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Advances in Remanufacturing

Proceedings of the VII International Workshop on Autonomous Remanufacturing

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Preface

Climate change, excessive waste generation and scarcity of natural resources are among the key factors that require the world to move towards the concept of sustainability. In this context, the production and manufacturing systems are challenged to adapt their processes to reduce the impact on the planet. A solution is represented by the realisation of circular economy models, which, in contrast to linear models, enable the reuse of resources, reducing waste and emissions. Remanufacturing represents an effective way to achieve circular models and, for this reason, is experiencing strong growth. Remanufacturing is the process that restores used products to "common operating and aesthetic standards", contributing to saving resources considering both financial and environmental perspectives. However, the remanufacturing process may be very difficult to manage because of the many uncertainties affecting the quality of the used products and the still scarce knowledge on this topic.

This book collects chapters dedicated to enhancing remanufacturing processes, by discussing how modern technologies and new models integrating them may represent a great boost in this sector. The research associated with the chapters has been presented at the VII International Workshop on Autonomous Remanufacturing, held in October 2023 at the University of Campania Luigi Vanvitelli, in Italy.

The book opens with recent studies to assess the state of the art on different remanufacturing aspects. The development of sustainable remanufacturing systems is analysed in Chapter "Development of Sustainable Remanufacturing Systems: Literature Review"; the use of modern technologies, such as artificial intelligence, robotics and simulation, is assessed in Chapters "Artificial Intelligence in Remanufacturing Contexts: Current Status and Future Opportunities"–"The Role of Simulation-Based Optimization in Remanufacturing and Reverse Logistics: A Systematic Literature Review"; Chapter "Exploring Industry 5.0 for Remanufacturing of Lithium-Ion Batteries in Electric Vehicles" explores the use of Industry 4.0 concepts and technologies in remanufacturing; Chapter "Remanufacturing Decision-Making Tools: A State of the Art" highlights the use of decision support systems in remanufacturing;

and, finally, Chapter "Consumer Acceptance and Preferences Based on Environment Knowledge to Inform Remanufacturing End-of-Life Approach for Electric Vehicle Battery: A Scoping Review Study" assesses consumers' acceptance and preferences for remanufactured electric vehicle batteries.

The second part of the book includes chapters highlighting the benefits brought to remanufacturing by modern technologies, typical of the Industry 4.0 paradigm, including automation, artificial intelligence and the Industrial Internet of Things. This part is composed of 16 chapters. Chapters "Integration of Augmented Reality and Digital Twins in a Teleoperated Disassembly System"–"Exploring in the Application Slicing Technology to Determine Spatial Information to Assist and Facilitate Robotic Disassembly" discuss the use of robotics in remanufacturing. According to these chapters, the collaboration between humans and robots represents an effective solution for the disassembly process. Moreover, combining Human-Robot Collaboration (HRC) with other technologies, such as Digital Twin (DT) or Augmented Reality (AR), helps to further improve the overall process, by also guaranteeing adequate safety within the working environment. Chapters "Image-Based Incremental Learning for Part Recognition of Used Automotive Cores in Reverse Logistics"–"Knowledge Graph-Driven Manufacturing Resources Recommendation Method for Ship Pipe Manufacturing Workshop" discuss the use of Artificial Intelligence (AI) systems in remanufacturing. Different machine learning approaches are used for parts recognition, to evaluate the quality of returned cores, to estimate their remaining useful life or to identify defects that may compromise the goodness of the remanufacturing process. Finally, Chapters "Digital Twin-driven Dynamic Scheduling Cloud Platform for Disassembly Workshop"–"Knowledge–Driven Scheduling of Digital Twin-Based Flexible Ship Pipe Manufacturing Workshop" discuss the use of digital twins and the Industrial Internet of Things (IIoT) for the scheduling of remanufacturing activities.

