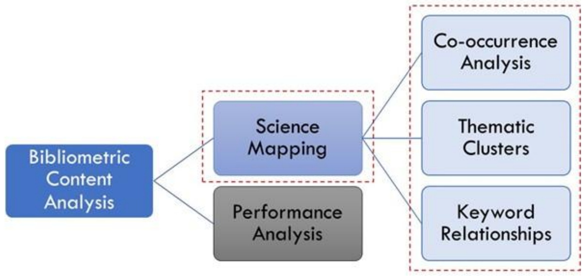

Fig. 2: Conceptual Framework

However, it is acknowledged that relying on a single database presents a limitation, as some relevant studies indexed in Web of Science, Google Scholar, or Dimensions may not be included in the dataset. While Scopus provides extensive coverage of journal articles, it may not fully capture conference proceedings, book chapters, and industry reports, which could also contribute valuable insights to remanufacturing policy research. Future studies could enhance coverage by incorporating multiple databases to obtain a more comprehensive dataset, ensuring a broader representation of research trends in remanufacturing.

2.2.1. Define the Research Questions

The primary aim of this research is to identify the commonly used methods in remanufacturing policy research. This includes exploring thematic clusters, trends, and intellectual structures within the field. The scope focuses on publications discussing remanufacturing in conjunction with policy, methodologies, and related concepts. Specific research questions were formulated to address gaps in the literature, particularly the intersection of methods and policy-related studies in remanufacturing. The main research question is: *"How have current methods been applied to support remanufacturing policy in the context of the circular economy?"*

This main question is supported by the following subsidiary questions:

1) What are the commonly used research methodologies in remanufacturing policy research, and how are they linked to specific policy focus areas and decision-making tools?

This question explores the main methodologies applied in remanufacturing policy research, such as LCA,

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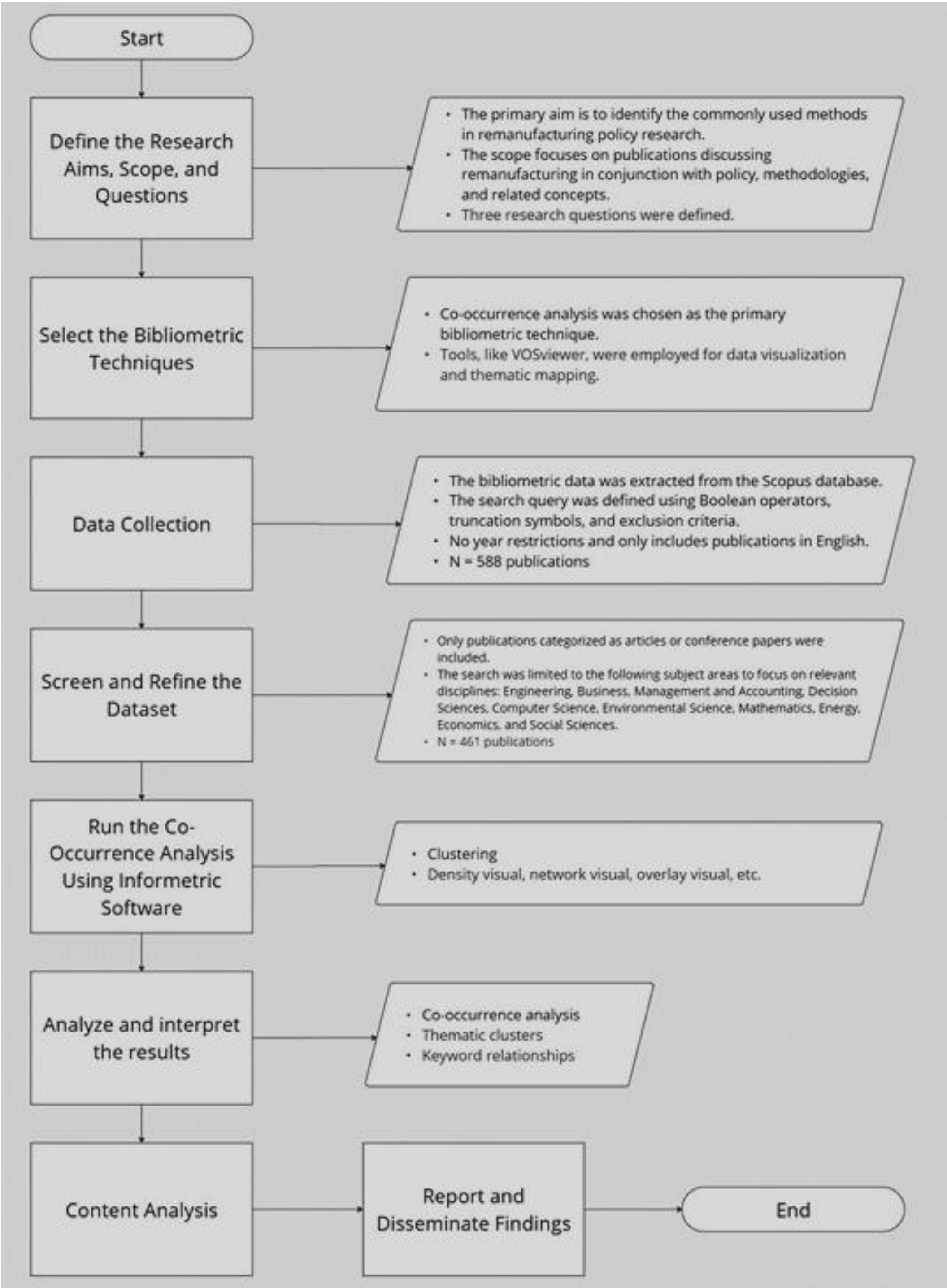

Fig. 3: Research Methodology

simulation modeling, and optimization methods. It also examines how these methodologies align with policy objectives like sustainability, environmental regulations, and decision-making tools used to address operational challenges.

2) What are the key thematic clusters, top-impact terms, and keyword connections that define the intellectual structure of remanufacturing policy research?

This question identifies the thematic clusters and key terms that frequently appear together in remanufacturing research. It aims to map how keywords like "reverse logistics" and "closed-loop supply chains" form thematic connections, defining the intellectual structure and focus of the research field.

3) What trends and gaps exist in remanufacturing policy research methodologies, and how can these be addressed to align with sustainability and policy goals?

This question focuses on emerging trends, such as the increasing use of data-driven decision-making, while highlighting gaps in certain clusters where methodologies or policy applications are underexplored. It addresses how future research can better align with sustainability goals by filling these gaps.

2.2.2. Data Collection and Verification

The bibliometric data was extracted from the Scopus database. The search query used to filter relevant studies is as follows:

```
("remanufacturing" OR "product
recovery") AND ("policy" OR
"strategic policy" OR "industrial
policy" OR "regulation" OR "law")
AND ("method*" OR "tool" OR
"framework" OR "approach*") AND NOT
("recycling" OR "waste management"
OR "wastewater treatment" OR
"build*" OR "construct*" OR “laser”
OR
```

This query is designed to precisely target publications that focus on remanufacturing and its connection to policy and methodologies while excluding unrelated topics such as recycling, waste management, and construction. The query incorporates Boolean operators, truncation symbols (*), and exclusion criteria (NOT) to ensure a high-quality dataset that aligns with the research objectives[48].

No year restrictions were applied to capture the full evolution of research in this field and this research only includes publications written in English. As a result, this process generated 588 publications with a publication year range of 1974–2024. The data retrieval was conducted on January 14, 2025.

2.2.3. Screen, Refine, and Verify the Dataset

The dataset was refined using specific inclusion and exclusion criteria. Only publications categorized as articles or conference papers were included, as they represent the most reliable and structured sources of research findings. Additionally, the search was limited to the following subject areas to focus on relevant disciplines: Engineering, Business, Management and Accounting, Decision Sciences, Computer Science, Environmental Science, Mathematics, Energy, Economics, and Social Sciences. Publications that did not meet these criteria or were duplicates were excluded to ensure the dataset was comprehensive yet focused.

$$NCS = \frac{Actual\ Citations\ of\ a\ Document}{Average\ Citations\ of\ All\ Documents\ Published\ in\ the\ Same\ Year} \quad (1)$$

To ensure that the selected papers specifically focused on remanufacturing research, a verification method was applied. The first step involved keyword filtering, where papers containing the terms “remanufacturing” and bibliometric-related keywords in their title, abstract, or keywords were prioritized. This step helped refine the dataset by removing publications that primarily discussed general sustainability topics without explicitly addressing remanufacturing. While sustainability, recycling, and waste management are closely related to remanufacturing, papers that focused predominantly on these topics without specific discussions on remanufacturing systems, policies, or methodologies were flagged for further screening.

Following keyword filtering, a title, abstract, and keyword screening process was conducted to confirm the relevance of each paper. Papers that did not provide a clear discussion on remanufacturing but rather focused on broader circular economy concepts were excluded. If the abstract alone did not provide sufficient clarity, the full text of the publication was reviewed to determine its alignment with the scope of this research. Specifically, papers were excluded if remanufacturing was only briefly mentioned without a detailed analysis of its policy implications, methodologies, or decision-making frameworks.

After applying this multi-step verification process, the dataset was refined to 461 papers, which were subsequently analyzed using VOSviewer. These papers formed the basis of bibliometric research which enables a structured analysis of research methodologies, thematic clusters, and trends in remanufacturing policy research. This process resulted in a final dataset of 461 publications to ensure a comprehensive yet focused collection of relevant studies.

