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**Integrating Industry 4.0 Technologies into
Contemporary Vision of Reverse Supply Chain
Activities: A Framework for Manufacturing
Sustainability**

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Date:

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Abstract:

Reverse supply chains and their integration with manufacturing technology have recently received considerable attention in academic research and practice because of their significant impact on manufacturing sustainability, environmental protection, and social benefits. This study specifically examines how Industry 4.0 technologies can be integrated into reverse supply chain activities, adopting a contemporary vision that extends beyond mere recycling to encompass meeting customer preferences, the rational use of raw materials, and ethical manufacturing. The conceptual framework builds on existing theories of sustainability-oriented innovation and resource orchestration. It develops a dynamic, interactive model that leverages Industry 4.0 technologies to improve manufacturing sustainability. The study investigates the mechanisms for integrating Industry 4.0 technology with the contemporary vision, both directly and indirectly. It clarifies the role of mediating variables, such as customer feedback and recycling, in strengthening the relationship between Industry 4.0 technologies and the contemporary vision. Data collection employed a mixed-methods approach. The quantitative method used a five-point Likert scale, aligned the questions with the research objectives, administered 250 validated questionnaires, and employed SEM analysis. The qualitative method involved 10 semi-structured interviews to support the quantitative results and provide deeper insights through thematic analysis of the interview transcripts. The results indicate that I4.0 technologies exert a statistically significant direct effect on reverse supply chain activities. In contrast, the indirect effect, although relatively weaker, remains important and reflects an integrated structure that is dynamically interactive through customer feedback and operationally supported by recycling. The research contributes by theoretically expanding and empirically verifying the reimagining of digitally supported reverse supply chain activities, illustrating how Industry 4.0 technologies are reshaping sustainable manufacturing practices. The study recommends expanding the knowledge base and exploring new opportunities to leverage Industry 4.0 technologies for reverse supply chain activities and to keep pace with rapid manufacturing advancements.

Keywords: Reverse supply chain, Industry 4.0, Rational use, Smart factory, Sustainable, Reverse logistics, Manufacturing ethics.

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List of abbreviations:

Reverse Supply Chains.	RSCs
Industry 4.0.	I4.0
Reverse Supply Chain Management.	RSCM
Internet of Things.	IoT
Cyber-physical system.	CPS
Resource Orchestration Theory.	ROT
Sustainability-Oriented Innovation.	SOI
Original Equipment Manufacturer.	OEM
Information and Communication Technology.	ICT
Information Technology.	IT
Circular Economy.	CE
End-of-Life.	EOL
Industrial Internet of Things.	IIoT
Research and Development.	R&D
Reverse Supply Chain Planning Matrix.	RSCPM
Reduce, Recover, Reuse, Redesign, Remanufacture, and Recycle.	6Rs.
Circular Supply Chain Management.	CSCM
Mixed-Integer Linear Programming.	MILP
Reveres logistic.	RL
Organisation Information Processing Theory.	OIPT
Artificial intelligence.	AI
Small and medium Enterprises.	SMEs

Automated Guided Vehicles.	AGVs
Supply Chain.	SC
Mixed-Integer Linear Programming.	MILP
Sequential Explanatory Design.	SED
Structural Equation Modelling.	SEM
Common Method Bias.	CMB
Goodness of Fit Index.	GFI
Adjusted Goodness of Fit Index.	AGFI
Normative Fit Index.	NFI
Parsimony Goodness of fit index.	PGFI
Relative Fit Index.	RFI
Root Mean Square Residual.	RMSR
Generalised Least Squares.	GLS
Unweighted Least Squares.	ULS

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<https://pureportal.strath.ac.uk/en/publications/reverse-supply-chains-in-industry-40>

Chapter 1

Introduction and Research Foundation

1.1 Introduction:

Over the past decade, reverse supply chains (RSCs) have gained prominence in both industrial practice and academic scholarship, reflecting their growing strategic importance in advancing sustainability, resource efficiency, and circular-economy objectives. Several factors drive this expansion: environmentally conscious consumers prefer more eco-friendly manufacturing, and as raw material costs rise, reuse becomes more attractive. Additionally, RSCs can help firms gain a competitive advantage and boost profits (Larsen et al., 2018; Gao et al., 2024). The reverse supply chain has become increasingly important for managing the challenges of remanufacturing and waste disposal, as manual operations in this area are relatively costly (Omair et al., 2022; Mishra et al., 2023). Furthermore, collecting end-of-life products poses a significant challenge for transactions, underscoring the need for research on firms that provide solutions (Sun et al., 2019). Consequently, RSCs are a vital part of circular economies (Niyommaneerat et al., 2023; Dos et al., 2023). Firms benefit from RSCs through increased operational capabilities, public benefits, improved customer satisfaction, reduced production costs, and more efficient return management (Doan et al., 2019).

Reverse supply chains can be defined as “accepting returned customer products and returning them to suppliers for potential remanufacturing” (Sun et al., 2019). Moreover, Larsen et al. (2018) define Reverse Supply Chains (RSCs) as the processes of recovering returned products from customers, reusing them, or disposing of them in an environmentally friendly manner. Hence, the collection and dismantling processes for end-of-life products should be optimised, and the related procedures automated (Habibi et al., 2017). However, further studies are needed to identify waste streams and disposal methods, thereby improving productivity across industries (Muharom et al., 2019). RSCs network design involves long-term strategic decisions that are critical to RSCs performance (Singh et al., 2024; Doan et al., 2019). Consequently, designing the SC network is complex because it involves multiple echelons and effective connections among them. Network design aims to determine the optimal number and location of facilities and to manage the network's material flow. The main objective of most companies is to establish RSCs networks that minimise total costs while considering both environmental and manufacturing sustainability (Doan et al., 2019; Öksüz et al., 2025). With competition among sellers and increased market shares in immediate sales through online channels and mail requests, customer returns have become a critical issue that manufacturers and dealers cannot ignore. An illustrated survey further reviews the range of values and benefits of goods and services

prior to purchase. As a result, 'satisfaction ensured' policies have gradually become a practical element in modern market competition, encouraging sales growth by reassuring customers (Sun et al., 2019). On the other hand, Industry 4.0 is a current approach in manufacturing organisations, linked to the concept of a Smart Factory, which involves integrating and automating the planning, control, and monitoring of technological and environmental processes (Hernes et al., 2020). It challenges many organisations to understand the concept of Industry 4.0, which remains in its early stages, to develop comprehensive digital transformation strategies, and to assess implementation outcomes in terms of costs (Colli et al., 2020). Therefore, I4.0 has become an essential concept across various sectors, from academia to modern manufacturing; however, many aspects of its meaning remain unclear.

Industry 4.0 can be viewed as a more attractive, internet-based version of industry. In contrast, Industry 3.0 emphasised operational automation and facilitation through digital technologies, but overall process control still required greater precision, centralisation, and human oversight (Oesterreich et al., 2016). The Internet of Things (IoT) becomes a capability within RSCM. Real-time information from the IoT, based on the frequency of Radio Frequency Identification/Electronic Product Code signals, enables immediate control over nearly every step in the supply chain, including warehousing, raw material purchasing, production, transportation, storage, allocation, sales, returns processing, and after-sales service. This real-time data will help teams in the reverse supply chain quickly and cost-effectively evaluate the quality of used products (Gu & Tagaras, 2014).

Global concerns, particularly those related to sustainability, are escalating and may be addressed through Industry 4.0 technologies (Masood et al., 2021). Historically, manufacturers have perceived reverse supply chains (RSCs) or reverse logistics operations as expensive and cumbersome; nevertheless, recent studies indicate that RSCs can enhance a company's financial performance (Larsen et al., 2018; Adesoga et al., 2024). Industry 4.0 utilises digital technology to facilitate data sharing, hence transforming production processes; it is frequently regarded as a more attractive, internet-centric model of industry (Oesterreich et al., 2016). These contribute significantly to supporting reverse supply chains by enhancing the rational use of raw materials, aligning with customer preferences, and upholding manufacturing ethics. In the field of reasonable use, it can support Internet of Things sensors in collecting data on raw material consumption to identify waste and facilitate continuous process improvement. Recent research has shown that RSCs can enhance a company's competitive advantage (Larsen et al., 2018; Xuetong et al., 2024). Regarding customer preferences, one of the most critical components of Industry 4.0 systems, CPS enables the integration of physical and virtual spaces (Rossit et al., 2019). Understanding and analysing customer preferences to meet them optimally enables flexible smart manufacturing joints to quickly adapt to customers' requirements (Chang, 2011; Qu et al., 2019). In the context of manufacturing ethics, Industry 4.0 technology is a valuable solution, as it

enables tracking of the entire supply chain to ensure products are manufactured in accordance with specifications. In addition, IoT sensors integrated with monitoring tools can identify instances of unethical behaviour (Kumar et al., 2020). Similar to cloud technologies, the Internet of Things and cyber-physical systems evolve digital platforms that enable communication between manufacturers, suppliers, and customers, which optimise resource utilisation, minimise waste, detect inefficiency, minimise material loss, and increase the life cycle of products (Ahmed et al., 2021; Delpla et al., 2022). Big data advances ethical production by enhancing transparency in the supply chain, responsible sourcing choices, risk assessment and reduction, quality management and product safety, energy efficiency and sustainability, and customer insights and feedback (Dey & Shekhawat, 2021; Delpla et al., 2022).