The third part of the book discusses the remanufacturing strategy as an enabler of circular economy concepts. Nine chapters are included in this part. Chapter "Impact of Incentive Policies on the Profitability of Manufacturers and Third-Party Remanufacturers in the Circular Economy" discusses the impact of incentive policies on the profitability of remanufacturers; Chapters "Analysis of Strategies and Models for Industrial Symbiosis in Manufacturing Ecosystems" and "Assessing the Impact of Remanufacturing Through Industrial Symbiosis on Supply Chain Performance" address industrial symbiosis as a driver to reduce waste, which is also the main objective of the proposal of Chapter "Manufacture of a New Sustainable Material from Bacterial Cellulose from Organic Waste in a Circular Economy Framework", through the production of a new material obtained from waste; Chapter "Circular Economy and Autonomous Remanufacturing for End-of-Life Offshore Wind Turbines" discusses the remanufacturing of offshore wind turbines to promote circular economy; Chapters "Industry 4.0 Support of Remanufacturing Operations"–"Science Mapping Analysis for the Development of a Remanufacturing Readiness Model" discuss the impact of remanufacturing on circularity by proposing new methodologies, using frameworks, readiness models and life cycle cost analysis.

The fourth and last part of the book introduces new methods for improving three crucial aspects of remanufacturing: the design of products to be remanufactured, in Chapters "Tools and Methods for Designing Mechanical Components for Multiple Remanufacturing Cycles in Agricultural Machinery"–Product Design Evaluation of Refrigerators to Facilitate Remanufacturing Process; the disassembly process, in Chapters Modelling Remanufacturing Process of End-of-Life Batteries Using Discrete Event Simulation–"Disassembly Strategies for Remanufacturing: Experiences from a Learning Factory"; and the repairing of damaged components, in chapters RE-AM Combined Use to Facilitate Decision-Making in Remanufacturing–"Integrating Remanufactured and 3D Parts in Asset Maintenance Improvement".

In realising this book and the associated workshop, we aimed to demonstrate how remanufacturing is gaining even more attention all over the world, a clear sign that the focus on sustainability and the circular economy is intensifying. This book also demonstrates that there is much room for improvement in the remanufacturing sector and that research represents the base to reach it.

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Contents

Development of Sustainable Remanufacturing Systems: Literature Review

Paraskeva Wlazlak and Kerstin Johansen

Abstract Implementing remanufacturing as a strategy to achieve circularity in manufacturing companies offers significant benefits in terms of both environmental sustainability and financial performance. However, the development of sustainable remanufacturing systems is accompanied by various complexities and challenges. Companies engaged in remanufacturing must consider solutions that address the three dimensions of sustainability: economic, social, and environmental. Moreover, they need to tackle the unique characteristics associated with remanufacturing systems. This paper aims to investigate aspects covered in existing studies related to the development of sustainable remanufacturing systems. The methodology involves a literature review focusing on three aspects: (1) the triple bottom line of sustainability; (2) capabilities required for establishment of a sustainable remanufacturing system; (3) enablers that can support the development of a sustainable remanufacturing system. By classifying the published literature and conducting a thorough analysis, this paper provides valuable insights for practitioners and researchers, facilitating the creation and accumulation of knowledge in the field of sustainable remanufacturing systems. Furthermore, the paper aims to underscore the significance of this area of research and identify potential avenues for future investigation.

Keywords Remanufacturing · Sustainability · Circularity · Manufacturing system development

1 Introduction

The concept of sustainability has become paramount in urgency to reduce the impact on industrial activities on our planet [1, 2]. In strive to achieve a greener future, companies have started to redo their manufacturing processes to incorporate sustainable concerns [3, 4]. The attention towards sustainability performance has increased

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significantly, primarily because manufacturing can have adverse effects on the environment [5]. However, it is crucial to acknowledge that manufacturing also plays a vital role in promoting economic growth and societal well-being [6]. Because of the impacts on environment, society, and economic growth sustainable manufacturing has emerged as a concept [7]. Sustainable manufacturing has emerged as a concept that seeks to minimize environmental harm while maximizing the positive contributions of manufacturing to society. This is referred to as the triple bottom-line of sustainability [8, 9]. Thus, the performance of a manufacturing company should be holistically evaluated including not solely financial performance, but also social and environmental performance [1].