2.2.4. Running and Summarizing the Co-Occurrence Analysis

The refined dataset was analyzed using VOSviewer, which provides advanced co-occurrence analysis capabilities. This analysis involved mapping relationships between keywords based on their frequency of co-occurrence in titles, abstracts, and keywords. VOSviewer enabled the generation of keyword co-occurrence networks and thematic clusters, allowing for a deeper understanding of the intellectual structure of remanufacturing policy research. Key clusters and their dominant themes were visualized through bibliometric network maps. To ensure that only significant keywords were included in the analysis, a minimum occurrence threshold of five (5) times was applied. This threshold was set to filter out rarely used terms while retaining keywords that frequently appear in the dataset which allows for a more meaningful co-occurrence network. The results revealed several thematic clusters, which are further analyzed in Chapter 3. These clusters highlight the dominant approaches and underexplored policy areas in remanufacturing research.

2.2.5. Analyze and Interpret the Results

The results of the co-occurrence analysis were further processed to identify top trending terms, top impact terms, and thematic clusters. The top impact terms were determined based on their Normalized Citation Scores (NCS), which measure the relative impact of a keyword by comparing its citation count to the average citation count of all keywords in the same dataset[49]. The NCS formula is as in (1).

This metric enables fair comparison across terms, accounting for differences in publication years and citation practices. For example, Cluster 1 focused on themes like Circular Economy and Sustainability, while Cluster 7 emphasized Game Theory and Pricing. The analysis revealed the methods and approaches frequently employed in these thematic areas. The findings were derived from the Excel tables provided, which include details on top trending terms, dominant methodologies, and their thematic connections.

2.2.6. Content Analysis

To complement the bibliometric analysis, content analysis was conducted to gain a deeper understanding of how various methodologies are applied in remanufacturing policy research. While bibliometric techniques provide an overview of research trends, they rely on keyword occurrences, which may not fully capture the context, purpose, or methodological details of studies. Therefore, content analysis was integrated to validate and refine the bibliometric findings which ensure a more comprehensive mapping of research methods, scope, objectives, and impacts.

The selection of studies for content analysis was based on two main criteria. First, to ensure a balanced representation across research domains, one representative research was chosen from each major thematic cluster identified in the bibliometric analysis (see Sub-Chapter 3.1). The selection of the indicative publications was based on their relevance to the cluster's core focus, with priority given to studies that provided clear methodological details. Second, the most highly cited papers published between 2020 and 2024 were selected to capture recent methodological advancements in remanufacturing research (see Sub-Chapter 3.2 and 3.3). Citation count was used as an indicator of academic influence to make sure that the selected studies represent impactful contributions to the field.

After that, content analysis was conducted by examining key methodological insights. Each paper was reviewed to identify the research problem, followed by an assessment of how specific research methods such as mathematical modeling and game theory were applied. Key findings were extracted to highlight major conclusions related to remanufacturing policies, supply chain strategies, and sustainability outcomes. Plus, the limitations of each research were analyzed, particularly in terms of assumptions about policy enforcement, market uncertainties, and data constraints.

The results of this content analysis were then compared with the bibliometric findings to determine whether the identified methodologies aligned with the broader research trends. This process ensured that the research was not solely dependent on bibliometric techniques but also incorporated qualitative insights to strengthen the reliability of conclusions. By integrating content analysis with bibliometric analysis, this research provides a more thorough assessment of the methodologies used in remanufacturing policy studies.

2.2.7. Report and Disseminate Findings

The findings are presented through detailed tables, Figures, and narrative explanations. The results highlight the intellectual contributions to remanufacturing policy research and provide actionable insights for policymakers and researchers. Visualizations, such as keyword co-occurrence maps and impact analysis, were generated using VOSviewer to ensure clarity and accessibility. These findings are intended to advance the understanding of methodological trends and inform future research directions.

3. Results and Discussion

This chapter presents the findings of bibliometric analysis, structured around the three research questions. The analysis covers the commonly used methodologies in remanufacturing policy research, the key thematic clusters defining the field, and the trends and gaps.

3.1. Common Methodologies in Remanufacturing Policy Research

Understanding the methodologies applied in remanufacturing policy research is crucial for identifying strengths, limitations, and potential areas for future exploration. The analysis reveals that different methodological approaches are used across various thematic clusters. This section provides a cluster-wise breakdown of the methodologies used in remanufacturing policy research, citing relevant publications from each cluster.

The analysis of bibliometric clusters, as presented in Figure 4, shows that remanufacturing policy research incorporates a diverse range of methodologies. LCA, Optimization Models, Simulation Modeling, and Supply Chain Analysis emerge as the most frequently used methods. LCA is particularly linked to sustainability and environmental policy, while optimization and simulation approaches are widely used in decision-making for supply chain efficiency and remanufacturing operations. Furthermore, the relationship between methodologies and policy focus areas is summarized in Table 2. It highlights that sustainability policies are often supported by LCA and mathematical modeling, while supply chain policies are linked to simulation and numerical modeling. However, some clusters, such as Clusters 8, 9, and 10, show a lack of well-defined methodologies which indicates potential gaps for certain policy applications.

3.1.1. Cluster 1: Sustainability and Circular Economy

This cluster focuses on sustainability, circular economy, and environmental impacts in remanufacturing. Key methodologies include LCA and design for remanufacturing, which assess the environmental and economic benefits of reusing products. Topics such as eco-design, reliability, reuse, and product life cycle highlight the importance of designing products for extended use. Research in this cluster also explores warranty policies, which influence consumer trust in remanufactured goods. These studies contribute to sustainable development and policymaking by providing data-driven insights into material efficiency and waste reduction, as explained in two indicative publications from this cluster[50,51].

The role of eco-design and product life cycle analysis were investigated to enhance remanufacturing sustainability[50]. The research applies LCA to evaluate environmental impacts and cost-effectiveness across different remanufacturing scenarios. The findings indicate that integrating eco-design principles significantly reduces waste and improve material efficiency. However, the research is limited by the lack of consideration for regulatory factors and market acceptance, which are crucial for successful policy implementation.

Furthermore, an environmental risk assessment in remanufacturing processes was examined by developing a multi-criteria decision-making framework that incorporates environmental impact metrics, regulatory compliance, and economic feasibility[51]. The results highlight the importance of balancing sustainability goals with operational efficiency, showing that stricter environmental regulations drive companies to adopt cleaner technologies. However, the research does not account for the financial challenges that firms may face in adopting these sustainable practices.

These studies contribute to the broader understanding of sustainability in remanufacturing by emphasizing life cycle thinking, regulatory impacts, and eco-design strategies. The insights gained to support the development of more comprehensive policies that promote sustainable remanufacturing practices while addressing economic feasibility and regulatory constraints.

3.1.2. Cluster 2: Optimization and Control Policies

This cluster is centered on control policies, optimization, and simulation modeling in remanufacturing. Methods such as genetic algorithms and lot-sizing models are commonly used to optimize production and inventory management. Research in this area emphasizes the importance of inspection, maintenance, and production planning to ensure that remanufactured products meet quality standards. Additionally, simulation tools are frequently applied to model policy scenarios, aiding in the

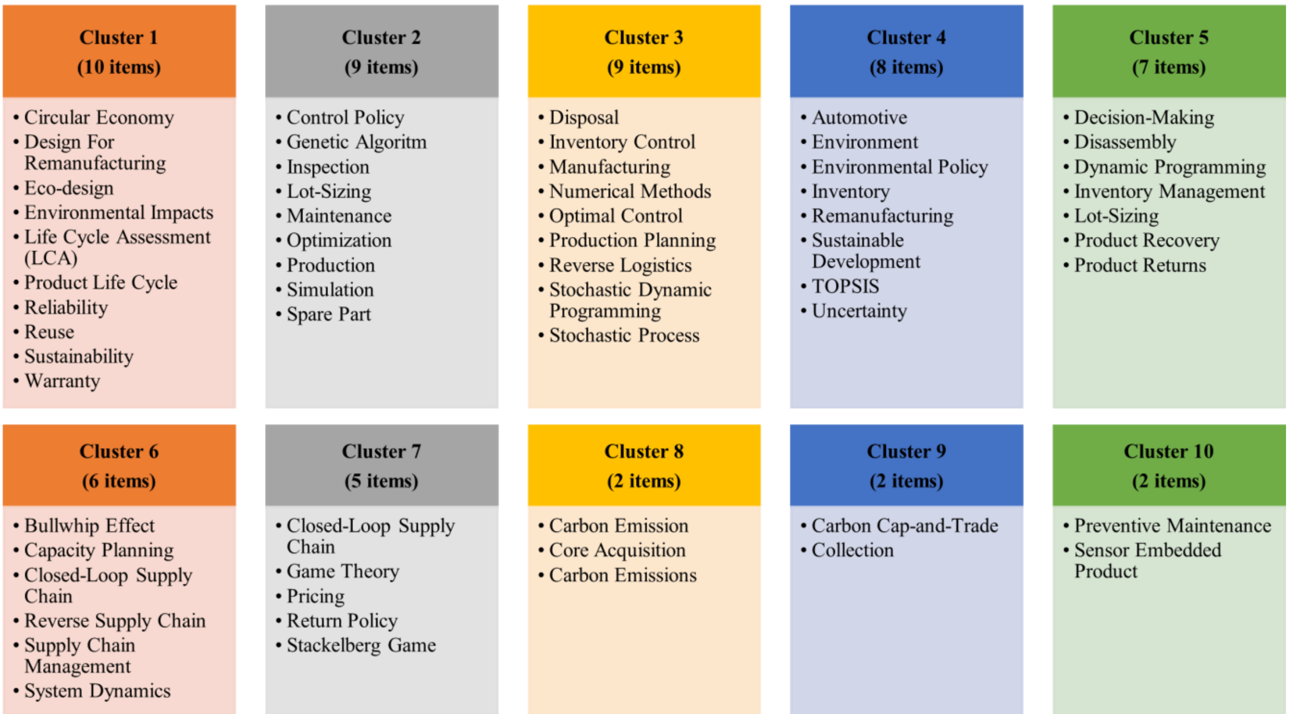

Fig. 4: Thematic Clustering

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Table 2: Previous Studies Related to Bibliometric Analysis on Remanufacturing