Although Industry 4.0 technologies have previously contributed to reverse supply chain activities, to the best of our knowledge, no framework has been proposed to guide their successful integration. Additionally, the available literature on recycling and material recovery is largely focused on reverse supply chains. The relevance of our research, in this regard, lies in its timeliness, focus on customer preferences, rational use of raw materials, adherence to manufacturing ethics, and integration of Industry 4.0 technologies.

The research highlights issues related to manufacturing ethics and the extent to which manufacturers consider them. It provides a contemporary vision of reverse supply chain activities combined with Industry 4.0 technology. Beyond traditional reverse supply chain tasks such as recovery and recycling, the study aims to illustrate how Industry 4.0 technology can be integrated into the contemporary vision of reverse supply chain activities through direct and indirect pathways, mediated by intermediate variables, to enhance manufacturing sustainability. It also emphasises the efficient use of raw materials, the use of customer feedback to improve production quantities and quality, and the satisfaction of customer requirements. Furthermore, as the pace of technological change accelerates and customer data sharing becomes more common, protecting customer data and providing environmentally friendly products are essential to ensuring greater manufacturing sustainability and environmental protection. Therefore, we propose combining Industry 4.0 technology with reverse supply chain activities to achieve this goal. Based on this, we introduce a new framework with metrics that reflect the joint contribution of these mechanisms to the I4.0 role in the contemporary vision of RSCs activities. In doing so, our study aims to contribute to the development of resource orchestration theory and offer practical guidance on how these technologies can be used as resources to enhance the contemporary vision of RSCs activities.

The research vision, which focuses on the dependent variable of reverse supply chains prior to the advent of Industry 4.0 technologies, is reflected in the abstract, introduction, and background,

indicating a phenomenological and contextual research perspective. This research falls within the field of sustainable and circular manufacturing practices, where reverse supply chains constitute the core experimental domain and are central to operational and strategic complexity. Accordingly, the research first identifies the structural, managerial, and performance-related challenges inherent in reverse supply chains to establish the research context and clarify the scope of the core problem. Industry 4.0 technologies are then presented as proposed explanatory and enabling frameworks for addressing these challenges. This methodological sequence aligns with problem-framing approaches in explanatory research, in which the central organisational phenomenon is conceptually established before theorising the underlying technological factors assumed to influence it. This structure enhances analytical clarity by clearly distinguishing between the experimental domain under investigation and the causal mechanisms examined within it.

1.2 Research problem:

Industrial firms compete globally using modern manufacturing technologies that have increased the production and consumption of goods, making older technologies obsolete and prompting consumers to replace them with newer ones. This has highlighted the need for RSCs activities to recover and recycle obsolete materials. Production has also changed significantly, resulting in increased waste. International indicators show that despite the implementation of treatment processes and environmental programs in this sector, waste continues to grow at an excessive rate. These effects have become a global problem, especially in the manufacturing industry. In response, scholars and government agencies have proposed various initiatives that, in some cases, have helped reduce these impacts. However, waste levels continue to rise, and production processes need to become more environmentally friendly. That is why new mechanisms to help make manufacturing sustainable must be discovered and studied. This study proposes a mechanism that could facilitate the achievement of manufacturing sustainability through the use of I4.0 technologies to support RSCs activities, aligning with a contemporary vision of contributing to sustainable manufacturing, creating consumer value, and protecting the environment.

1.3 Research gap:

Manufacturing operations and RSCs have been significantly modified to improve efficiency and produce high-quality materials; however, additional efforts and operations are still needed, as waste and pollution continue to rise. Therefore, it is necessary to conduct studies to make it more sustainable (Tansel, 2020; Kibria et al., 2023). In recent years, the growth and production rates of consumer goods have accelerated due to advances in manufacturing technology, leading to a greater number of obsolete

products and, consequently, a higher waste volume (Singh et al., 2017). Firms should work hard to identify waste and eliminate it through environmentally friendly means, and invest in industrial productivity and manufacturing sustainability (Muharom et al., 2019). To achieve sustainability across production, manufacturing, and environmental conservation, researchers are integrating RSCs activities with Industry 4.0 technologies (Zaknini et al., 2022).

Reviewing prior literature in the researcher's field of specialisation revealed a weakness in studies that adopted Industry 4.0 technologies to support RSCs' activities. Additionally, there is a lack of studies examining RSCs activities. Their focus is on recycling operations, and they have not benefited from their other activities in managing customer information, which can yield several sustainability benefits in manufacturing.

The relationship between Industry 4.0 and RSCs activities has been the subject of many recent studies. However, the scholarship still lacks a systematic understanding of how and when Industry 4.0 technologies can facilitate sustainable RSCs. Older systems researched by Morella et al. (2023) and Federico et al. (2021) address green supply chains and forward logistics, focusing on the operational efficiency, traceability, and automation of RSCs, rather than extending reverse logistics to circular resource management. This relates to sustainable manufacturing or state-of-the-art technology. In this regard, the assessment by Agnosdy et al. (2022), *Infrastructure for Digital Transformation of Supply Chains in Industry 4.0 Applications in RSCs and Circular Manufacturing Practices*, though it described the challenges of integrating these two elements, addressed only the initial and final phases of integration, rather than the strategic, organisational, or managerial implications of integrating Industry 4.0 technology into RSCs activities as a whole.

This gap highlights a shortage of information in the literature. Current knowledge lacks integrated mechanisms to explain how Industry 4.0 technology can simultaneously integrate and facilitate the interconnected operational, informational, and ethical dimensions of customer-oriented manufacturing practices in RSCs activities. Prior studies conceptualised RSCs, customer integration, digital transformation, and sustainability as disjunctive areas of research rather than as an integrated framework within the context of sustainable practices enacted through digitally enabled RSCs activities. Hence, an intellectual problem worth solving is to determine whether an emerging large-scale integrated framework exists. That can account for and elucidate the pathways through which Industry 4.0 technologies may be leveraged to develop sustainable solutions that foster RSCs. Based on a contemporary vision capable of addressing contemporary phenomena regarding the advancement of manufacturing technologies at a pace, if not rapidly.

In the context of sub-research gap 1, including Industry 4.0 technologies in aiding the efficient and rational utilisation of raw materials as a contemporary activity carried out by RSCs, previous literature

identifies that IoT, big data analytics, CPS, and smart factories could be employed to improve the efficiency with which resources are utilised while minimising waste generation or energy consumption. For example, Morella et al. (2023) note that Industry 4.0 technologies advance the efficiency of real-time monitoring, recycling, and the sustainable use of resources, as well as transparency.

Nevertheless, the rich literature on this topic examines only sustainability objectives related to the efficiency of resource use in forward logistics and green supply chains. These RSCs activities involve different operational challenges, uncertainties regarding shipment and redistribution (recovery), variability in the demand-supply chain process, and low quality assurance. As a result, further research in forward logistics cannot be applied to reverse logistics. Moreover, previous research has reached different conclusions about the actual sustainability impact of implementing Industry 4.0 technologies. Some researchers argue that Industry 4.0 is driving the potential to eliminate waste through analytical circular manufacturing practices, whilst others emphasise technology- and process-based solutions that face barriers to digital transformation, coupled with challenges related to technological waste and economic feasibility studies. Therefore, a research gap remains. This event explores whether Industry 4.0 technologies support sustainability in manufacturing and how digital technologies can be used to enhance a rational raw materials story amid changing conditions and recycling uncertainties.

The purpose of this research is to address the theoretical and empirical gap by proposing a model that explains how Industry 4.0 technologies enhance sustainable RSCs activities that implement circular practices to optimise the rational use of raw materials.

Regarding our research sub-gap 2, past literature on Industry 4.0 technologies and RSCs has instead primarily emphasised automation-based approaches, tracking and monitoring systems, or transportation and digitalisation infrastructures. Agnosdy et al. (2022) highlighted enabling technological advancements in reverse logistics activities, especially in the initial and final last-mile delivery processes, through transparency-tracking support systems aided by IoT and networking technologies.

Likewise, research on RSCs is usually conducted through the lens of operational efficiency, predictive analytics, and data integration. Nevertheless, the customer-oriented parts of RSCs have not been studied extensively. The current literature rarely informs how customer feedback should be instigated when making decisions in RSCs driven by Industry 4.0 technologies. This omission is of central theoretical relevance because one of the main dimensions RSCs have often focused on is customer feedback on returns and recycling practices, particularly customers' preferences for recycled products. However, prior literature has largely treated customers as mere data sources rather than as active partners in co-creating the digital RSCs ecosystem.

In addition, previous studies have made inconsistent assumptions about customer preferences for RSCs. On the one hand, while some findings suggest that digital technologies inherently enhance customer choice and preference reporting via RSC systems, other studies identify privacy, trust, or transparency tensions associated with the detection of customers by these new data sources, which may decrease consumer engagement in providing their preferences and desires.

At the same time, it remains an open intellectual question how Industry 4.0 technologies can transform customer feedback into actionable data that enables companies to adapt their reverse logistics processes more thoroughly and holistically than at present, while improving RSCs adaptability to customer desires.

Under the green sub-gap 3, most of the Industry 4.0 literature recognises that RSCs activities need to take ethical and social issues into account (the economic dimension can be found under pressure by accounting). Federico et al. (2021) conducted similar work, demonstrating the need to balance economic efficiency and social sustainability in digitally enabled RSCs.

The literature on sustainable RSCs also highlights the increasing influence of stakeholders, such as environmental organisations and consumers, on manufacturing practices. Still, a large part of Industry 4.0 research focuses on technology only, perhaps efficiency and productivity, or automation (or both), with no concern for ethics in the production process; no customer-driven quality controls or transparency mechanisms exist.