Among the new approaches remanufacturing systems have emerged as a solution that has the potential to foster a circular economy and is an important step towards achievement of sustainability development goals [1]. Remanufacturing is a process that involves restoring used products (or also called cores) to their original conditions and hence it has gained significant place in the research in the last decades [10, 11]. It offers benefits regarding minimizing of waste, resource consumption and mitigate the burden on landfills [12]. Remanufacturing systems enable companies to tap into the value of discarded goods, extend their life span hence contribute to economic and environmental sustainability aspects [13]. However, achievement of sustainable remanufacturing systems and its operation has its unique challenges and complexities [14] that are different from those that occur in traditional manufacturing such as low degree of automation and high manual work [15]. To ensure successful operations of a sustainable remanufacturing system that corresponds to internal and external requirements requires us to look into its development [1, 16]. Effective development of a system often is described with respect to 3 dimensions; process, people, and technology [17] which can be also applied to a remanufacturing system.

While the existing literature contains multiple literature reviews in the field of sustainable remanufacturing, with focus for instance on the role of emerging technologies in facilitating circular systems [18, 19] or performance indicators [13, 20] these reviews often lack a comprehensive or systems-oriented perspective when it comes to the development of sustainable remanufacturing systems. Such a holistic view is valuable for enhancing our understanding of the complex nature of remanufacturing systems. Furthermore, many of these reviews primarily concentrate on various circularity strategies, with remanufacturing being partially discussed [21, 22]. Consequently, there is a clear need for reviews that are specifically focused on remanufacturing as a key circular economy strategy.

Therefore, this paper delves into development of sustainable remanufacturing systems, exploring the different aspects that have been addressed in the existing research. Hence, the paper aims to answer the question '*What aspects have been addressed in the existing research on development of sustainable remanufacturing systems?*'.

By shedding lights into development of sustainable remanufacturing system, future research and direction can be proposed.

2 Introduction to the Main Topics

2.1 Remanufacturing System

Depending on the relation to the product manufacturer different companies can carry out remanufacturing activities. These are for example: (1) Original Equipment Manufacturers (OEMs) that remanufacture their own products; (2) contracted remanufacturers that carry out remanufacturing as a service to the OEMs; (3) and independent manufacturers that remanufacture products bought from other companies [1].

Remanufacturing encompasses the process of rebuilding used products (cores) to restore them to a useful state. The remanufacturing process involves several activities, including inspection, cleaning, disassembly, reprocessing, reassembly, storage, and testing, as depicted in Fig. 1 [10]. The order and purpose of these operations are not standardized and depend on individual remanufacturing cases and the specific requirements for core recovery [1].

Remanufacturing can be organized in multiple ways, presenting both similarities and unique characteristics when compared to traditional manufacturing. These unique characteristics introduce additional challenges that must be effectively managed within a remanufacturing system [15]. Some examples of these challenges include dealing with small batch sizes of mixed products and a low degree of automation, relying heavily on manual labor, comparable with high-mix low volume challenges [23]. Given the diverse nature of remanufacturing tasks, flexibility becomes a crucial requirement for a successful remanufacturing system [24]. To achieve profitability in remanufacturing, companies must address uncertainties

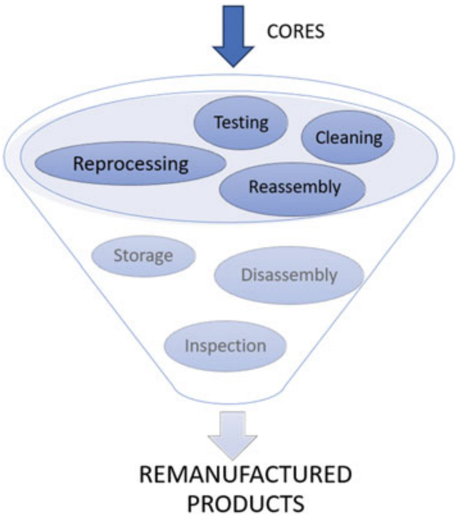


Fig. 1 Remanufacturing activities: adapted from Sundin and Bras [10]

surrounding core quantities and qualities, process variations, and capacity requirements. Overcoming these challenges is essential, as failure to do so may result in an unprofitable remanufacturing endeavor [19].