Cluster	Research Methodology	Policy Focus Area	Decision-Making Tools
1	LCA, Design for Remanufacturing, MCDA	Sustainability Policy, Environmental Policy, Warranty Policy, Product Design Regulations	MCDM, Environmental Impact Assessment Tools
2	Mathematical Modelling, Genetic Algorithms, Lot-Sizing Models	Production Planning, Inventory Control Policies	Optimization Models, Simulation-Based Decision Support
3	Stochastic Dynamic Programming, Stochastic Processes, Numerical Optimization	Reverse Logistics, Material Flow Policies	Inventory Control Models, Stochastic Decision-Making Models
4	Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Analytical Hierarchy Process (AHP), LCA	Environmental Policy, Sustainable Development, Carbon Emission Reduction	Policy Evaluation Frameworks, Environmental Decision-Support Systems
5	Discrete Event Simulation, Metaheuristic Algorithms (Simulated Annealing, Ant Colony Optimization)	Product Recovery Policies, End-of-Life (EOL) Management	Dynamic Programming, Heuristic Optimization
6	System Dynamics (SD), Capacity Planning Models	Supply Chain Resilience, Bullwhip Effect Policies	Scenario-Based Decision Support, Policy Simulation Models
7	Game Theory (Stackelberg, Nash Equilibrium), Closed-Loop Supply Chain Models	Pricing Policies, Return and Collection Policies	Economic Incentive Models, Contract Theory, Auction-Based Pricing Models
8	Mathematical Modelling, Mixed-Integer Nonlinear Programming (MINLP)	Environmental Policy, Carbon Trading, Grandfathering Policy	Optimization Models, Game Theory (for regulatory impact analysis), MCDM
9	Regulatory Compliance Models, Simulation-Based Policy Evaluation	Carbon Emission Policies, Regulatory Standards for Remanufacturing	Legislative Decision-Support Systems, Compliance Optimization Models
10	Sensor-Embedded Products; Discrete Event Simulation	Maintenance Strategies; Warranty Policy	Predictive Maintenance Models; Fuzzy Logic-Based Decision Models; Warranty Optimization Models; Machine Learning-Based Diagnostics

design of cost-effective and environmentally sustainable remanufacturing strategies. These studies play a crucial role in policymaking by identifying efficient remanufacturing frameworks that balance economic and environmental concerns, as shown in these indicative publications from this cluster[52,53)].

The impact of spare parts remanufacturing on the operation and maintenance of offshore wind turbines was explored[52)]. The research addresses the need for cost-effective maintenance strategies by investigating how remanufactured gearboxes affect turbine performance. A multi-agent simulation model is used to evaluate different spare part management scenarios, considering factors such as carbon footprint, total cost, and failure rates. The findings suggest that remanufactured components can extend the lifecycle of turbines and reduce overall operational costs, but they require careful coordination between maintenance, monitoring, and supply chain logistics. A limitation of the research is that external disruptions, such as unpredictable weather conditions, are not fully integrated into the model.

Additionally, the role of reverse logistics was examined to determine optimal production and storage capacities in remanufacturing[53)]. The research focuses on the challenge of integrating remanufactured products as a new supply source, requiring adjustments in manufacturing and storage policies. A mathematical modeling approach is developed to optimize production and storage decisions in a deterministic demand environment. The findings reveal that incorporating product returns into production planning significantly reduces waste and improves efficiency. However, the research assumes a fixed return rate, which may not accurately reflect real-world fluctuations in consumer returns and market demand.

These studies help to understand how optimization and simulation modeling improve remanufacturing. They show that using reverse logistics and remanufactured spare parts can reduce costs and make operations more efficient. The findings support the bibliometric analysis, which shows that mathematical modeling, inventory optimization, and simulation tools are widely used in remanufacturing research.

3.1.3. Cluster 3: Reverse Logistics and Inventory Control

This cluster examines reverse logistics, inventory control, and numerical methods used in remanufacturing. Disposal and optimal control methods help determine the best strategies for handling returned products. Stochastic dynamic programming and stochastic processes are widely applied to manage uncertainty in the supply chain. The role of manufacturing and production planning in remanufacturing is also explored, ensuring that recovered materials can be reintegrated into the production process efficiently. These studies assist policymakers in developing regulations that improve material flow and resource recovery, as explained in these indicative studies from this cluster[24,53)].

Production planning and control (PPC) strategies were investigated in a hybrid manufacturing-remanufacturing system (HMRS) with unreliable facilities and varying quality conditions of returned products[24)]. The research addresses the challenge of matching demand and production while considering quality-based return categorization. The authors apply optimal control theory and numerical techniques to develop production control policies that integrate remanufacturing, manufacturing, and inventory management decisions. Their findings indicate that hedging-point policies and stock-based switching decisions significantly reduce costs and optimize production. However, the research assumes fixed demand and return rates, which may not fully capture real-world fluctuations.

These studies reinforce the bibliometric findings that stochastic modeling, numerical optimization, and quality-based categorization play a key role in remanufacturing decision-making. They highlight the importance of flexible production planning strategies that can adapt to uncertain supply chain conditions.

3.1.4. Cluster 4: Environmental Policy and Decision Support

This cluster focuses on environmental policy, sustainable development, and decision-making tools like Techniques for Order Preference by Similarity to Ideal Solution (TOPSIS). Topics such as automotive remanufacturing, inventory management, and uncertainty are frequently studied to enhance sustainable business practices. Research in this area provides policymakers with frameworks for evaluating different remanufacturing policies and understanding their long-term environmental and economic impacts, as presented in these indicative publications[54,55)].

The selection of sustainable manufacturing facility locations was investigated by integrating MCDM techniques[54)]. The research addresses the complexity of incorporating economic, environmental, and social dimensions, known as the triple bottom line (TBL), into location selection decisions. The authors employ a hybrid methodology that combines the Analytical Hierarchy Process (AHP) and TOPSIS to evaluate different manufacturing facility locations. AHP is used to determine the relative importance of various sustainability factors, while TOPSIS ranks the alternatives based on their proximity to an ideal solution. The research findings suggest that the location's quality and reliability of utilities significantly contribute to sustainability outcomes. Sensitivity analysis further validates the robustness of the model, demonstrating that changes in the weighting of sustainability factors can shift location preferences. However, the research does not fully account for uncertainty in data collection, which may affect the generalizability of its conclusions. Additionally, the research assumes that all sustainability criteria are independent, overlooking potential interdependencies that could influence decision-making.

Furthermore, optimal control techniques were explored for mechanical vibration suppression in remanufacturing-repaired mechanical systems[55)]. The research focuses on a cantilever beam structure used in remanufactured components and applies linear quadratic optimal control methods to reduce vibration caused by external disturbances. The findings suggest that active vibration control through modal feedback regulation significantly enhances the mechanical stability of remanufactured parts, ensuring longer operational lifespans and improved performance. However, the research is limited by its focus on simulation-based results, without empirical validation in industrial settings. These studies reinforce the bibliometric findings by confirming that decision-making models, environmental policy assessments, and optimal control methods play a crucial role in remanufacturing research.

3.1.5. Cluster 5: Disassembly and Dynamic Programming

This cluster addresses disassembly, dynamic programming, and product recovery strategies in remanufacturing. Decision-making models assist in optimizing lot-sizing, inventory management, and product returns. These studies help industries streamline remanufacturing processes, ensuring that recovered products are disassembled efficiently and reintegrated into production cycles. The focus on dynamic programming also supports decision-making in uncertain conditions, helping businesses and policymakers develop strategies for resource efficiency, as examples in these indicative publications[56,57)].

A simulated annealing (SA) algorithm was proposed to solve the sequence-dependent disassembly line balancing problem (SDDLBP), which aims to optimize the assignment of disassembly tasks while considering sequence-dependent time increments[56)]. The research highlights the challenge of balancing efficiency and cost in disassembly processes, particularly under regulatory and operational constraints. The SA algorithm is tested against other metaheuristic approaches, including ant colony optimization (ACO), particle swarm optimization (PSO), river formation dynamics (RFD), and tabu search (TS).

The findings demonstrate that SA outperforms these approaches in achieving better resource allocation, reduced idle times, and increased automation efficiency in disassembly lines. However, the research does not account for uncertainties in product quality and variability in return flows, which can impact real-world applications.

A fuzzy disassembly optimization model (FDOM) was developed by integrating fuzzy logic and an Algorithm of Self-Guided Ants (ASGA) to determine the optimal disassembly sequence and depth of disassembly[57]. The model addresses uncertainties in product quality at the end-of-life (EOL) stage, which influences the decision to fully or partially disassemble a product. The ASGA, inspired by ant colony optimization (ACO), enhances decision-making by improving the trade-off between speed and accuracy in determining optimal disassembly sequences. The results show that incorporating fuzzy logic improves the adaptability of the model when dealing with uncertain product conditions, leading to more cost-effective and environmentally friendly disassembly strategies. However, the research assumes perfectly structured data and does not consider external disruptions, such as policy changes or market fluctuations, that could impact its practical implementation.