Additionally, most available knowledge offers a limited perspective on information governance in RSCs. Current research focuses on data collection and digital transparency. Still, it rarely addresses the ethical manufacturing perspective of protecting customer data from exposure to strategic evil or of listening attentively to RSCs' activities. Moreover, this is important because RSCs contain sensitive information on product use and waste behavior, which is integral to a company's sustainability performance and compliance practices.

A second theoretical dilemma is that different assumptions about digital transparency conflict with one another. While mainstream researchers suggest that Industry 4.0 technologies foster ethical accountability through traceability and transparency, sceptics point to increased digital surveillance as an ethical risk, driven by enhanced data centralisation, which is prone to privacy issues and data misuse due to the concentration of stakeholder power.

Thus, an open research problem concerns how Industry 4.0 technologies could support ethical manufacturing practices in RSCs by enabling trade-offs among transparency, stakeholder engagement, and customer information management, with sustainability accountability. The primary objective of this study is to address the gap between Industry 4.0 technologies and ethical manufacturing in repair environments by investigating how such technologies can facilitate ethics-based feedback collection

involving customers and stakeholders, how they can support environmentally focused manufacturing practices by leveraging their crude characteristics at the socio-heuristics levels, thereby enabling sustainable cycle times.

Accordingly, the researcher identified the research gap as follows:

The main research gap: More work is needed on how I4.0 technologies support RSCs activities.

Sub gap1. More work is needed on how I4.0 technologies can support the rational use of raw materials in reverse supply chain activities.

Sub gap 2. More work is needed on how Industry 4.0 technologies support reverse logistics, particularly on using customer feedback to meet customer preferences as a key activity in the reverse supply chain.

Sub gap 3. More work is needed on how I4.0 technologies can improve manufacturing ethics in RSCs by managing customer information in response to customer feedback and input from environmental organisations.

1.4 Conceptual framework for research:

According to previous research, Industry 4.0 technologies can more effectively support reverse supply chain activities at all levels. Therefore, it is crucial to emphasise that proper implementation requires an integrated approach that connects these activities. Close attention must be given to linking Industry 4.0 technologies with reverse supply chain activities. Furthermore, these technologies should be evaluated to determine whether they contribute to responsible and sustainable manufacturing. This paper presents a theoretical model of the reverse supply chain rooted in Industry 4.0, focusing on establishing a complementary relationship between reverse supply chains and Industry 4.0 technologies. The study will outline reverse supply chain activities, drawing from traditional concepts of recycling, manufacturing, and recovery, as well as modern perspectives that reflect customer preferences, efficient utilisation of raw materials, and manufacturing ethics. This topic is important because it requires effective approaches that leverage the enabling features of Industry 4.0 technology in reverse supply chain activities, as outlined in our research perspective, to support sustainable manufacturing. Figure 1-1 illustrates a hypothetical model of the key variables in the research, their sub-dimensions, and their connections.

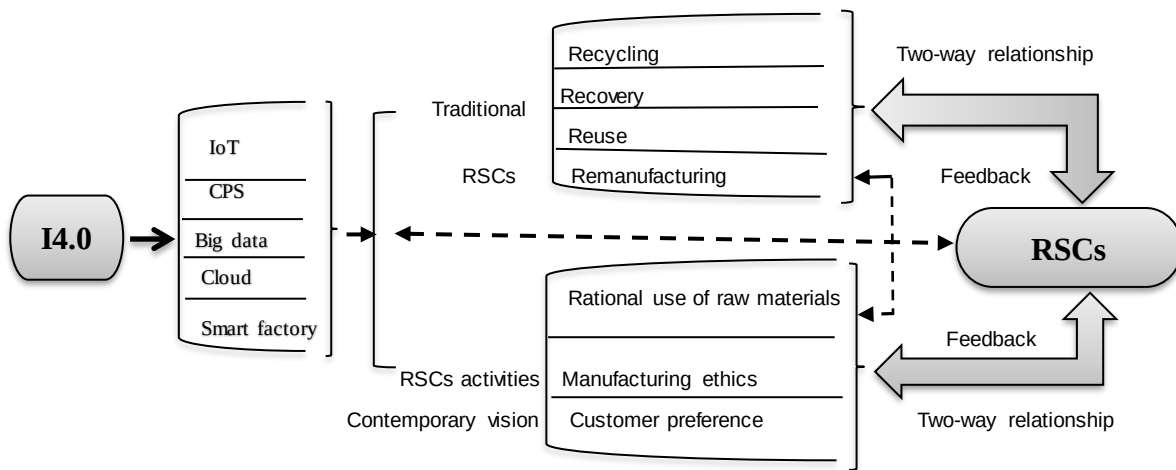


Figure 1- 1 Conceptual framework for integrating I4.0 technology with RSCs activities (Source: authors).

This research examines the global challenges of achieving sustainable manufacturing, including recycling, efficient use of raw materials, meeting customer demands, and ethical production practices. Emerging Industry 4.0 technologies, especially those that integrate reverse logistics, can effectively address these issues. Moreover, implementing smart factories influences the integration of resource management systems to foster sustainability in manufacturing and protect the environment. The primary goal of this research is to answer the question: “How can Industry 4.0 technology be integrated with reverse supply chain activities?” This study seeks to explore the relationship between Industry 4.0 technology and reverse supply chain activities, focusing specifically on customer preferences, the rational use of raw materials, and manufacturing ethics.

1.5 Research importance:

The significance of the research is as follows:

- Presenting a theoretical framework for research variables according to the contemporary vision.
- Maximising the benefit of Industry 4.0 technologies in supporting reverse supply chain activities.
- Updating the concept of reverse supply chain activities and investing them optimally in manufacturing.
- Enhancing manufacturing sustainability and preserving the environment.

- Achieving benefits for the customer, which in turn is reflected in increasing the welfare of society.
- Integrating Industry 4.0 technology with the contemporary vision of RSCs activities will help link forward and backwards logistics, improving the overall process.

The importance of this research lies in creating a conceptual framework that combines existing theories and broadens current knowledge. It also investigates the role of Industry 4.0 technology as a crucial component in improving sustainable manufacturing practices. Additionally, it redefines reverse supply chain activities through sustainable manufacturing practices that prioritise meeting customer preferences, the efficient use of raw materials, and ethical manufacturing. The study also develops and tests a new research model that links Industry 4.0 technology to the contemporary vision of reverse supply chain activities. This connection follows a direct effect, where technology directly enhances the contemporary vision of reverse supply chains, and an indirect effect through mediating variables such as customer feedback and recycling. This integrated approach is underpinned by a strategic organisational effort to allocate available company resources to enhance sustainable manufacturing practices.

1.6 Research Aim and Objectives:

These study objectives were informed by the nature of knowledge gaps observed in the extant literature on the use of Industry 4.0 to inform RSCs activities. This study aims to provide theoretical and practical implications of digital technologies for facilitating sustainability, resource recovery capabilities (RRC), customer-centric sustainable RSC practices, and ethical manufacturing practices in the context of an RSC. It aims to augment theoretical knowledge of how Industry 4.0 technologies align with sustainable RSC activities and to provide a practical solution to aid the achievement of sustainable manufacturing by minimising waste generation at every stage of the supply chain. The goals have been defined within a structured and comprehensive research framework to guarantee conceptual cohesion, analytical precision, and valid results.

Accordingly, the study aims to achieve the following research objectives:

1. To conduct a critical review of the literature related to Industry 4.0 technology and RSCs activities, including their sub-dimensions, theoretical foundations, and the integration relationships between them within the context of sustainable manufacturing and circular practices.

2. To examine the role of Industry 4.0 technology in supporting RSCs activities, particularly in relation to resource recovery, recycling, reuse, remanufacturing, and reverse logistics.
3. To investigate how Industry 4.0 technology contributes to supporting the rational use of raw materials and customer preferences within RSCs activities by improving monitoring, data integration, direct communication channels, and decision-making mechanisms, in accordance with the principle of customer-centric sustainability.
4. To examine the role of Industry 4.0 technology in promoting ethical manufacturing practices within RSCs activities, particularly through customer information management and the integration of environmental stakeholder perspectives enabled by this technology.
5. To develop a conceptual framework based on the literature that develops and expands existing theories, linking Industry 4.0 technology to the contemporary vision of RSCs activities, including the mediating role of customer perspectives and recycling in strengthening this relationship.

1.7 Research contributions:

This study extends the literature by providing an integrated framework that demonstrates how on-the-ground Industry 4.0 technologies promote the modern orientation of RSCs activities through customer feedback and recycling as mediators. This system-based study is different from previous studies that investigate the impact of digital technologies, sustainability, and RSCs separately.

The two theoretical contributions of the study are that, by applying SOI theory, it justifies both the direct and indirect effects of I4.0 technologies on RSCs activities. This research builds on existing knowledge by conceptualising customer feedback and recycling not as ancillary operational antecedents but as strategic mediating processes through which digital technologies advance customer-oriented reverse logistics while promoting the rational use of raw materials and ethical manufacturing. In that, the research directly addresses gaps in understanding how Industry 4.0 supplements this by examining the number of research disciplines or domains that link Industry 4.0 to sustainability-oriented RSCs systems.