2.2 Systems-Oriented Approach to Remanufacturing

A manufacturing system encompasses a series of manufacturing processes that enhance the value of inputs to generate desired outputs [1]. In this paper manufacturing and production are used interchangeably. The manufacturing process entails the utilization of machinery, tools, power, and labor. Adopting a systems perspective in manufacturing helps us approach it holistically and gain a deeper understanding of its complexity. A similar line of thinking can be employed when the focus is on remanufacturing. This systems-oriented approach focuses on the various components that constitute the system and their interrelationships. A system can be defined as a collection of interconnected components, such as people and machines, working together in an organized manner to achieve a specific goal [25]. Different researchers may have slightly different descriptions of the components of a (re)manufacturing system. For instance, Hubka and Eder [26] argue that the primary components of a transformation system are the transformation process, the operand, and the operator. The operators, which include the human system, technical system, information system, and management and goal system, drive the transformation process. The relationship among these components contributes to the conversion of input into output, involving a value-added transformation.

Morgan and Liker [17] propose a model for product development systems, which emphasizes the integration of three subsystems. Similarly, when examining remanufacturing development systems, we can observe the integration of process, people, and tools and technology subsystems (see Fig. 2). The process subsystem includes actions, activities/tasks, and decisions associated with remanufacturing development, the way the development is carried out. It focuses on waste removal and standardization to increase flexibility. The people subsystem covers individuals representing organizational functions and competences related to remanufacturing development. It involves coordinating efforts and developing technical skills across different disciplines. The tools and technology refers to the use of different tools, methods to support development of remanufacturing systems.

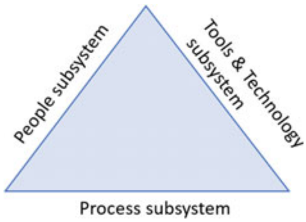


Fig. 2 A conceptual view of system approach to remanufacturing: adapted from Morgan and Liker [17]

The development of a (re)manufacturing system involves both its design and implementation. Previous research has highlighted that the practical development of manufacturing systems often lacks a systematic perspective, relying instead on ad hoc principles and uncertain, unstructured activities [25]. Manufacturing development is commonly described in terms of a project management stage-gate process. To address this challenge, literature and practical handbooks have proposed various processes and frameworks to support the development [25, 27].

3 Research Methodology

The aim of this paper is to investigate aspects covered in existing studies related to the development of sustainable remanufacturing systems. To achieve this, a literature review methodology was employed, following the recommendations of Jesson and Lacey [28]. The search was conducted in the Web of Science database using the search term “sustainable remanufacturing” within a period between 1999 and May 2023, resulting in 782 publications.

To refine the results and focus on relevant meso-level topics, four specific areas were selected: sustainability science, design and manufacturing, management, and manufacturing. Publications on other topics (for example, supply chain and logistics), were excluded, leaving a total of 249 identified publications. The literature overview encompassed various types of publications, including journal articles, conference papers, proceeding papers, and review articles. Two editorial materials were excluded as they were deemed irrelevant to the aim of the paper, resulting in a final selection of 247 papers.

The titles and abstracts of these papers were carefully reviewed for relevance, leading to the exclusion of many papers due to their lack of relevance to the subject area. Ultimately, 27 papers were considered relevant and progressed to the next step of the review process, which involved a thorough reading of the entire papers. To be included in the final review, these 27 papers needed to strongly focus on sustainability, remanufacturing systems, and development, excluding those that only briefly mentioned one of these areas. After conducting a thorough review of the papers, 15 additional papers were excluded from the study as they primarily focused on business models, the process of business model innovation, had a supply chain perspective, or only mentioned sustainability or remanufacturing systems. These papers were considered outside the scope of this study. The final selection of papers included 12, which were then classified based on their content. The classifications focused on three aspects: (1) the triple bottom line of sustainability; (2) capabilities required for establishment of a sustainable remanufacturing system; (3) enablers that can support the development of a sustainable remanufacturing system.

4 Literature Review Results: Sustainable Remanufacturing

This section is divided into two main sub-sections: "Descriptive overview" and "Aspects addressed".

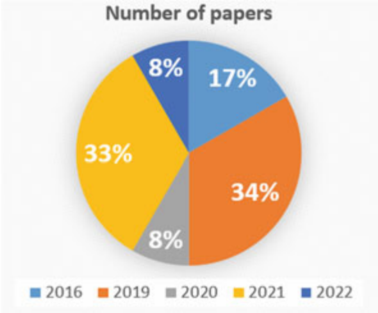
4.1 Descriptive Overview

Table 1 provided overview of the research methods employed and the topic addressed in the selected 12 papers. It revealed that 7 of the papers utilized literature review as their research method, while 5 papers utilized case studies.