These studies reinforce the bibliometric findings that metaheuristic optimization, dynamic programming, and stochastic decision-making are crucial for remanufacturing planning. They highlight the importance of adaptive decision models that can handle uncertainty and optimize disassembly operations, ensuring greater sustainability and cost efficiency in remanufacturing.

3.1.6. Cluster 6: Supply Chain Management and System Dynamics (SD)

This cluster explores bullwhip effects, capacity planning, and SD in closed-loop supply chains. Managing reverse supply chains efficiently is a major challenge, as variability in returns can create supply chain disruptions. Researchers use SD models to simulate supply chain behaviors and develop policies that stabilize supply networks. Findings from this cluster are crucial for policymakers aiming to implement regulations that improve supply chain resilience in remanufacturing, as presented in these indicative publications[58,59]

Capacity planning strategies in closed-loop supply chains were examined by focusing on how product lifecycles and return patterns influence expansion and contraction decisions in remanufacturing[58]. Using SD modeling, the research simulates different policy scenarios to determine how firms should adjust collection and remanufacturing capacity over time. The findings suggest that remanufacturing capacity expansion policies are largely independent of total demand, while collection expansion and contraction strategies should be adapted based on product lifecycle stages and return rates. The research provides valuable insights for policymakers and industry leaders looking to develop long-term capacity planning frameworks but does not fully account for external factors such as fluctuating regulatory policies or unexpected market shifts.

Dynamic capacity planning for remanufacturing in closed-loop supply chains was investigated by integrating economic, environmental, and legislative factors into the decision-making process[60]. The research applies SD simulations to analyze how take-back obligations, environmental regulations, and market conditions affect remanufacturing facility expansion decisions. The results highlight that firms adopting proactive capacity expansion strategies gain a competitive advantage, as they can better manage fluctuations in product returns and regulatory constraints. The research also emphasizes the role of the “green image” effect, showing that companies engaging in sustainable remanufacturing practices can positively influence customer demand. However, a key limitation is that the model assumes a relatively stable regulatory environment, which may not reflect the rapid changes in real-world legislation.

These studies confirm the bibliometric findings that SD models are widely used for analyzing remanufacturing capacity planning and supply chain resilience. They highlight the importance of flexible policies that account for uncertainty in product returns and legislative shifts.

3.1.7. Cluster 7: Pricing and Game Theory

This cluster investigates pricing strategies, game theory, and return policies in remanufacturing. Stackelberg games and closed-loop supply chain models are used to analyze interactions between manufacturers, consumers, and policymakers. Understanding pricing mechanisms is key to encouraging remanufacturing adoption while maintaining profitability. Research in this area supports the development of pricing policies and incentives that encourage circular economy practices, as examples from these indicative publications[61,62].

The remanufactured electric vehicle battery (EVB) supply chain was examined by considering the impact of government subsidies and carbon trading policies on pricing and return rates[61]. Using a Stackelberg game theory model, the research defines four decision-makers: regular EVB suppliers, green EVB suppliers, EV manufacturers, and third-party collectors. The model evaluates how these entities interact in setting wholesale prices, selling prices, and return rates to maximize profits while adhering to sustainability goals. The findings reveal that carbon trading policies significantly reduce overall emissions but do not directly increase return rates or remanufactured EVB production volume. However, government subsidies positively affect green EVB suppliers, leading to increased return rates and reduced material costs. The research highlights that integrating both regulatory mechanisms is essential to balance economic and environmental objectives. A limitation of this research is that it assumes fixed regulatory conditions, without considering potential fluctuations in subsidy levels or carbon credit pricing, which may impact real-world applicability.

Furthermore, a game-theoretical approach for pricing in a dual-channel socially responsible closed-loop supply chain (CLSC) was presented under a reward-penalty mechanism (RPM)[62]. The research examines a CLSC that includes a manufacturer, a retailer, and a third-party collector, where used products are collected and remanufactured for resale. The authors develop three decision-making models, namely centralized, decentralized, and coordinated, to analyze pricing and collection rates in a competitive environment. The results show that the coordinated model, which employs a two-part tariff contract, improves collection rates and overall profitability compared to the decentralized model. Additionally, the research finds that implementing an RPM enhances remanufacturing benefits by incentivizing higher collection rates and reducing environmental impact. However, the research assumes consistent regulatory enforcement and does not fully account for variations in consumer behavior, which could impact the effectiveness of pricing and collection strategies in real-world application studies reinforces the bibliometric findings that game theory, Stackelberg models, and pricing mechanisms are essential tools for remanufacturing policy and strategy development.

These studies confirm the importance of pricing strategies, game theory, and return policies in remanufacturing, particularly in closed-loop supply chains. They highlight how government subsidies, carbon trading regulations, and reward-penalty mechanisms influence remanufacturing profitability and collection rates. The findings support the bibliometric analysis, which identifies Stackelberg models and game-theoretic approaches as essential tools for pricing and policy optimization in remanufacturing. However, most models assume fixed regulatory environments and rational decision-making, which may not fully reflect real-world complexities.

3.1.8. Cluster 8: Carbon Emissions and Core Acquisition

This cluster focuses on carbon emissions and core acquisition in remanufacturing. Studies highlight the environmental benefits of reducing emissions through remanufacturing while addressing challenges in securing used products for reuse. Research in this area supports policy decisions that promote green initiatives and carbon reduction strategies in manufacturing industries, as explained in these indictive publications[63,64].

How different carbon permit allocation methods influence remanufacturing production decisions was investigated[63]. The research contrasts two methods: grandfathering, which allocates permits based on historical emissions, and benchmarking, which assigns permits based on industry best practices. A mathematical optimization model is developed to examine the effectiveness of these methods in motivating firms to adopt low-carbon remanufacturing. The results show that benchmarking more effectively encourages firms to engage in low-carbon remanufacturing compared to grandfathering. The research also finds that higher carbon prices and greater emissions savings per remanufactured product positively impact firms' decisions to remanufacture. However, the model assumes that firms respond rationally to permit allocation policies, overlooking potential market dynamics and behavioral factors that might influence decision-making.

Optimization of core acquisition policies in remanufacturing systems was examined under a quantity discount and carbon tax scheme[64]. The primary challenge addressed is the uncertainty in the quantity and quality of returned cores, which affects remanufacturing efficiency and cost. The authors propose two models: one considering only quality variability and another incorporating both quality variability and condition uncertainty. Using a mixed-integer nonlinear programming approach, they determine optimal acquisition strategies that balance economic and environmental objectives. The findings suggest that quantity discounts incentivize firms to acquire more cores, increasing the likelihood of selecting high-quality units and reducing overall costs. Additionally, carbon taxes play a crucial role in shaping acquisition decisions by penalizing higher emissions. However, the research is limited in its application to real-world supply chains, as it does not account for logistical constraints and variations in market conditions.

These studies highlight the significance of carbon emission regulations and core acquisition strategies in shaping remanufacturing practices. They present how carbon permit allocation methods, carbon taxes, and quantity discount schemes influence a firm's decisions to engage in low-carbon remanufacturing while ensuring cost efficiency. The findings support the need for policy interventions that encourage sustainable practices through financial incentives and regulatory mechanisms. However, both studies assume ideal market conditions and rational decision-making, which may not fully reflect real-world complexities.

3.1.9. Cluster 9: Carbon Cap-and-Trade and Collection

This cluster looks at carbon cap-and-trade policies and collection systems for remanufacturing. Efficient collection systems are crucial for ensuring a steady supply of used products for remanufacturing. Cap-and-trade policies are explored to regulate emissions while promoting sustainable industrial practices. These studies inform policymakers on the best strategies for integrating remanufacturing into carbon reduction frameworks, as shown in these publications from this cluster[65,66].

The impact of both take-back and carbon emission capacity regulations on remanufacturing enterprises was investigated by developing a mathematical optimization model[65]. The research considers different regulatory scenarios to determine how firms should adjust their operational decisions to maximize profit while complying with environmental regulations. The findings highlight that carbon emission regulations not only reduce emissions but also encourage remanufacturing. However, while regulations effectively lower environmental impact, they also reduce firm profitability, necessitating pricing and production adjustments. A limitation is that the model assumes a monopolistic market without considering competitive dynamics.

Whether carbon cap-and-trade mechanisms can benefit remanufacturing was explored by developing a single-period optimization model for a monopolistic manufacturer involved in both manufacturing and remanufacturing under carbon cap-and-trade regulations[66]. The research finds that remanufacturers can profit from these mechanisms by leveraging lower carbon emissions in remanufacturing compared to new production. Carbon pricing significantly affects manufacturers' profitability, making optimal pricing strategies crucial. However, the paper does not fully address market competition, which could influence remanufacturing decisions under different regulatory environments. The studies in this cluster emphasize the role of regulatory mechanisms, particularly take-back laws, and carbon cap-and-trade policies, in shaping remanufacturing strategies. Both papers demonstrate that regulatory policies can serve as incentives for remanufacturing, reducing environmental impact while posing economic challenges for firms.

3.1.10. Cluster 10: Preventive Maintenance and Sensor-Embedded Products

This cluster explores preventive maintenance and sensor-embedded products in remanufacturing. Sensor technology is increasingly used to monitor product performance and determine the best time for remanufacturing. Preventive maintenance strategies ensure that products remain functional for longer, reducing waste and improving resource efficiency. Research in this area supports policies that encourage smart technologies to enhance sustainability in remanufacturing, as presented in these indicative publications[67,68].