The study also uniquely contributes by reconceptualising RSCs as digitally enabled sustainability systems rather than as dominant end-of-life recovery mechanisms. Research shows that sustainability in RSCs requires more than technology adoption; it results from the collaborative integration of digital capabilities, stakeholder engagement practices, recycling infrastructure, and support for Eco-feedback engineering for customers.

Practically, the study provides an evidence-based framework to guide both manufacturing organisations and policymakers in aligning I4.0 technologies with sustainable RSC strategies. The results offer practical guidance on how digital technologies can be used alongside customer feedback systems and recycling processes to directly improve sustainability performance by minimising waste, facilitating responsible manufacturing practices, and enabling responsive operations that adapt to evolving consumer preferences.

1.8 Theoretical Foundations and Research Questions:

Adams et al. (2016) propose Sustainability-Oriented Innovation (SOI) theory, which offers a new approach to achieving sustainable goals in innovation processes. The theory underscores that innovation should extend beyond economic value creation to encompass social issues and environmental responsibility, making it highly relevant to the contemporary vision of RSCs activities. In our study, I4.0 technologies (cyber-physical systems, the Internet of Things, big data, the cloud, and the smart factory) are enabling innovations that can produce fundamental changes in meeting customer preferences, the rational use of raw materials, and manufacturing ethics.

Moreover, we drew on the Resource Orchestration Theory (ROT) proposed by Sirmon, Hutt, & Ireland (2007). The theory focuses on administrative and technical procedures for the effective use of available resources to achieve strategic outcomes. In the context of our study, I4.0 technologies (cyber-physical systems, the Internet of Things, big data, the cloud, and the smart factory) play a crucial role. However, their impact on the contemporary vision of RSCs activities depends on how companies structure these technologies within operational processes and integrate them with other processes, such as customer feedback and recycling, to enhance effectiveness. Therefore, ROT provides a strong theoretical foundation for understanding how mediating variables (such as customer feedback and recycling) serve as mechanisms that facilitate the transformation of I4.0 technology inputs into sustainable RSC practices, ultimately affecting customer preferences, the rational use of raw materials, and manufacturing ethics. Improving sustainability is not just about adopting digital tools but about using them effectively within an integrated system that leverages customer feedback and recycling. These tools can strengthen the connection between I4.0 technology and the contemporary vision of RSCs activities.

Based on these theoretical foundations, the study intends to fill gaps in the literature by answering the following questions:

Research main Question 1: "How can Industry 4.0 technologies be effectively integrated into the Contemporary vision of RSCs activities?"

- Research Question 2: What is the role of Industry 4.0 technologies in affecting customer feedback and recycling as mediating variables in the Contemporary vision of RSCs activities?
- Research Question 3: How do mediating variables of customer feedback and recycling affect the contemporary vision of RSCs activities?
- Research Question 4: How do customer feedback and recycling influence the relationship between Industry 4.0 technologies and the Contemporary vision of RSCs activities?

The research questions stem from gaps in the limited integration of Industry 4.0 technologies with sustainable RSCs activities. Current knowledge offers a limited understanding of the mechanisms for integrating forward logistics and RSCs, particularly how they integrate with intermediary mechanisms such as customer feedback and recycling, in line with organisational strategies. Furthermore, the literature presents a fragmented approach to sustainability, ethical manufacturing, and stakeholder-oriented practices. Taken together, these questions provide a coherent analytical framework that aligns with the research objectives and supports the development of a comprehensive framework explaining how Industry 4.0 technology supports RSCs activities through customer-centric mechanisms focused on enhancing sustainable manufacturing practices.

1.9 Thesis structure:

Chapter 1: The thesis's first chapter presents the introduction and motivation for the research. As highlighted in the introduction to the research, a review of the research variables of Industry 4.0 and reverse supply chains, the relationship between them, and the path of research into mechanisms for strengthening the relationship between them through the main research question, which includes how Industry 4.0 technology can be integrated with the activities of reverse supply chains. At the end of the introduction, the researcher presents an illustrative form that reflects the researcher's vision and course of action for the relationship and integration mechanism between the two research variables. The chapter also introduces the research problem, its importance, and objectives.

Chapter 2 presents the research variables and their sub-dimensions in detail, based on an in-depth review of the previous literature. The chapter begins by highlighting the research's dependent variable, namely reverse supply chains, and outlining their traditional activities. It also presents a contemporary vision of their activities, based on the literature on reverse supply chain activities in the context of Industry 4.0. Diagrams prepared by the researcher to illustrate the classifications of traditional and contemporary reverse supply chain activities reinforce the review. A review framework for the independent variable, Industry 4.0, and the stages of industry development is then presented,

highlighting the most prominent industrial technologies examined in the current research and their roles in manufacturing processes.

Chapter 3: included a literature review of the research variables. Based on systematic literature reviews, research papers, and articles, the literature was identified for review. The review presentations were categorised to explore the current research area in depth, highlight the contributions of previous researchers in our field, and analyse and discuss their findings. The review specifically addressed the relationship between Industry 4.0 technologies and reverse supply chain activities within the current research context. Furthermore, this chapter highlights the most important journals that have published research on this topic and the most prominent researchers, based on results from specific Scopus searches.

Chapter 4: This chapter developed a conceptual framework for the key research variables, specifically Industry 4.0 and reverse supply chains. The chapter presented an in-depth conceptual framework for the interrelationship between the research variables. Moreover, it explains how Industry 4.0 technology can support and integrate with reverse supply chain activities to enhance manufacturing sustainability. A conceptual framework for the research was also developed, reflecting current research trends, aligning with the research objectives and questions, and providing a clear vision for designing the research model. This, in turn, answers the research questions and outlines the research methodology underpinning the data collection and analysis. Furthermore, the second section of the chapter included developing hypotheses and proposing a research model, as the researcher worked by reviewing previous literature and explaining the relationships between the research variables, relying on the Contributions of previous researchers and benefiting from their experiences and research results in developing current research hypotheses as well as proposing a research model.

Chapter 5: The fifth chapter covers the research methodology and the essential matters that the researcher must address in the methodology chapter of a doctoral dissertation. After that, and within the core of the research methodology, the researcher presents the research methods and philosophy through the research paths. In the chapter he worked on, the researcher developed a research scale to collect and prepare research data for analysis. The researcher also clarified the details of the research sample and the companies investigated, and stated the most important statistical methods for data analysis.

Chapter 6 presents and analyses the research data. At the beginning of the chapter, the research sample details are presented and illustrated with graphical charts. Then, a description of the research variables is presented, and the variables are diagnosed. This is presented in detailed tables based on descriptive

statistics. After that, the statistical results for the research variables were presented, including the reliability of the research scale, the suitability of the research variables and their questions, the consistency among them, and the credibility of the findings. After that, the results and charts of testing the research hypotheses were presented, discussed, and analysed in detail. This section presents the survey results, which were collected using a quantitative research method.

Chapter 7: This chapter presents the results of semi-structured interviews conducted by the researcher, utilising a qualitative research methodology that complements the quantitative approach. The objectives of the interviews were highlighted, and a brief profile of the participants was presented. Furthermore, the steps and procedures for formulating interview questions were outlined, along with a table categorising them by research scope. Participants' responses to the semi-structured interviews were presented, and the chapter's final section discusses the interview results.

Chapter 8: This chapter summarises the quantitative and qualitative research results, based on the research findings and hypothesis testing. It also discusses and interprets the results using quantitative methods for interpreting figures, supported by an interpretation of the qualitative results.

Chapter 9: In this chapter, the researcher presents the research conclusion, including a summary of findings on the role of Industry 4.0 technology in supporting and integrating with reverse supply chain activities to enhance manufacturing sustainability, reduce waste, and preserve the environment. In the second section of the chapter, the researcher also presented recommendations for emerging researchers to enhance manufacturing sustainability, integrate forward and reverse logistics, and address challenges in the integration mechanisms. This would contribute more broadly to expanding the knowledge base on the mechanisms for integrating Industry 4.0 technologies and reverse supply chain activities, as these are key elements in supporting manufacturing sustainability.

Chapter Two

Theoretical Framework and Research Construction

2.1 Introduction:

This chapter presents the research framework, providing a theoretical basis for the research variables and their sub-dimensions in a systematic academic sequence. It begins by reviewing reverse supply chains, followed by a discussion of their sub-dimensions, which the researcher divides into two sections: traditional reverse supply chain activities and the contemporary vision of reverse supply chain activities. This is then followed by an overview of the Industry 4.0 variable and a separate presentation of Industry 4.0 technology, based on the integrated structure identified in our research.

It is also important to highlight the inclusion of customer feedback and recycling within reverse supply chain practices, which the researcher used as mediating factors, based on the strategy of investing available organisational resources to improve manufacturing sustainability, in line with existing literature and theories. In line with our research context, which supported the research questions, hypotheses, and the subsequent conceptual framework developed to expand the Sustainability-Oriented Innovation (SOI) theory and the Resource Orchestration Theory (ROT) theory, the research background was designed and presented within its theoretical frameworks to establish a strong foundation for our current study.