Table 1 Overview of the selected papers

Ref	Method	Topic addressed
Literature reviews		
[13]	Literature review	Indicators for a circular economy
[18]	Literature review	The role of Fourth Industrial Revolution in remanufacturing in developing countries
[19]	Literature review	Smart remanufacturing and sustainable application of I4.0 enablers
[20]	Literature review	Decision support systems for sustainable (re)manufacturing
[21]	Systematic literature review	Information management for adopting CE strategies
[22]	Literature review	Considering the three sustainability dimensions for circular economy realisation
[29]	Literature review	Outline five research fields in remanufacturing literature and propose future directions
Case study		
[14]	Case study	Barriers (technical, economic, organizational, structural, legal and societal) and recommendations for achieving circular and efficient production systems
[15]	Case studies	Application of lean methods in industrial remanufacturing operations
[24]	Case study	Integrative perspective to drive sustainable value creation in remanufacturing contexts
[30]	Case study	Propose an environmental-impact based indicator that complements existing measures (mass-based indicators)
[31]	Case study	Interconnections between the lean and the circular systems

Fig. 3 Distribution of papers by year of publication



A total of 12 papers were included and they were categorized according to the year of publication (see Fig. 3).

4.2 Aspects Addressed

4.2.1 Sustainability Aspects

Table 2 presents a compilation of the selected papers along with the sustainability dimensions (economic, environmental, and social) they focus on.

Of the selected 12 papers, 11 focused on economic sustainability, addressing areas such as monitoring costs in remanufacturing operations and discussing productivity and profitability [14, 15, 19, 21, 22, 31]. Key performance indicators (KPIs) for

Table 2 Overview of sustainability dimensions

References	Sustainability dimensions		
	Economic	Environment	Social
Kristensen and Mosgaard [13]	x	x	
Despeisse et al. [14]	x	x	
Pawlik et al. [15]	x		
Chau et al. [18]		x	
Kerin and Pham [19]	x	x	x
Zarte et al. [20]	x	x	x
Acerbi et al. [21]	x	x	x
Lieder and Rashid [22]	x	x	x
Jensen et al. [24]	x	x	x
Esmaeilian et al. [29]	x	x	x
Haupt and Hellweg [30]		x	
Schmitt et al. [31]	x	x	

measuring economic sustainability were summarized, including net present value, life cycle costing, total cost of ownership, product reliability, cycle time, process flexibility, reuse rate [29]. The economic indicators in Zarte et al. [20] and Acerbi et al. [21] covered cost, profit, investments, quality, delivery, and flexibility. Regarding environmental sustainability, 11 of the papers emphasized the collection of environmental data, resource usage, emissions, and reducing waste and CO_2 emissions throughout the product lifecycle [14, 18, 21, 22, 31]. KPIs for measuring environmental sustainability included emissions, waste, energy consumption, and land use [29, 31]. Haupt and Hellweg [30] introduced the environmental-impact based REV indicator to measure retained environmental value through activities like reuse, remanufacturing, repairing, and recycling. Zarte et al. [20] discussed indicators related to material, energy, waste, and greenhouse gases. In terms of social sustainability, only six papers addressed this aspect, focusing on monitoring workers' ergonomic and safety conditions [21]. KPIs for measuring social sustainability encompassed equity, ethical considerations, employee welfare and development, employee turnover rate, training, employee health and safety, supplier commitment, and consumer satisfaction [29]. The social indicators in Zarte et al. [20] pertained to employee health and safety, satisfaction, and development.

4.2.2 Capabilities Required for a Sustainable Remanufacturing System

In Table 3, the identified capabilities necessary for establishing a sustainable remanufacturing system are presented. These capabilities are classified based on the three dimensions of a manufacturing development system: process, people, and tools and technology.