The impact of renewable warranty policies was analyzed on sensor-embedded remanufactured products[67]. The research identifies that consumer skepticism toward remanufactured products can be mitigated through extended warranty policies, enhancing customer confidence and market acceptance. A discrete-event simulation is employed to optimize two-dimensional renewable warranty policies, where the warranty coverage is based on both time and usage parameters. The Advanced Remanufacturing-To-Order (ARTO) system is used as a case-study, incorporating Taguchi's Orthogonal Arrays for experiment design. The findings indicate that sensor-embedded products (SEPs) improve warranty cost efficiency by reducing failure uncertainty, leading to better preventive maintenance scheduling and cost savings. However, the research assumes ideal data availability from embedded sensors, which may not always be practical in real-world applications.

Non-renewable warranties and preventive maintenance strategies were examined for remanufactured products within reverse supply chains[68]. The research highlights that while warranties can enhance customer confidence, they also impose costs on manufacturers. A discrete-event simulation is conducted to optimize the implementation of non-renewable one-dimensional warranties, balancing cost reduction for remanufacturers and reliability assurance for consumers. The ARTO system is used to illustrate warranty implementation. The research integrates Poisson distributions to model the arrival of end-of-life products and uses a preventive maintenance framework to reduce failure rates. Results demonstrate that effective warranty and maintenance policies can reduce product failure risks and improve overall sustainability. However, the research does not consider dynamic pricing mechanisms, which could impact profitability in different market conditions.

3.1.11. Distribution of methodologies across clusters

After discussing the methodologies applied in each cluster, the distribution of research methodologies across clusters is further illustrated in Figure5. This Figure highlights the frequency of various methodological approaches used in remanufacturing policy research, offering insights into the dominant and underrepresented methods. As shown in the diagram, optimization models, case studies, and simulation modeling are the most frequently employed methodologies, particularly in Cluster 2, which focuses on control policies, production planning, and decision-making tools. These methods are commonly used to enhance decision-making efficiency in remanufacturing operations. Cluster 1, which emphasizes sustainability and environmental policies, frequently employs LCA to evaluate the environmental impact of remanufacturing activities. Meanwhile, Clusters 3 and 5, which deal with logistics, supply chain management, and reverse logistics, prominently feature supply chain analysis and decision support systems.

Interestingly, optimization models are the most frequently used methodology in remanufacturing policy research, reflecting a strong focus on efficiency. Other methods, including game theory and mathematical modeling, appear at similar frequencies. This suggests a potential research gap where alternative modeling techniques could

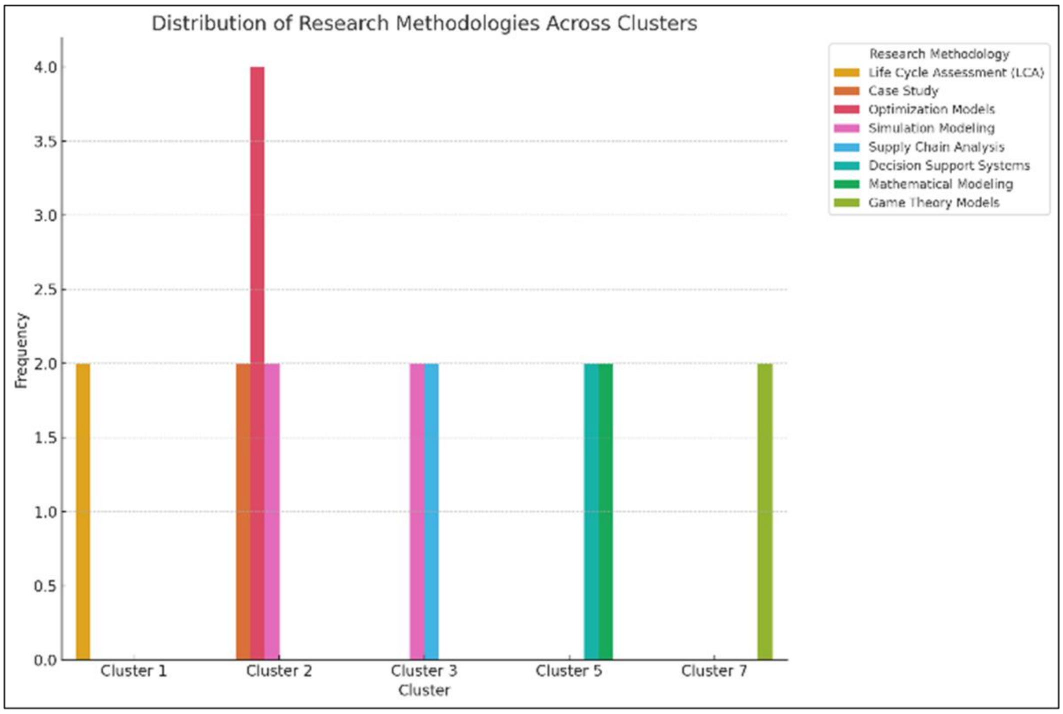

Fig. 5: Distribution of research methodologies across clusters

complement optimization approaches in policy development. Overall, Figure 5 visually supports the findings from the cluster analysis which focuses on the importance of optimization, simulation, and decision-support methodologies while also identifying less-explored areas that present opportunities for future research.

3.2. Thematic Clusters and Keyword Analysis

This section explores the key thematic clusters, top-impact terms, and keyword connections that define the intellectual structure of remanufacturing policy research. By analyzing network, overlay, and density visualizations, we can understand how different research themes are interconnected, how they have evolved, and where the most intensive research efforts are concentrated.

3.2.1. Network Visualization: Core Research Themes and Their Connections

The network visualization (Figure 6) provides a structural overview of the remanufacturing policy research landscape. The most central and highly connected keywords include remanufacturing, reverse logistics, closed-loop supply chains, inventory management, and circular economy, suggesting that these themes form the foundation of the research field. Their strong linkages indicate that studies frequently explore these topics together, highlighting their relevance in policy-oriented discussions.

Several sub-clusters emerge around these dominant themes. For example, optimization, numerical methods, and simulation modeling are closely linked, signifying that a large portion of research focuses on computational and mathematical techniques to improve remanufacturing efficiency. Similarly, environmental policy, sustainability, and product LCA appear in the same network, indicating that researchers often examine remanufacturing in the context of regulatory and ecological frameworks.

Interestingly, some terms are positioned toward the periphery of the network, such as carbon emissions, pricing models, and game theory. These keywords have fewer connections, suggesting that while they are present in the literature, they are not yet as deeply integrated into the mainstream discussions of remanufacturing policy. This highlights potential areas for further exploration, where emerging economic and decision-making tools could be applied to remanufacturing challenges.

3.2.2. Overlay Visualization: Evolution of Research Trends Over Time

The overlay visualization (Figure 7) offers a dynamic perspective on how remanufacturing policy research has evolved. Older research themes are represented in blue, while more recent topics appear in yellow and green, indicating shifts in focus areas.

Earlier studies primarily concentrated on remanufacturing, reverse logistics, and LCA, reflecting a foundational interest in sustainability and resource efficiency. Over the years, the research focus has expanded to SD, uncertainty, and decision-making frameworks, as seen in more recent publications. This suggests that researchers are now integrating more advanced analytical tools to tackle policy-related challenges in remanufacturing.

The emergence of carbon cap-and-trade policies, return policies, and game theory applications in the latest studies

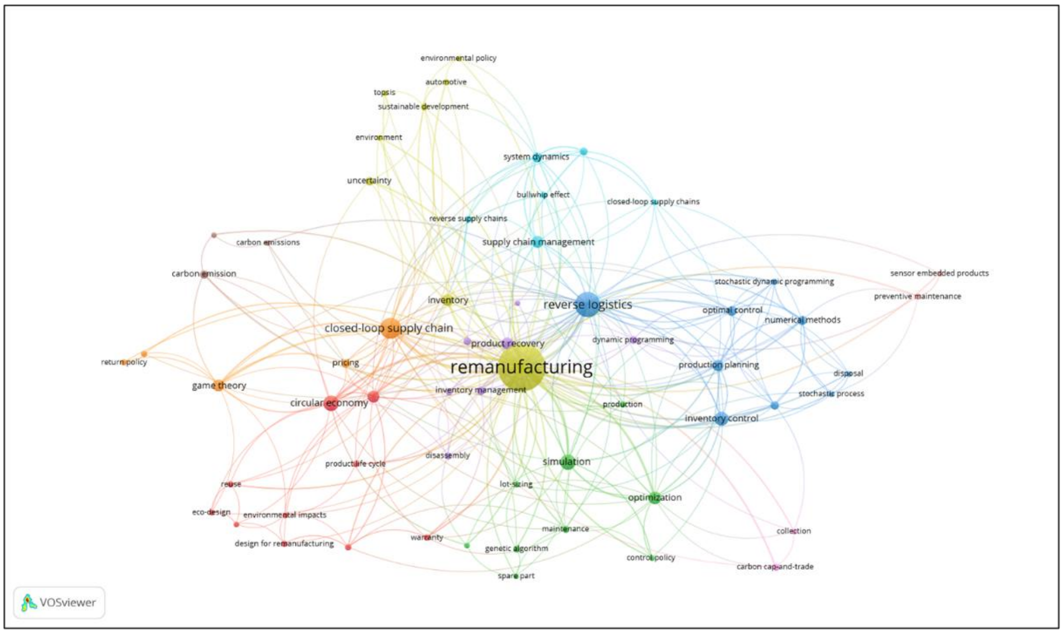

Fig. 6: Network Visualization

signifies a growing interest in the economic and regulatory aspects of remanufacturing. These developments highlight an ongoing transition from purely technical research toward a more policy-driven and interdisciplinary approach, incorporating economic incentives and strategic decision-making models into remanufacturing studies.