2.2 Theoretical Framework of Research Variables:

2.2.1 Reverse Supply Chains (RSCs):

The growing interest of legislative bodies globally in environmental issues and the rapid pace of competition in the global manufacturing system have prompted manufacturers to integrate greening initiatives into their forward and reverse supply chain activities (Mathiyazhagan et al., 2021). The world is increasingly focused on environmental and sustainable development issues across legislative bodies. Manufacturing firms must respond accordingly to maximize the utility of their goods and services (Sandberg et al., 2018). They must also liaise with other partner organisations that form part of their supply chains. The need among suppliers, distributors, logistics service providers, and retailers to be perceived as environmentally and socially responsible has led to the emergence of Reverse Supply Chain Management (RSCM). In the industrial context, RSCM includes the flow of recycled, reused, or end-of-life products, as well as consumer feedback to suppliers or manufacturers (Mathiyazhagan et al., 2021; Ramasamy & Anand, 2024). To enhance sustainability in manufacturing and environmental conservation, producers and consumers share a collaborative responsibility through reverse supply chains (RSCs) to minimise waste by recycling, remanufacturing, reusing, and properly disposing of unwanted products (Binalla & Mateo, 2022).

The utilisation of reverse supply chains (RSCs) and academic and business interest in the subject have surged significantly over the past twenty years. Numerous factors contribute to green customers' readiness to pay a premium for ecologically sustainable industrialisation. Moreover, given the high cost of raw materials, recycling is increasingly attractive, and RSCs can provide a competitive advantage (Larsen et al., 2018). Genovese et al. (2017) define it as "a process of recovering, reusing, or disposing of products returned by consumers in an environmentally sustainable manner." Circular economies provide a crucial element of RSCs. RSCs offer numerous business advantages, including enhanced project proficiency, public benefits, client satisfaction, and reduced product costs (Doan et al., 2019). Designing an RSC network entails several long-term strategic decisions critical to RSC performance. Hence, the design of a supply chain network is complex because it involves dynamic relationships at various levels (Khalili et al., 2014). According to Doan et al. (2019) and Aras (2018), network design involves determining the optimal locations and configurations of facilities, as well as the material circulation. In this context, the primary objective of most companies is to develop supply chain networks that reduce gross costs more quickly.

Due to the rapid expansion of manufacturing, innovation, and consumer demand, a perfect storm of products has emerged, resulting in shorter product life cycles, faster development, and increased waste. Therefore, environmental management has benefited from joint attention among companies, policies, and customers, leading to increased interest in reverse supply chains, including those involving the processing of returned products (Kianpour et al., 2019). Manufacturing technology accelerates product development and enables shorter product life cycles. Therefore, reverse supply chain coordination is critical (Sun et al., 2019). Feedback on the quality of products composed and applied by reverse supply chains is fundamental to the production facility performing the remanufacturing operation. Generally, it can only assess the current quality of used products after disassembly, a time-consuming and costly process. Therefore, obtaining high-quality information about products used in the earlier stages of the reverse supply chain is essential, even if only partially accurate (Gu & Tagaras, 2014).

In forward supply chains, manufacturing and selling processes convert raw materials into finished products. In contrast, reverse supply chains involve collecting, consolidating, and reusing materials to facilitate reuse, recovery, and recycling (Hong & Ke, 2011; Corrêa & Xavier, 2013). Therefore, the implementation of CEs is fundamentally linked to the use of reverse supply chains (RSCs), which are often considered a key factor in a company's sustainability (Nuss et al., 2015). Practitioners and researchers are motivated by various factors to raise awareness of environmental, rational, and sustainability issues. External factors such as laws, environmental regulations, and consumer expectations also play a role. The scarcity of natural resources and the increasing amount of waste

have pushed the industry to expand its recycling and remanufacturing capabilities. Addressing this issue promptly is essential within the reverse supply chain (Sadeghi et al., 2015). A reverse supply chain encompasses product design, operations, and end-of-life management to maximise the recovery of value from used products, whether by the original manufacturer or a third party, thereby creating value throughout the product lifecycle (Genovese et al., 2015; Altuntas et al., 2025).

Many recent studies address product returns (Sun et al., 2019), a traditional concept in reverse supply chains. In this research, we are developing the concept and activities of reverse supply chains, which have become a broad concept closely linked to Industry 4.0, encompassing several activities aimed at meeting customer preferences by responding quickly to their needs and desires. Industry 4.0 allows production flexibility (Mass Customisation). It also provides insight into the rational use of raw materials through reverse logistics, informed by production processes and customer feedback, and uses sorting and analysis feedback to inform decisions that improve the process by reducing damage and losses during manufacturing. On the other hand, it helps meet customer preferences regarding both quantity and quality. In addition, rapid production growth increases the number of unsold or obsolete goods due to short product life cycles, necessitating further measures to develop reverse supply chains. In addition, industrial companies face significant ethical responsibilities toward their customers, whether individuals or other companies, and must consider ethical issues in their manufacturing processes. This involves providing goods that deliver genuine customer benefits and are supported by reverse logistics services, including maintenance, repair, and recycling.

2.2.2 Conceptual definition of research terms:

The contemporary vision of RSCs activities, supported by this research, suggests a more expansive and strategic view that extends beyond classic functions such as product returns, recycling, and end-of-life management. Highlighting this strategic shift can inspire the audience to see their role as vital in shaping future practices, fostering a sense of importance and motivation.

The literature highlights that RSCs should not only focus on operational recovery and recycling processes but also promote sustainable manufacturing operations, including responsiveness to customer needs, resource efficiency, and responsible manufacturing practices (Setyadi et al., 2025; Kazakova & Lee, 2022).

Given this, the research proposes an updated vision for RSCs across three interrelated dimensions: customer-centricity, environmental consciousness, and manufacturing ethics. Your feedback and involvement in improving processes for reverse logistics, which represent the decisions made to align these practices with sustainability principles, are crucial. It involves the recovery, recycling, reuse, and remanufacturing of raw materials to reduce waste generation and increase efficiency. RSCs processes

put these advanced practices in the hands of makers, ensuring responsible production (Manufacturing Ethics), transparency in manufacturing, and environmental responsibility and stakeholder-centered behavior.

Therefore, this perspective aligns with current literature on sustainability and the circular economy, which views RSCs as strategic systems that extend beyond end-of-life management. It recognises environmental objectives, customer engagement, and resource recovery as interconnected activities, building a holistic framework that reflects the evolving role of RSCs in modern manufacturing systems.

Our research focuses primarily on manufacturing-oriented RSCs environments and emphasises one aspect of sustainable manufacturing practices. Broader institutional, organisational, and technical factors remain outside the scope of this study.

Definition of Reverse Supply Chain Activities:

In the context of this research, reverse supply chain activities refer specifically to sustainability-oriented recovery activities within manufacturing systems, including recycling, reuse, remanufacturing, raw material recovery, customer feedback integration, and ethical manufacturing practices. The focus is on activities that directly contribute to sustainable value recovery, the rational use of resources, and environmentally responsible production processes. Accordingly, reverse supply chain activities in this study represent a targeted sustainability and recovery dimension within broader reverse logistics systems.

Definition of Reverse Logistics:

Reverse logistics refers to the broader process of planning, implementing, and controlling the efficient flow of returned products, materials, and related information from the point of consumption to the point of origin for purposes such as return management, transportation, inspection, sorting, recycling, disposal, remanufacturing, or value recovery (Rogers & Tibben-Lembke, 1999). This perspective views reverse logistics as a comprehensive operational system encompassing multiple recovery and return processes.

From this perspective, the present research does not treat reverse supply chain activities and reverse logistics as synonymous. Rather, reverse supply chain activities are viewed as a specific sustainability-oriented component within the broader reverse logistics framework. Therefore, the research focuses only on those reverse activities linked to sustainability objectives, customer preferences, rational use of raw materials, and manufacturing ethics, rather than the entire operational scope of reverse logistics.

2.2.3 Reverse supply chains effectiveness:

To assess the effectiveness of their reverse supply chains, firms must enhance the performance measurement index and employ an integrated, comprehensive approach to achieve the desired performance level (Shaharudin et al., 2017). The company also employs measurable performance objectives to assess the effectiveness of actions within the organisation, in line with its vision. In this context, effectiveness is defined as the extent to which products and services satisfy customer needs. Secondly, effectiveness is assessed by the achievement of goals, and the definition of effectiveness is excellent: the capacity of an organisation to utilise its resources for specific ends (Skapa & Klapalova, 2019).

Multiple studies demonstrate the importance of integrating forward and reverse supply chains, highlighting that this approach improves the effectiveness of reverse supply chains. Therefore, measuring their performance is essential because reverse supply chains play a key role in boosting organisational competitiveness, ensuring environmental compliance, and increasing market demand for recoverable products (Shaharudin et al., 2017; Bag, 2025). Research indicates that companies with efficient supply chain networks save 40% more money, achieve 28% better logistics management, and deliver 44% better customer service than those with inefficient supply chains. Several researchers have examined issues related to RSC networks (Doan et al., 2021). Consequently, targeted development of reverse supply chains significantly affects the efficiency and effectiveness of industrial production systems.

Through the researchers' vision, as demonstrated in their previous contributions to the field of strategy for building an effective reverse supply chain in the industry. Based on the contributions of previous researchers, the researchers worked to crystallise their research visions, as shown in Figure 2-1, which outlines the steps for building effective reverse supply chains.