Remanufacturing systems possess distinct characteristics that distinguish them from traditional manufacturing [19, 29]. These unique features necessitate the development of specific capabilities. In particular, eight process-related capabilities were identified. The identified capabilities referred to system's capacity to effectively manage and adapt to uncertainties in volume and requirements. Additionally, capabilities focused on the system's ability to effectively manage situations where production volumes are low and process times exhibit high variability. It involved addressing the challenges associated with fluctuating demand levels, unpredictable processing times, and potentially inefficient resource allocation. Capabilities were also required to handle complexities related to production planning and control [15]. Many complexities were mentioned to arise from scheduling diverse workflows and remanufacturing activities based on the core's condition [15, 19]. Ensuring efficiency within remanufacturing systems presents a significant challenge [15]. In remanufacturing operations, ensuring that cores are reassembled with the exact same components can be challenging, especially when multiple cores are involved [15]. Furthermore, five people-related capabilities were highlighted. It was indicated that labor-intensive processes pose challenges [15], emphasizing the importance of providing a safe working environment. Upskilling operators with the necessary skills and competencies to effectively use digital technologies and handle highly variable tasks [14,

Table 3 Capabilities related to process, people, tools and technology

Capability	References
Process	
To adapt and adjust processes effectively in response to changing market dynamics and product demands	[15, 18, 19, 21, 29]
To adapt to variations, unpredictability, or fluctuations in the quality and quantity of inputs and outputs within the process	[15, 18, 19, 21, 29]
To handle low production volumes and highly variable process time	[15, 29]
To effectively handle inventory planning in response to market demands while addressing challenges related to inventory costs and waste	[29]
To effectively manage scheduling and coordination of various remanufacturing activities to ensure efficient and timely production	[15, 19, 21, 29]
To manage complexities caused by different product generations and the numerous variants often found within a product family	[15]
To effectively handle the disassembly of returned products into their component parts and subsequently reassemble them into functional products	[14, 15, 31]
To effectively oversee and coordinate operations that rely heavily on manual labor	[15, 29]
People	
To ensure a safe and ergonomic work environment that promotes the well-being, health, and safety of its workers	[21]
To identify, recruit, and develop personnel with the necessary skills and competencies to effectively operate and utilize digital technologies in the workplace	[18, 19]
To identify, recruit, and develop personnel with the necessary skills and competencies to handle highly variable and complex operations	[14]
To educate and inform personnel about the positive aspects and potential environmental consequences associated with industrial operations	[22]
To foster effective communication and collaboration between departments	[31]
Tools and technology	
To monitor and track the costs associated with remanufacturing processes	[21]
To monitor and track environmental impacts associated with remanufacturing processes (energy, material waste, and CO_2)	[19]

18]. Two capabilities were related to tools and technology. They focused on the developing of the ability of the systems to monitor, gather and distribute information with respect to cost and environmental impacts [21, 31].

4.2.3 Enablers

In Table 4, the identified enablers necessary for establishing a sustainable remanufacturing system are presented. These enablers are classified based on the three dimensions of a manufacturing development system: process, people, and tools and technology.

Only one process-related enabler was revealed. It aids in decision-making regarding the implementation of remanufacturing practices and considers their economic and operational viability [31]. A single people-related enabler was recognized, focusing on training and education in various Industry 4.0 technologies, such as virtual reality (VR), augmented reality (AR), and human–robot collaboration. It emphasized the significance of sustainability and the benefits of utilizing IoT to drive progress and ensure quality. The training and education focused on providing knowledge on effectively managing multiple tasks, disassembly, and rework activities [15, 19, 22]. Eight tools/technology-related enablers were identified. Digital tools were particularly important for gathering information about product conditions [21]. The introduction of sensors in product design enables real-time data collection, facilitating the gathering of data and information on products throughout their lifecycle [22]. Utilizing supporting technologies like virtual reality (VR), digital tests, and digital line layouts provide a means to minimize the reliance on physical test assemblies. This approach effectively reduces material waste and CO_2 emissions associated with production preparation, leading to significant economic savings. Data generation and processing are of great importance in factory management,