3.2.3. Density Visualization: Areas of High and Low Research Concentration

The density visualization (Figure 8) provides insights into which topics receive the most research attention. The bright yellow areas indicate highly studied themes, while the darker blue areas represent less explored but emerging topics.

As expected, remanufacturing, reverse logistics, and closed-loop supply chains are at the core of the research landscape, showing intense academic interest. These areas are well established in the literature, emphasizing their importance in both academic research and practical applications in industries such as automotive, electronics, and heavy machinery.

However, several terms appear in darker regions, signifying research gaps. Topics such as carbon emissions, return policies, pricing models, and uncertainty management are less frequently studied, despite their increasing relevance in policy discussions. This suggests that while remanufacturing has been extensively examined from an engineering and supply chain perspective, its economic, regulatory, and sustainability dimensions require further exploration.

Overall, the findings from the network, overlay, and density visualizations provide a comprehensive picture of the current state of remanufacturing policy research. The most well-established themes revolve around reverse logistics, inventory management, and supply chain policies, demonstrating their foundational role in remanufacturing. Additionally, simulation, optimization, and mathematical modeling techniques play a key role in guiding policy decisions.

On the other hand, newer and less explored topics such as carbon trading mechanisms, pricing models, and game theory-based decision-making indicate potential areas for future research. These findings suggest a growing need for interdisciplinary approaches, where remanufacturing policies are analyzed not just through an operational and technical lens, but also from an economic, regulatory, and sustainability perspective.

By addressing these gaps, future studies can contribute to better policy frameworks, integrating environmental, financial, and strategic factors into remanufacturing decision-making. This shift could enhance the effectiveness of remanufacturing as a key driver of the circular economy, supporting long-term sustainability and industrial innovation.

3.2.4. Top Trending Terms, Top Impact Terms, and Indicative Publications

To further illustrate the key themes and their impact on remanufacturing policy research, Tables 3 and 4 summarize the most frequently used terms, their normalized citation impact, and representative studies. The Top Trending Terms column highlights the most frequently occurring keywords in remanufacturing policy research. These terms represent the central themes and recurring concepts in the field. Key topics such as reverse logistics, circular economy, LCA, and sustainability appear frequently, indicating their critical role in shaping remanufacturing strategies. The strong presence of terms

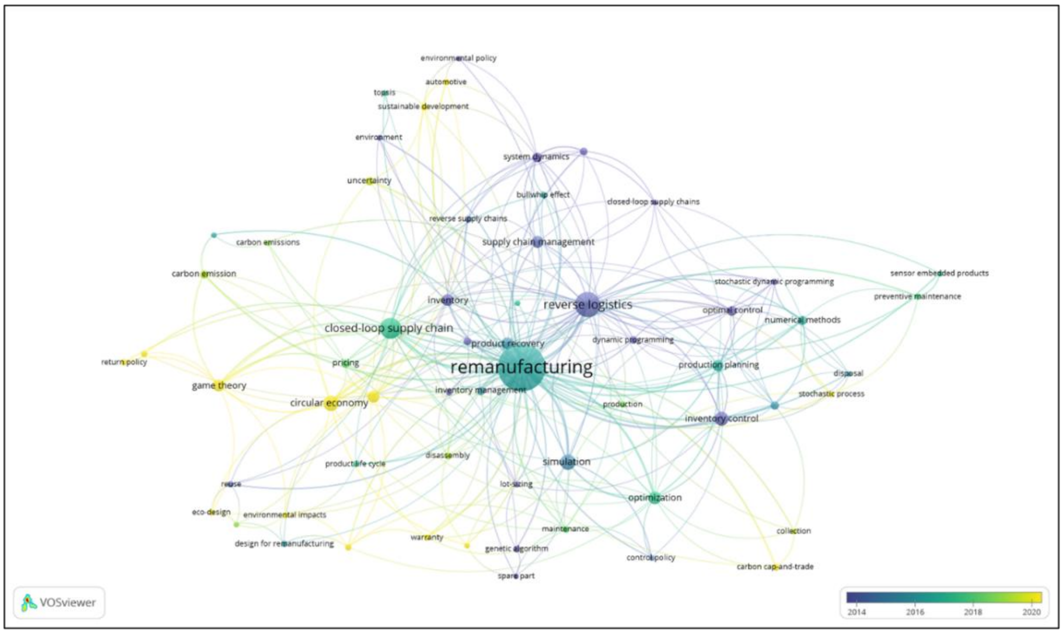

Fig. 7: Overlay Visualization

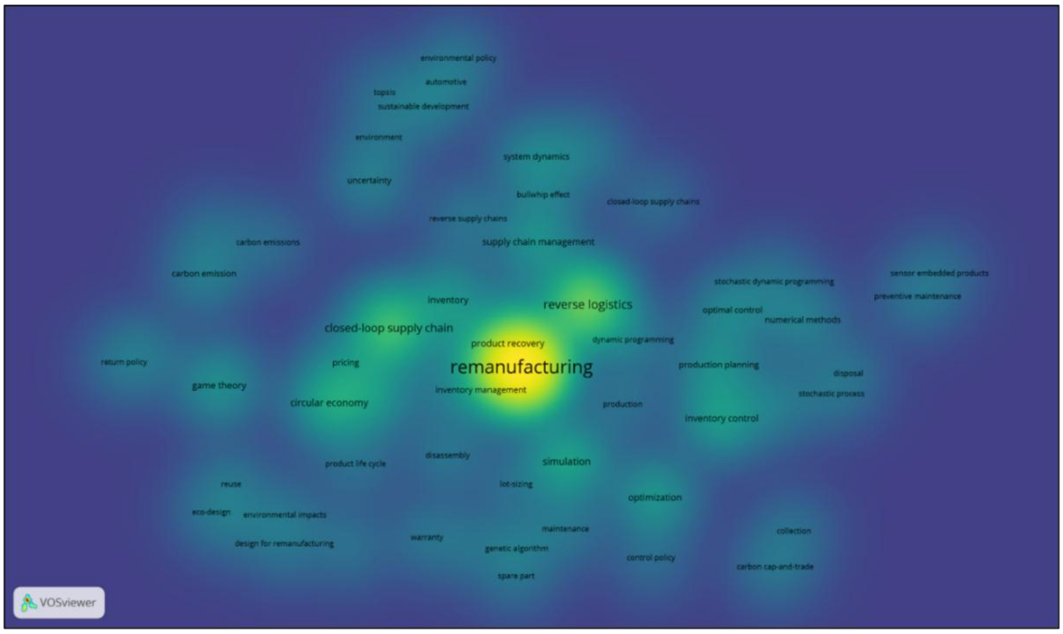

Fig. 8: Density Visualization

like lot-sizing, optimization, and simulation suggests a focus on operational and decision-making aspects of remanufacturing. Additionally, terms related to environmental policy and product life cycle underscore the integration of sustainability considerations into policy frameworks. The prevalence of game theory, pricing models, and carbon emissions suggests emerging areas that are gaining attention but require further exploration.

The Top Impact Terms by Normalized Citations column identifies the keywords that have the highest influence in remanufacturing policy research based on citation impact. Environmental impacts (1.17) and sustainability (1.09) rank among the most impactful terms, reflecting the growing emphasis on remanufacturing as a sustainability-driven approach. Similarly, circular economy (1.01) and reuse (0.97) show strong influence, highlighting their relevance in policy discussions. Operational terms such as lot-sizing (1.43), inventory control (0.96), and production planning (1.02) indicate the importance of optimizing remanufacturing processes. The presence of carbon emissions (0.96) as a high-impact term aligns with global efforts to reduce carbon footprints through policy-driven initiatives. Less common but emerging impact terms like pricing (0.98) and return policy (1.31) suggest an increasing focus on economic aspects of remanufacturing. Several key studies illustrate the dominant themes in

Table 3: Top Trending Terms, Top Impact Terms by Normalized Citations, and Indicative Publications

Cluster	Top Trending Terms	Top Impact Terms by Normalized Citations	Indicative Publications
1	environmental impacts sustainability circular economy reuse reliability life cycle assessment (lca) warranty eco-design design for remanufacturing	environmental impacts 1.17 sustainability 1.09 circular economy 1.01 reuse 0.97 reliability 0.97 life cycle assessment (lca) 0.89 warranty 0.83 eco-design 0.73 design for remanufacturing 0.71	[50,51]
2	lot-sizing genetic algorithm inspection optimization simulation maintenance production control policy spare part	lot-sizing 1.43 genetic algorithm 1.39 inspection 1.35 optimization 1.09 simulation 1.02 maintenance 0.72 production 0.71 control policy 0.7 spare part 0.51	[52,53]
3	production planning disposal inventory control stochastic process manufacturing optimal control reverse logistics numerical methods stochastic dynamic programming	production planning 1.02 disposal 0.96 inventory control 0.96 stochastic process 0.91 manufacturing 0.9 optimal control 0.85 reverse logistics 0.82 numerical methods 0.63 stochastic dynamic programming 0.47	[24,53]
4	automotive sustainable development remanufacturing inventory uncertainty environmental policy environment	automotive 1.16 sustainable development 1.1 remanufacturing 1.0 inventory 0.94 uncertainty 0.94 environmental policy 0.75 environment 0.39	[54,55]
5	disassembly lot sizing product returns dynamic programming inventory management product recovery decision-making	disassembly 1.34 lot sizing 1.11 product returns 0.95 dynamic programming 0.84 inventory management 0.83 product recovery 0.73 decision-making 0.55	[56,57]

remanufacturing policy research. One example is a case-study of remanufactured photocopiers in Thai Firms, which explores how remanufacturing can support sustainability goals in emerging markets[69]. By focusing on photocopier remanufacturing, the research highlights how businesses can integrate circular economic principles to extend product life cycles and reduce waste. The findings provide insights into policy implications for promoting remanufacturing adoption in developing economies.