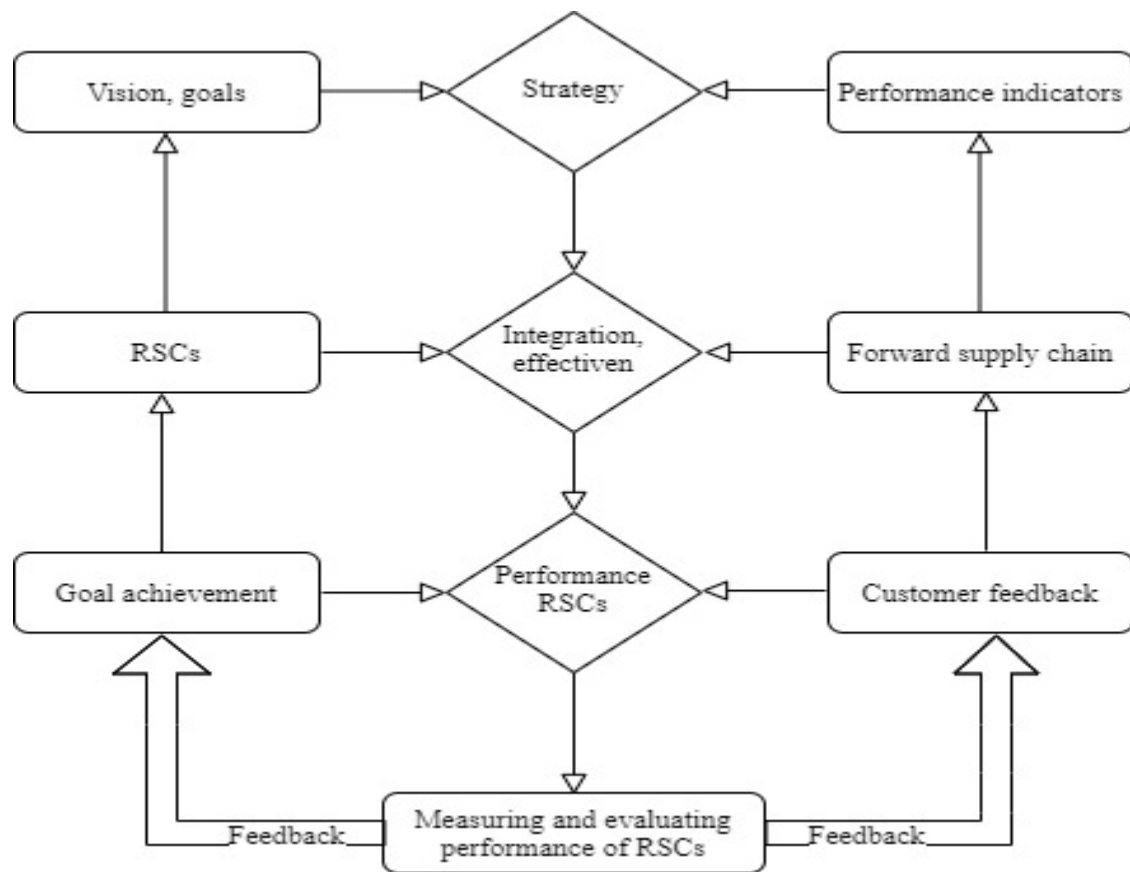


Figure 2- 1 Strategies for building effective reverse supply chains (Source: authors).

2.2.4 Reverse supply chain management (RSCM):

Legislative pressure and social initiatives by non-governmental organisations worldwide increase RSCM's dependence (Georgiadis & Besiou, 2010; Ramasamy & Anand, 2024). Environmental concerns, cost reduction, and consumer pressure have all become significant issues in RSCM in recent decades. Topics such as reverse supply chains, product recovery, remanufacturing, and reuse have emerged as important areas for development due to resource depletion, constraints on landfill capacity in many countries, and government legislation requiring the take-back of end-of-life products (Mathiyazhagan et al., 2021). Most RSCs studies assume that all input parameters are either deterministic or predefined. On the other hand, actual RSCs systems are widely recognised as complex and dynamic. They contain numerous uncertain variables (e.g., number of used products, capacity, and costs) (Doan et al., 2021). Uncertain parameters, in particular, may have a severe impact on the performance of RSCs networks in general. (Liao, 2018). The fuzzy approach has come as a potential solution to such problems. It can readily handle inaccurate input from managers or experts and can address many uncertain parameters with high computational efficiency (Doan et al., 2021; Bressane et al., 2024). Fuzzy logic has been extensively applied to decision-making across many applications

(Guillaume et al., 2016). Consequently, the RSCs model is structured around four key criteria: economic, managerial, strategic, and social (Doan et al., 2021; Sathiya et al., 2021).

Moreover, RSCs are now considered a revenue stream rather than a cost-reduction project (Mathiyazhagan et al., 2021). The RSCM encompasses the movement of recycled, reused, or end-of-life (EOL) products, as well as the transfer of end-customer product information to suppliers or manufacturers (Doan et al., 2019). Reverse supply chains are the joint responsibility of producers and consumers to minimise waste through recycling, remanufacturing, reusing, and proper disposal of unsuitable products, thereby improving environmental sustainability. (Mathiyazhagan et al., 2021). Moreover, reverse supply chain management can reduce production costs (Zeng, 2013). Customer feedback and reverse supply chain management are closely linked, and awareness of this connection can help companies enhance operations and track customer trends (Hsu et al., 2016). According to what was mentioned in the conceptual frameworks of the earlier researchers, the activities of RSCs management can be stated based on the following diagram (2-2):

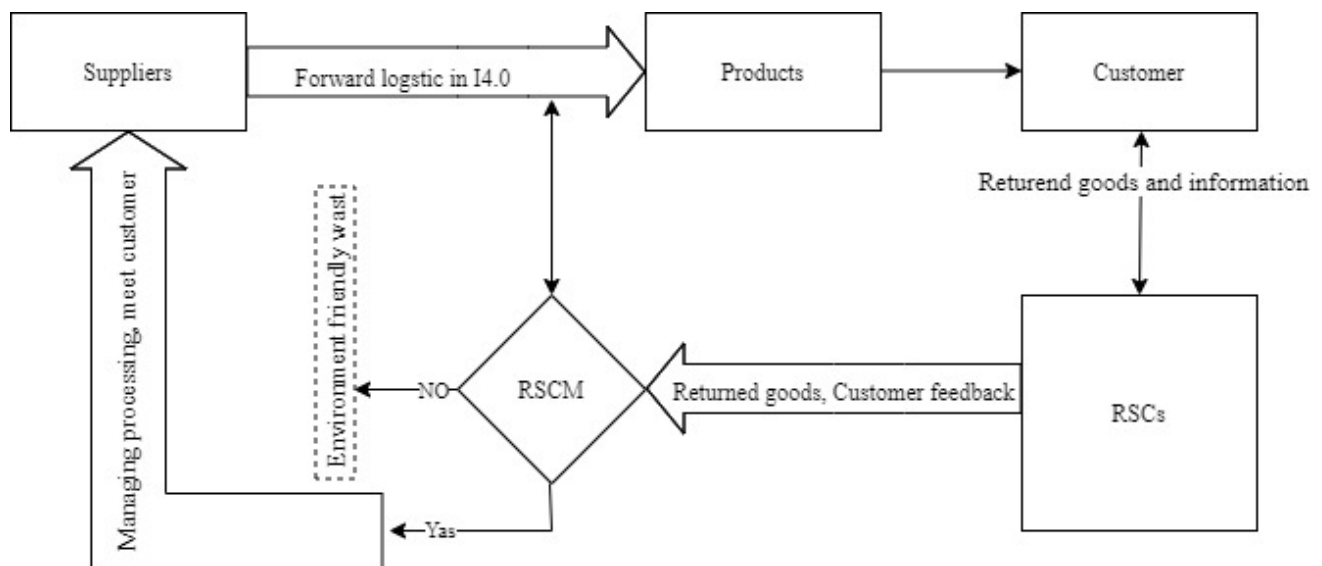


Figure 2- 2 Reverse supply chain management (Source: authors).

2.2.5 RSCs activities in the context of I4.0:

Based on the directions of our current research and our conceptual framework shown in Figure (1-1) in the first chapter. In addition, in accordance with the classifications that will be presented to review previous studies in the next chapter. In this chapter, we present the theoretical background for the research, including its variables and their sub-dimensions, as well as our research vision for classifying reverse supply chain activities. It will be explained from two perspectives: the first represents traditional activities, and the second represents the contemporary vision of reverse supply chain

activities, which is the independent variable of the research, reinforced by a presentation of the dependent variable, Industry 4.0, and its sub-dimensions.

2.2.6 Traditional RSCs activities:

According to the literature, traditional reverse supply chain activities include end-of-life material recovery and subsequent recycling, remanufacturing, reuse, or environmentally friendly disposal, depending on the material's condition. Additionally, customer feedback is another reverse supply chain activity, serving as a communication channel between manufacturers and customers that directly informs manufacturers of evolving customer needs and desires, allowing them to respond accordingly.

2.2.6.1 Recycling, Recovery, Remanufacturing, and Reuse:

Given the high complexity, uncertainty, and specificity of many aspects and activities, RSCs require robust knowledge management to support companies' operations (Bernard, 2011). A reverse supply chain provides greater information density, especially when organisations have multiple recovery options. The reverse supply chain, when designed, should be a network of different actors. In addition, recycling can significantly reduce environmental waste and plays a critical role in the reverse supply chain (Yu et al., 2021).

Recycling is the practice of collecting outdated materials and transforming them into new, useful items for the same purpose or other purposes (Kumar et al., 2017). Industry 4.0 digital technologies are essential to recycling, as they can facilitate the development of a sustainable global economy through rapid technological advancement (Kurniawan et al., 2022). Businesses are striving to align their strategies with their business management procedures, based on the level of development, organisational structure, and the maximisation of product gains through recycling (Rosa et al., 2019). With advances in technology, the industry can develop practical methods for waste treatment and recycling, yielding long-lasting societal benefits. As a means of value creation, Industry 4.0 technologies have been shown to support recycling by optimising resource recovery processes and reducing operational costs through waste-flow tracking (Zhang et al., 2023; Kumar et al., 2025).