Table 4 Enablers related to process, people, tools and technology

Enabler	References
Process	
Evaluation of economic and operative feasibility of a remanufacturing strategy	[31]
People	
Training and education	[15, 19, 22, 31]
Tools and technology	
Remanufacturing technologies with advanced automation levels	[18, 19, 21]
Decision support tools	[19, 21]
Simulations tools	[21]
Digital technologies of Industry 4.0 (IoT platform, Virtual Reality, Augmented Reality, and Big Data)	[14, 18, 19, 21, 31]
Design for X methods such as design for disassembly or remanufacturing	[14, 22, 29, 31]
ICT systems that enable product lifecycle management	[22]
Lean practices	[15]
IT infrastructure	[31]

allowing managers to have a comprehensive understanding of production situations and the success of remanufacturing operations. Automation devices, including robots, address workforce challenges in smart factories, where employees can focus on assembling complex parts while robots handle repetitive tasks, benefiting the social environment [18]. Additionally, Kerin and Pham (2020) explored the relationship between Industry 4.0 (I4.0) and Internet of Things (IoT) technology in terms of economic sustainability. They highlighted the potential for improved manufacturing efficiency and cost reduction through the adoption of these technologies. The authors also discussed the environmental benefits of implementing I4.0 and IoT in remanufacturing processes. However, they noted a lack of emphasis on the environmental impacts of I4.0 in the remanufacturing field. Additionally, the authors pointed out that the social sustainability effects of I4.0 in remanufacturing are similar to other areas where IoT is applied. These effects involved changes in the skills, attributes, and behaviors of the individuals involved. To reduce variability, best practices for disassembly should be documented and shared with employees to make such operations more effective. Furthermore, Pawlik et al. [15] discussed the application of lean methods (e.g. standardization, visual management, 5S, Total Productive Maintenance) in industrial remanufacturing operations.

5 Discussion and Conclusions

The aim of this review paper was to examine the various aspects addressed in existing studies concerning the development of sustainable remanufacturing systems. The study primarily focuses on sustainability at a micro level, which pertains to the organizational level [11]. The identified indicators are designed to evaluate the sustainability of companies' remanufacturing systems, while some indicators also assess the contribution of remanufacturing towards achieving broader sustainability goals. Kristensen and Mosgaard [13] emphasize that the primary focus in remanufacturing activities lies in ensuring economic viability and environmental sustainability. This review highlights that the majority of emphasis is placed on the economic and environmental dimensions of sustainability, while the social dimension receives comparatively less attention. However, six of the reviewed papers highlighted the importance of balancing between environmental impacts, costs, and social impacts when making decisions related to sustainability in a remanufacturing system [22, 24, 29]. It is underscored the importance of establishing sustainability performance objectives and indicators to measure the effectiveness of a remanufacturing system across economic, environmental, and social dimensions. However, despite the growing body of research, there is a lack of tools, methods or frameworks that could support the development of remanufacturing systems capable of effectively balancing all three pillars of sustainability. The lack of frameworks integrating sustainability principles into the development of manufacturing systems is underlined by prior research [3, 4].

To achieve optimal performance in terms of these sustainability dimensions, it is crucial to design and develop remanufacturing systems with the capability to meet these performance requirements. The design and development process of a manufacturing system plays a critical role in achieving the desired sustainable performance [16]. Johansson et al. [1] underscore the importance of implementing appropriate development processes that align with sustainability objectives at every phase of the development. Overall, the reviewed literature provides insights into important sustainable objectives and indicators, but falls short in providing evidence on how to develop remanufacturing systems that effectively meet these objectives.

This study indicated unique capabilities that are required for a remanufacturing system, and they are related to process, people, tools and technology. Remanufacturing systems require specific capabilities to effectively manage and adapt to uncertainties in volume and requirements, handle complexities related to production planning and control, and address challenges associated with labor-intensive processes [21, 29]. In addition, this study investigated the enablers that can facilitate the establishment of sustainable remanufacturing systems. Among the dimensions of process and people, only one specific enabler was mentioned, while the primary emphasis was placed on the role of tools and technology as enablers for achieving sustainable remanufacturing systems. However, the link between these enablers and the sustainable performance of the system remains unclear. There seems to be a common assumption that introducing certain enablers into a remanufacturing system will automatically improve its sustainability performance. This review highlights a deficiency in establishing explicit connections between the identified enablers for sustainable remanufacturing systems and the corresponding performance objectives and indicators. Consequently, the effects of these enablers on fulfilling different performance objectives during the operational stages of the systems' life cycle remain unclear. There are some exceptions, for example the literature review by Kerin and Pham [19] provide a discussion regarding the impact of existing and emerging digital technologies on the three pilar of sustainability.

In conclusion, further research is needed in several areas. Firstly, there is a need to develop guidelines, processes, and frameworks that specifically support the development of sustainable remanufacturing systems. Designing and developing for sustainability in the context of remanufacturing systems requires additional research and investigation.