In the domain of optimization, research on balancing a Sequenced-Dependent Disassembly Line Using a Simulated Annealing Algorithm focuses on improving disassembly efficiency in remanufacturing[70]. The research applies a simulated annealing approach to optimize disassembly sequences, which can enhance cost-effectiveness and resource utilization. These findings support policy efforts to standardize disassembly practices, leading to improved sustainability in remanufacturing.

Another research, a notable one examines pricing strategies and return policies using a game-theoretic framework in a dual-channel socially responsible closed-loop supply chain[71]. By analyzing the financial incentives that encourage product returns and remanufacturing adoption, the research provides a foundation for designing

Table 4: Top Trending Terms, Top Impact Terms by Normalized Citations, and Indicative Publications (2)

Cluster	Top Trending Terms	Top Impact Terms by Normalized Citations	Indicative Publications
6	capacity planning system dynamics reverse supply chains bullwhip effect supply chain management	capacity planning 1.15 system dynamics 1.04 reverse supply chains 1.01 bullwhip effect 0.99 supply chain management 0.92	[58,60]
7	return policy stackelberg game pricing game theory	return policy 1.31 stackelberg game 1.23 pricing 0.98 game theory 0.89	[61,62]
8	carbon emission core acquisition carbon emissions	carbon emission 0.96 core acquisition 0.85 carbon emissions 0.51	[63,64]
9	collection, carbon cap-and-trade	collection 1.43 carbon cap-and-trade 1.1	[65,66]
10	preventive maintenance	preventive maintenance 1.2	[67,68]

economic policies that support sustainable supply chains. Furthermore, environmental concerns are addressed to discuss the integration among three problems (production, inventory, and routing) with remanufacturing under carbon cap-and-trade[72], which integrates carbon emissions regulations with remanufacturing supply chain optimization. This research demonstrates how companies can comply with carbon cap-and-trade policies while maintaining operational efficiency, offering useful recommendations for policymakers developing environmental regulations. Lastly, research on optimizing two-dimensional renewable warranty policies for sensor-embedded remanufactured products focuses on improving warranty strategies to enhance consumer confidence and reduce costs for remanufacturers. The research proposes a discrete-event simulation methodology to optimize warranty pricing, renewal policies, and preventive maintenance strategies, ensuring both economic efficiency and sustainability in remanufacturing operations[73].

Together, these studies illustrate the breadth of remanufacturing policy research, addressing sustainability, optimization, pricing strategies, carbon emissions, and reverse logistics. They highlight key areas where policy interventions can drive improvements in efficiency, environmental impact, and economic viability.

3.3. Content Analysis of Selected Studies

To complement the bibliometric analysis, content analysis was conducted on highly cited and thematically relevant studies to gain deeper insights into the problems, methodologies, key findings, and limitations of remanufacturing policy research. These studies were selected from different thematic clusters to ensure a balanced representation of key research areas such as Industry 4.0 integration, supply chain sustainability, environmental regulations, and optimization models. The summary of these studies is presented in Table 5 which highlights their research focus, methods, key findings, and number of citations. The following section provides a detailed discussion of each research which offers qualitative insight into how specific methodologies have been applied in remanufacturing policy research.

How Industry 4.0 technologies can improve reverse supply chain operations was explored within the circular economy framework[74]. The main problem addressed is the lack of real-time decision-making capabilities in reverse logistics, which affects operational efficiency. The authors apply simulation modeling and Taguchi experimental design to analyze how integrating IoT, Artificial Intelligence (AI), and smart automation enhances performance. The findings show that real-time data sharing and automation significantly improve operational efficiency, reducing delays and costs in reverse logistics. However, a limitation is that the research focuses mainly on technological.

feasibility, without fully considering policy constraints and economic viability for widespread adoption.

Remanufacturing strategies were examined within a three-echelon closed-loop supply chain while considering uncertainties in demand and return rates[75]. The authors develop a mathematical model to determine optimal remanufacturing, production, and transportation decisions. Sensitivity analysis is applied to test how different factors, such as remanufacturing costs and policy incentives, influence supply chain efficiency. The research finds that hybrid remanufacturing strategies significantly enhance cost-effectiveness and environmental sustainability. However, the model assumes perfect coordination among supply chain participants, which may not always be practical in real-world applications.

How Industry 4.0 technologies contribute to the circular economy in logistics was investigated by improving resource efficiency[76]. The main challenge addressed is the

Table 5: Summary of Content Analysis for Selected Studies

Refs.	Year	Focus/Topic	Method	Findings	No. of Citations
74)	2020	Industry 4.0 and Circular Economy in Reverse Supply Chain	Simulation, Experimental Design	Integration of Industry 4.0 enhances operational excellence in reverse logistics.	337
75)	2021	Sustainable Three-Echelon Closed-Loop Supply Chain	Mathematical Modeling, Sensitivity Analysis	Hybrid remanufacturing strategies improve efficiency; remanufacturing costs and policies significantly impact supply chain decisions.	157
76)	2020	Industry 4.0 and Circular Economy in Logistics	Survey, Structural Equation Modeling	Industry 4.0 resources significantly influence intelligent logistics, remanufacturing, and business sustainability.	156
77)	2021	Sustainable Supply Chain Management Trends	Data-Driven Analysis, Fuzzy Delphi, Decision Modeling	Key indicators include big data, closed-loop supply chains, and policy frameworks shaping sustainable supply chains.	87
78)	2020	Hybrid Circular Economy in a Dual-Channel Green Supply Chain	Game Theory (Stackelberg and Nash Equilibria)	Manufacturer-Stackelberg (SM) strategy maximizes profits and enhances circular economy goals; Nash equilibrium creates conflict, reducing supply chain efficiency.	72
79)	2020	Remanufacturing under Take-Back and Carbon Emission Regulations	Mathematical Modeling, Economic Analysis	Regulations on carbon and take-back policies significantly impact remanufacturing strategies and firm profitability.	70
80)	2020	Two-Sided Disassembly Line Optimization	Mixed-Integer Linear Programming, Genetic Algorithm	The genetic algorithm outperforms traditional optimization methods in balancing disassembly lines for EOL products.	50
81)	2020	Circular Business Models in Automobile Remanufacturing	Qualitative Case-Study, Interviews	Identified key barriers (policy constraints, consumer awareness, technology) to circular business model adoption in remanufacturing; government incentives and infrastructure improvements are needed.	49
82)	2021	Closed-Loop Supply Chain under Carbon Tax Mechanism	Mathematical Modeling, Optimization	Carbon tax policies influence inventory and remanufacturing decisions, optimizing supply chain costs and sustainability.	47
83)	2021	Systematic Literature Review on Product Returns	Machine Learning, Bibliometric Analysis	Categorized product return research into operational efficiency, retailer-manufacturer coordination, and consumer behavior; AI-powered return management improves profitability but lacks empirical validation.	44

lack of structured decision-making frameworks for integrating smart technologies into green logistics. The research employs survey research and structural equation modeling (SEM) to assess the impact of big data analytics, IoT, and automation on logistics efficiency. Results indicate that Industry 4.0-driven intelligent logistics significantly reduce waste and enhance remanufacturing processes. However, the research relies on self-reported survey data, which may introduce biases and limit the generalizability of the findings.

A data-driven analysis of global trends in sustainable supply chain management was provided to identify key factors shaping industry practices[77]. The authors use Fuzzy Delphi and decision modeling to analyze large-scale sustainability-related data. The research highlights big data analytics, closed-loop supply chains, and government policies as critical drivers of sustainable supply chains. Findings show that regional variations influence how sustainability policies are implemented, with some countries prioritizing environmental regulations while others focus on economic incentives. However, the research is limited by data availability, as some regions have incomplete datasets, which may affect the accuracy of cross-regional comparisons.

A game-theoretical approach to optimizing decision-making in a dual-channel green supply chain was presented under a circular economy framework[78]. The research addresses the challenge of balancing economic and environmental objectives by integrating remanufacturing, carbon emissions regulations, and marketing activities. The authors employ three game-theoretical models, namely Manufacturer-Stackelberg, Distributor-Stackelberg, and Nash Equilibrium, to explore the impact of different power structures within the supply chain. The findings indicate that the Manufacturer-Stackelberg approach, where the manufacturer leads the decision-making process, results in the highest overall supply chain profitability and effective carbon emission reduction. However, the research is limited by its assumption of rational decision-making and does not consider uncertainties in consumer behavior and regulatory enforcement.

How carbon emission limits and take-back laws influence remanufacturing decisions were examined using a mathematical model[79)] to find the optimal remanufacturing and collection strategies under different regulatory constraints. The results show that firms with stricter environmental policies tend to invest more in remanufacturing, while companies with lenient regulations prioritize cost reduction over sustainability. The research suggests that financial incentives, such as carbon credits, can encourage higher remanufacturing rates.