Consequently, industrial users are gradually shifting from a linear to a circular economy in waste management. This promotes resource recovery by recycling materials for consumer products and mitigates the negative effects of the linear economy. For this reason, identifying new opportunities and challenges in recycling, reuse, and recovery (3Rs) is essential. Modern industrial technologies can effectively support these activities (Kurniawan et al., 2022). Recycling is a reverse supply chain activity that encompasses several key processes. In addition, Remanufacturing is a form of recycling that involves restoring used durable goods to new condition. Recycling reduces raw material

consumption and helps avoid post-consumer waste. Remanufacturing is "returning a used product to at least the original equipment manufacturer (OEM). From the customer's perspective, performance specifications must be met, and the resulting product must have a warranty that is at least as good as a newly manufactured equivalent product." Many companies have engaged in remanufacturing to increase revenue. Xerox and Canon, for example, have saved millions of dollars by remanufacturing their products. As a result, the quality, efficiency, control, and evaluation of the remanufacturing process are critical, as they directly determine whether remanufactured parts achieve the same level of reliability as new parts. Inspection is essential in remanufacturing engineering because it assesses the extent of damage and the quality of repairs to the cores, ensuring that the remanufacturing process proceeds smoothly (Huang et al., 2021).

Thus, recycling is linked to sustainable production and society and is gaining popularity worldwide (Matsumoto et al., 2016). As a result, recycling can be viewed as a helpful option for product recovery. It is not only confirmed that less waste needs to be disposed of and that fewer raw materials are consumed in manufacturing, but that the value added in remanufacturing "recovered" components is even higher (Langella, 2007; Diener & Tillman, 2015). Finally, remanufactured products (intended to be as good as new) are often substantially less expensive than their new counterparts.

Recycling begins with the sourcing of recovered materials through the reverse supply chain. The next step is to collect the materials and transport the cores to the remanufacturing facility, where they will undergo the necessary remanufacturing and remarketing processes (Huang et al., 2021; Zhang et al., 2021). Three parties must recycle used items and extract value from them. They are consumers, retailers, and manufacturers. We focus on two questions for three-stage reverse supply chain management (Zeng, 2013).

1. What should retailers do to encourage customers to return used goods?
2. What should retailers and manufacturers do to work together to devote more time and effort to collecting used goods?

Our previous literature review reveals a research gap in sustainable recycling that aims to increase industrial productivity while promoting environmentally friendly waste disposal. To achieve sustainability in production and manufacturing, we must address gaps by integrating RSCs with I4. Therefore, we aim to address this issue in our research. The goal of Industry 4.0 is to maximise the closed flow of materials while retaining the fundamental value that circulates via technological innovation across the reverse supply chain (Rajput & Singh, 2021).

In light of the contributions of previous literature and the paths of our current research, this is represented according to the following figure 2-3:

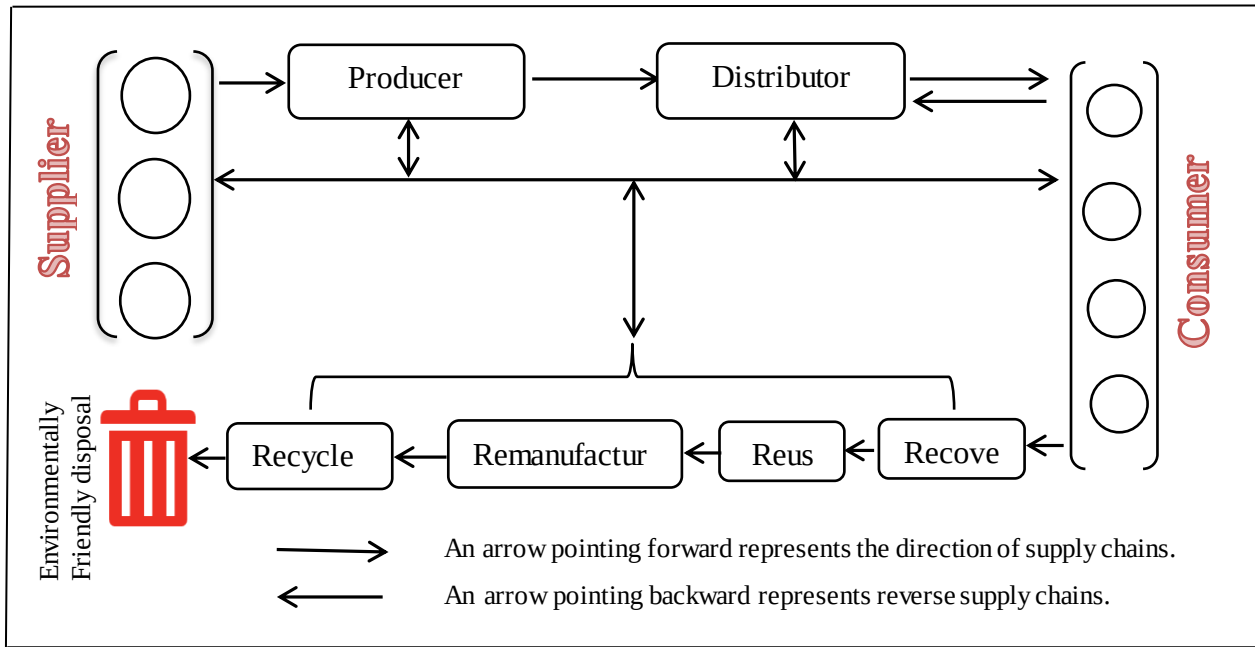


Figure 2- 3 Traditional RSCs activities (Source: authors).

2.2.6.2 Customer feedback:

In recent years, with the emergence of digital technologies and communication media, customer feedback has received significant attention as an activity of the reverse supply chain, especially in academic and industrial fields alike, due to its role in enhancing sustainability, supporting innovation, and meeting customer preferences (Taghikhah et al., 2019; Paula et al., 2020).

Supply chain activities encompass processes and activities, from sourcing raw materials to delivering goods to consumers (Ivanov et al., 2016). Conversely, the reverse supply chain is the exchange of goods between consumers and producers that facilitates information flow, an element that manufacturers often consider decisive in their decision-making (Govindan et al., 2019).

Producers may glean much information from customer feedback about what is wrong with the returned materials, whether they are of poor quality, and what customers prefer. Customer feedback can be an excellent source of information. In addition, customer feedback, as a diagnostic tool, plays a vital role in product design, defect prevention, and meeting expectations (Moldavska & Welo, 2017). Govindan et al. (2015) found that reverse supply chain and customer feedback implementations could contribute to manufacturing efficiency and sustainability. Redesign allows for maximising resource usage and minimising waste. In addition, advances in Industry 4.0 technologies have given industrial firms an advantage in collecting and analysing customer feedback, thereby enabling more efficient investment decisions (Zhang et al., 2020).

The results are consistent with those of Govindan et al. (2015), who demonstrate that customer feedback is significant in implementing reverse supply chain activities in the industrial sector. The study review was conducted after the researcher examined its key aspects and results. The researcher proposed developing and investing in customer feedback to support the relationship between emerging Industry 4.0 technologies and reverse supply chains, serving as an intermediary variable that can effectively improve their integration, in line with the paths of our current research.

2.2.7 Contemporary vision of RSCs activities:

In recent years, reverse supply chain activities have undergone significant changes, particularly in meeting customer demand, enhancing the efficient utilisation of raw materials, and promoting ethical practices (Plaza-Úbeda et al., 2020). With the ongoing shift toward sustainable practices among consumers, businesses are seeking to integrate reverse supply chain activities with these trends, including product return management policies that meet consumer expectations (Mishra et al., 2023; Hsu et al., 2016). Moreover, some customers prefer to purchase lower-cost products that do not harm the environment, including refurbished or remanufactured items. For example, Apple and Dell offer refurbished products that meet customer demand for eco-friendly, cost-effective solutions (Vogtlander et al., 2017).

Furthermore, some companies reclaim products used by customers for customisation or upgrades, specifically to meet customers' preferences for tailored or improved models (Wang et al., 2017). These efforts aim to enhance customer loyalty and address the rising demand for sustainable and responsible consumption (Zhang et al., 2021). Regarding the rational use of raw materials, reverse supply chains play a key role in boosting resource efficiency by reducing waste and extending material lifespans through various initiatives (Daramola et al., 2023; Gao et al., 2024). Using advanced manufacturing technologies enables organisations to recycle raw materials such as metals, plastics, and components for remanufacturing (Dev et al., 2020). This helps minimise raw material consumption and promotes more responsible usage. Additionally, reverse supply chain activities support ethical manufacturing by fostering transparency across production stages as manufacturers integrate ethical principles into their reverse supply chain practices (Carvalho et al., 2018). Moreover, reverse logistics services help companies comply with environmental regulations and fulfil their corporate social responsibility commitments (Richnák & Gubová, 2021).