Moreover, there is a pressing need for a well-defined development process that takes into account the sustainability pillars at each phase of the remanufacturing system development. A sustainability performance-driven approach is essential, with the goal of integrating sustainability considerations at every stage of the remanufacturing system development process.

A holistic perspective is essential during the development of sustainable remanufacturing systems, considering the dimensions of people, process, tools and technology. A more holistic perspective is necessary to effectively develop and understand the complexities of sustainable remanufacturing systems development.

A future study could expand its scope by concentrating on databases such as SCOPUS.

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Artificial Intelligence in Remanufacturing Contexts: Current Status and Future Opportunities

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Abstract Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL), rapidly evolving in both academia and practice, allow for improved manufacturing processes thanks to data analysis. These technologies provide benefits to production systems in several ways by enabling resilience and improving sustainable growth. However, the manufacturing challenges and issues need to be revised according to the new trends provided by remanufacturing, i.e., an emerging and new "mode" of manufacturing able to bring used products to a "like-new" state, potentially profitable and less environmentally harmful compared to the classical manufacturing systems. This research work, methodologically based on a scoping literature review, provides the state-of-the-art related to AI, ML, and DL use in remanufacturing contexts, identifying the main field of applications and their challenges and limitations. The findings revealed an increasing interest in the topic in the last three years. Most of the studies focused on disassembly and inspection processes, whereas further applications (e.g., repair, demand forecasting, cost prediction, etc.) have not been fully investigated and need further research. DL represents the most widely used technique (followed by ML). Even though the literature confirmed that AI-based methods could increase productivity and lower time and costs, further attention needs to be paid to real industrial case study applications.

Keywords Sustainable development · Circular economy · Remanufacturing

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1 Introduction

Remanufacturing is one of the key elements of the circular economy, i.e., a production and consumption paradigm that aims to maintain the circulation of products, components, materials, and energy for adding, restoring, and maintaining their value over a long time [1]. Keeping resources in use for as long as possible allows for less extraction of new raw materials and reduces waste, leading to more sustainable economic growth. In this picture, remanufacturing aims, in particular, to “return a used product to at least its original state with a warranty that is equivalent to or better than that of a newly manufactured product” [2, 3]. The concept of remanufacturing is not new at all. Already in 1985, Lund, a Boston University professor, introduced this typology of industrial process in which a new product can be reassembled from an old one and, where necessary, new parts are used to produce fully equivalent, and sometimes superior in performance and expected lifetime, to the original new product [4]. Remanufacturing plays a significant role in solving the problems of environmental pollution and resource shortage, as well as promoting global economic and social development since the basic raw materials are represented by second-hand products or cores collected from consumers so that the residual valued-added in forms of materials, energy, and labour can be captured and re-used [5].

The remanufacturing process generally starts with acquiring used products, which are then inspected to determine the quality conditions. After and according to the quality condition, used products are disassembled into corresponding constituent components, which are then reprocessed. Once all constituent components are reprocessed, these are reassembled and tested before being sold as remanufactured products [6, 7]. This process hides several problems, such as uncertainty regarding the quality conditions, quantity, and timeframe for the return of materials and components to be remanufactured, refurbished, or reused; the balance of customer demand with used-products supply, and the way to produce, plan, and generate demand for manufactured and remanufactured products simultaneously [1, 8–10].

The digital transformation enabled by the Industry 4.0 paradigm can help in overcoming some of these problems or at least reduce their impacts on the system. In particular, the increasing digitalization and the integration of smart devices and machines in production systems are more and more able to provide large amounts of data that can be stored, processed, and analysed. In this context, it is worth mentioning the growing interest in applications of Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) methods in the manufacturing environment. AI, a broad field of computer science, allows to building of smart machines capable of performing tasks that typically require human intelligence [11]. ML and DL instead represent the two essential sub-fields of AI. ML allows computers to recognize data correlations and make human-like decisions without defining rules. It is based on a generalization of data knowledge and can be realized by different methods, such as classification, clustering, regression, and anomalous detection [12]. DL, instead, refers to data-driven learning approaches that use multi-layer neural networks and processing to compute. The term “deep” highlights the high number of levels or stages through which data is processed to develop a model [11].