Optimizing disassembly line balancing in recoverable manufacturing systems was explored to address the inefficiency of traditional disassembly lines[80)], which results in high costs and resource waste. The authors develop a Mixed-Integer Linear Programming (MILP) model and apply a Genetic Algorithm (GA) to improve efficiency. Results show that the GA-based approach significantly reduces cycle time and operational costs. However, the model is tested in idealized conditions, and real-world constraints, such as labor skill variability and unexpected component failure, are not incorporated.

Circular business models in the automobile remanufacturing industry in China were examined to identify challenges and opportunities[81)]. Qualitative case research is conducted to analyze industry practices, regulatory barriers, and consumer perceptions. The findings reveal that lack of policy support, limited consumer awareness, and high investment costs are major obstacles to adopting circular business models. The research suggests that government incentives and public awareness campaigns could enhance adoption rates. However, since the research is limited to the Chinese market, its findings may not be fully applicable to other regions.

How carbon tax policies affect remanufacturing and inventory decisions in closed-loop supply chains were explored using a mathematical optimization model that incorporates environmental taxation into supply chain planning[82)]. The findings suggest that carbon tax mechanisms encourage firms to remanufacture more and reduce waste. However, the research does not consider consumer behavior and market demand, which can significantly affect the effectiveness of remanufacturing strategies under different tax policies.

A comprehensive review of product return management in supply chains was provided using machine learning and bibliometric analysis[83)]. The research categorizes product return research into three main areas: operational efficiency, retailer-manufacturer coordination, and consumer return behavior. Findings indicate that technology-driven return management strategies, such as AI-powered demand forecasting and real-time inventory tracking, improve profitability and sustainability. However, the research does not empirically test these findings, limiting its practical implications.

These studies provide a comprehensive view of methodologies applied in remanufacturing research which highlights the interplay between policy, sustainability, and optimization models. The combination of mathematical modeling, simulation, machine learning, and qualitative analysis reflects the diverse approaches used to enhance remanufacturing strategies. A recurring limitation across studies is the assumption of perfect regulatory enforcement and market conditions, which may not always be held in practical scenarios.

3.4. Trends and Gaps in Remanufacturing Policy Research

This section explores the prevailing trends in remanufacturing policy research while identifying critical gaps that require further investigation. By analyzing research methodologies and their alignment with policy objectives, it becomes evident that certain approaches dominate the field, while others remain underutilized despite their potential contributions.

3.4.1. Emerging Trends in Remanufacturing Research

A key trend in remanufacturing policy research is the widespread use of optimization models, simulation modelling, and supply chain analysis. These methodologies are particularly valuable in enhancing operational efficiency, as they allow researchers to develop models that optimize production planning, resource allocation, and logistics in remanufacturing systems. However, these methods primarily focus on maximizing specific performance metrics such as cost reduction or production efficiency, often neglecting broader policy considerations and stakeholder involvement. While they offer precise and quantitative insights, they may not fully capture the complexity of real-world policymaking, which requires balancing economic, environmental, and social factors.

Agent-Based Modelling and Simulation (ABMS) is an emerging approach with the potential to overcome the limitations of traditional optimization and simulation models. Unlike conventional models that assume centralized decision-making, ABMS enables research of decentralized interactions among different stakeholders, such as manufacturers, policymakers, and consumers. This method allows researchers to assess how different policies, incentives, and regulations influence the behavior of firms and consumers over time. However, its complexity and data requirements can be challenging, limiting its adoption in large-scale policy applications.

Decision support systems and game theory models have also gained traction, particularly in strategic decision-making and policy formulation. These approaches are instrumental in evaluating interactions between stakeholders in a remanufacturing ecosystem. Game theory, for instance, is useful in assessing competitive behaviours and incentive structures within supply chains, which can inform policies on pricing, return policies, and collaboration mechanisms. However, these models often rely on simplified assumptions about market behavior and may not fully account for dynamic changes in consumer preferences or regulatory environments.

A growing emphasis on sustainability and circular economy principles is evident in remanufacturing policy research, with increasing attention given to topics such as reverse logistics, closed-loop supply chains[84)], and carbon emissions[85)]. Many studies now incorporate LCA as a tool to measure the environmental benefits of remanufacturing. Although LCA provides valuable insights into the environmental impact of remanufacturing practices, its use in policy research remains somewhat limited. Most LCA studies focus on technical assessments rather than integrating their findings into policy recommendations, making it challenging to translate environmental benefits into actionable regulatory measures.

3.4.2. Identified Research Gaps and Future Research Direction

Despite advancements in remanufacturing research, several gaps persist that hinder its full potential in policy development. One major gap is the limited exploration of carbon emissions and environmental impact assessments in policy discussions. Although sustainability is a key driver of remanufacturing, relatively few studies have focused on quantifying its environmental benefits in a way that directly informs policy decisions[86)]. While optimization and simulation models are effective for operational improvements, they do not always consider environmental trade-offs or the broader socio-economic implications of remanufacturing policies[87)].

Another critical gap is the lack of integration between research methodologies and policy focus areas. Many studies prioritize operational aspects, such as production efficiency and inventory management, without explicitly connecting their findings to policy implications[88)]. As a result, there is limited understanding of how different regulatory mechanisms, such as tax incentives, extended producer responsibility programs, and sustainability certifications, affect remanufacturing practices. Bridging this gap would require interdisciplinary research that combines economic modelling, environmental impact assessments, and policy analysis.

Additionally, pricing strategies, return policies, and consumer behavior remain underexplored in remanufacturing policy research. Since the success of remanufacturing initiatives depends not only on technological efficiency but also on market acceptance, it is crucial to understand how different policy instruments can influence consumer decisions[89)]. For example, studies on game theory and decision support systems could be extended to examine how pricing mechanisms, warranties, and subsidies impact consumer willingness to purchase remanufactured products.

Another promising method for addressing policy gaps is SD modelling. Unlike static optimization models, SD enables researchers to simulate long-term effects of different policy interventions on remanufacturing systems. This method is particularly useful in understanding feedback loops, delays, and unintended consequences of policy measures, making it a valuable tool for policymakers looking to design resilient and adaptive regulations.

Addressing these gaps is important for developing policy frameworks that support sustainable remanufacturing. For instance, a better understanding of consumer behavior can guide the design of incentives, warranties, and labeling schemes to improve market acceptance. Similarly, relating environmental impact assessments more directly to policy decisions can help justify subsidies or regulatory support. Without highlighting these gaps, policies may lack the evidence needed for effective implementation.

To address these gaps, future studies should focus on integrating sustainability assessments into remanufacturing policy research, particularly through comprehensive carbon footprint analysis and environmental impact evaluations[90,91)]. This would allow for more informed decision-making, ensuring that remanufacturing policies contribute meaningfully to climate change mitigation efforts[92)]. Additionally, there is a need to explore the economic and regulatory dimensions of remanufacturing, particularly the role of subsidies, tax incentives, and policy interventions in shaping industry practices[93,94)].

Advanced data-driven techniques, such as machine learning (ML)[95–97)] and AI[98,99)], could also be leveraged to enhance decision-making in remanufacturing. These technologies have the potential to improve forecasting, optimize resource allocation, and assess policy impacts in real time. However, their adoption in policy research remains limited, largely due to challenges related to data availability and model interpretability.

Another promising direction for future research involves investigating consumer behaviour[100,101)] and market dynamics[102] to better understand how policy instruments can encourage remanufacturing adoption. This could involve exploring the effects of financial incentives, consumer education campaigns, and product labelling schemes on purchasing decisions. Furthermore, hybrid modelling approaches, combining ABMS with SD, can provide a more holistic view of remanufacturing ecosystems, allowing for better assessment of policy impacts on different stakeholders.

4. Conclusion

This research provides a bibliometric review of remanufacturing policy research, identifying key methodologies, dominant themes, and emerging trends. The analysis reveals that remanufacturing policies predominantly focus on sustainability, reverse logistics, and supply chain management. Methodologies such as LCA, optimization models, and simulation modelling are widely employed to support decision-making and policy formulation. However, gaps persist in integrating economic and regulatory perspectives, particularly concerning carbon emissions, pricing strategies, and stakeholder engagement.

Network, overlay, and density visualizations illustrate the intellectual structure of remanufacturing research. The network visualization highlights the centrality of circular economy principles, while overlay analysis reveals the evolution of research priorities over time. The density analysis underscores high-research-concentration areas and emerging but underexplored themes like game theory applications and policy-driven economic incentives.

Despite its advancements, remanufacturing policy research faces methodological limitations. Optimization models tend to prioritize operational efficiency over broader stakeholder concerns, while LCA studies focus more on environmental assessments than policy integration. The research suggests expanding the use of advanced analytical tools such as ABMS and SD to capture policy complexities more effectively. Furthermore, machine learning and artificial intelligence could enhance predictive decision-making in remanufacturing policies.

These gaps are not only academic concerns but also have real-world implications. For example, if consumer acceptance and pricing strategies remain underexplored, industries may hesitate to scale up remanufacturing due to market uncertainty. Similarly, without clear environmental assessment methods integrated into policy design, industries may lack incentives to adopt cleaner practices. Addressing these gaps can help businesses make more informed decisions and align with national and global sustainability regulations.

This research contributes to sustainable policy research by offering a structured methodological framework for future investigations. It provides actionable insights for policymakers, industry leaders, and researchers to design more effective remanufacturing policies. Although this research emphasizes qualitative mapping, future studies are encouraged to include quantitative comparisons of method performance or policy impact to enhance evidence-based policymaking in remanufacturing.

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