Based on the conceptual framework of our research in Figure (1-1), which includes the classification of RSCs activities into two categories: traditional RSCs activities and the contemporary vision of RSCs activities. In support of what we presented in reviewing previous studies by previous researchers in Tables (2-6), (2-7), and (2-8), which indicated the role of Industry 4.0 in enhancing RSCs activities

represented by (customer preferences, rational use of raw materials, and manufacturing ethics). The researcher adopted these activities as reverse supply chain activities from a contemporary perspective to test them in our developed research model. This aims to demonstrate the extent to which Industry 4.0 technologies have enhanced reverse supply chain activities, particularly with respect to customer preferences, the rational use of raw materials, and manufacturing ethics. The following presents each activity in detail.

2.2.7.1 Customer Preferences:

A review of the literature indicates that, in reverse supply chains, customer feedback is often used to express their preferences (Guo et al., 2017). Abraham Maslow's theory has significantly influenced sociologists, economists, marketers, and philosophers, particularly through the hierarchy of needs, which begins with physiological needs such as food and shelter and progresses through safety and social needs to self-actualisation. (Simpson, 2014). The term "need" carries weight, as it suggests a compulsion tied to survival. Additionally, as much as the word desire can be used to suggest indulgence, there is the connotation of mental prowess in determining and going after an objective.

Through customer feedback on the reverse supply chain, companies can understand and meet customer expectations concerning product quality, service, and returns (Ambilkar et al., 2022). Additionally, feedback helps businesses identify weaknesses, optimise their return policies, and improve their understanding of customer needs and preferences (Hjort et al., 2019). It also reveals trends in customisation, encouraging companies to tailor their offerings and services to meet individual customers' needs better (Esenduran et al., 2022). The current competitive environment emphasises product customisation. The shift from a seller-to-buyer market in the industrial goods sector has led to saturation, with supply surpassing demand (Blecker et al., 2004; Wen et al., 2021). As a result, many changes in the business environment have contributed to the trend of product customisation. This has compelled many suppliers to review their production policies and management to adapt to changing customer preferences.

Industrial 4.0 technologies (IoT) enable companies to communicate with customers through a co-design process quickly and efficiently, and to learn what they want regarding product and service characteristics. Big data analytics and artificial intelligence (AI) enable companies to collect and process customer data, thereby helping them understand customer needs and identify underlying needs (Ranjan & Foropon, 2021). In addition, automation and robotics improve production speed and quality, thereby accelerating delivery times and enhancing product quality, which, in turn, increases customer preferences regarding product quantity and quality (Dash et al., 2019). It also enhances transparency for customers, enabling the company to offer live tracking and updates throughout the product lifecycle

(Leng et al., 2020). The technology of Industry 4.0 promotes personalisation, sustainability, and responsiveness, and helps firms align with evolving customer preferences (Javaid et al., 2022). Customers today prefer quality, style, and individuality to mass-produced goods, as these qualities support a mass-customisation strategy by meeting consumers' unique and changing desires. As a result, the role of technology in capturing information resulting from customer feedback and electronic interactions is critical for product development (Cui & Wu, 2017; Parise et al., 2016). Knowledge management, or continuous learning from customers and stakeholders, is essential for developing and refining custom product and service offerings in response to customers' preferences (Helms et al., 2008; Chaithanapat & Rakthin, 2021).

In this research, we aim to accurately understand customers' preferences by leveraging feedback from reverse supply chains and Industry 0.4, which enable greater manufacturing flexibility. Therefore, we will integrate reverse supply chains with Industry 4.0 to best meet customers' requirements by responding quickly to their needs and utilising modern manufacturing technologies.

2.2.7.2 Rational use of raw materials:

Environmental evaluation and the assessment of ecological indicators are currently important topics. Consequently, the updated raw material policy establishes long-term goals and tools for the efficient use and conservation of raw materials, while also focusing on social sustainability and environmental protection (Kuzevič et al., 2019). Both ecological quality and the evaluation of environmental indicators are topical issues. It is essential to use raw materials efficiently, promote sustainable development, and maintain fundamental manufacturing processes. Firms and society should work to improve people's quality of life without further harming nature and our environment (KRŇANOVÁ, 2020).

Significant developments in industry, along with the associated environmental constraints, must be addressed to maintain ecological balance. Industrial companies must pay close attention to the utilisation of raw materials in industry and research, improving their use to minimise waste and damage during manufacturing processes and reduce environmental impact (Mancini et al., 2019). Rapid technological developments in the industry will generate numerous obsolete products and unsold goods (Zhou & Gupta, 2019). Reverse supply chains are a viable means of promoting sustainable manufacturing strategies, rationalising the use of raw materials, and preserving the environment (Govindan et al., 2016). Reverse logistics typically includes recycling, remanufacturing, and reuse as end-of-life management strategies to improve environmental performance and rationalise the use of raw materials (Islam et al., 2018).

Therefore, this research will focus on one activity in reverse supply chains, specifically on mechanisms to enhance the use of raw materials by aligning consumer needs and product attributes in terms of quantity, quality, and value realisation. Additionally, the benefits of the goods and services provided were shared between the processors and the producing companies. The goal is to deliver what consumers need in both quantity and quality, adhering to the principle of the general bequest in production to promote the efficient use of raw materials.

To illustrate the difference between the rational use of raw materials and lean production, lean production focuses on eliminating waste and adding value to products or services. Therefore, any element that does not improve the product or service from the customer's perspective is considered waste in lean production (Wickramasinghe & Wickramasinghe, 2017). The concept of "rational use of raw materials" is a key part of "sustainable growth" within sustainable development. Rational use of raw materials is a complex issue because it is not straightforward from an economic standpoint and does not easily fit standard economic measures such as economic effects or economic efficiency (Koryakina et al., 2021). Sustainable consumption and production involve using products responsibly, including the rational use of raw materials, reducing waste and pollution, and improving the quality of life. This means that modern product development, service delivery, and customer focus should support these goals (Saniuk et al., 2020).

Contemporary technical innovations in Industry 4.0 must enhance both output volume and quality while also emphasising environmental sustainability. This may include the use of recycled raw materials, reconditioned goods, and shared resources. Consumers expect products customised to their preferences, tastes, requirements, and lifestyles. Therefore, a completely new, more contemporary and innovative approach to manufacturing and business management is necessary. It should be adaptable and efficient, with a focus on customers' choices. This can be achieved through technological advancements of Industry 4.0 (Koren et al., 2015; Saniuk et al., 2020), which enable the efficient use of raw materials. The current understanding of fair use management considers three perspectives: economic, social, and environmental (Koryakina et al., 2021).

2.2.7.3 Manufacturing Ethics:

Understanding consumers' needs will enable commercial organisations to meet those (McIntyre-Bhatty & Parker, 2011). Product and processes include energy conservation, pollution prevention, waste recycling, green product design, and corporate environmental management. Furthermore, the benefits of products that enable customers to meet their needs and desires to a high standard are considered within the framework of manufacturing ethics (Chang, 2011).

Refers to the term manufacturing ethics in the field of I40. The definition of ethics, as set out in the context of I40, is as follows: extended organisations (including government agencies) are the institutions. In contrast, persons and others are human beings who are entirely concerned with the product life cycle in I40 production systems and who are the designers and manufacturers. Moreover, production personnel (operators and supervisors) use Industry 4.0 technologies. Defining precisely what the “good life” is complex. In the context of Industry 4.0, customers can translate the word “good” into technical, social (quality, value, and actual utility), and societal, environmental, and economic expectations. It suggests that manufacturing ethics are defined in I40 as follows: “Ethical design and use of ethical standards in Industry 4.0 production and logistics that deliver customer benefit without additional burden” (Trentesaux & Caillaud, 2020).

Recently, amid rapid technological advances, manufacturing ethics has come under scrutiny in the context of Industry 4.0, which focuses on the responsible integration of advanced technologies while considering social, environmental, and economic impacts (Saniuk et al., 2022). As more people adopt automation, artificial intelligence, the Internet of Things, and data analytics, ethical issues related to labor practices, environmental sustainability, data privacy, and product safety emerge (Ogbuke et al., 2022). Another significant factor is sustainability, as rapid technological changes in the production sector can lead to waste from the continued use of outdated products. Therefore, manufacturers are ethically obligated to minimise waste, conserve resources, and reduce environmental harm (Ford et al., 2016).

Some of the practices that manufacturers are expected to adopt include adopting energy-efficient systems and rationalising raw materials. Moreover, another questionable issue has become relevant in recent times: the ethics of manufacturing amid rapid technological advances (Mallik, 2023). The necessity of protecting the privacy and security of customer data has become evident as the number of connected devices and artificial intelligence systems increases and as these systems process enormous volumes of customer and operational information (Jagatheesaperumal et al., 2021). Companies should safeguard this information against unauthorised access, misuse, or exploitation, ensure transparency, and obtain consent when collecting and using data. Moreover, the security and reliability of products manufactured using Industry 4.0 technologies are also essential (Ogbuke et al., 2022). Manufacturers should also ensure that high safety standards are upheld in AI-driven production processes and that defective products are not produced, as such products can be disastrous for consumers (Javaid et al., 2022).

Put simply, manufacturers need to balance technological innovation, ethical manufacturing responsibility, and a strong commitment to data privacy and security. This research will focus on manufacturing ethics, arguing that companies should effectively introduce their products to customers,

highlight their advantages and benefits, and provide products that deliver value and meet required quality standards. They should also avoid imposing additional costs on customers that do not benefit them. Compliance with manufacturing ethics standards will be measured by companies' industrial production, utilising customer responses and opinions about their products through reverse supply chains.

2.3 Industry 4.0:

In this part of the chapter, we present a conceptual framework for the independent variable in our research: Industry 4.0. This builds on the conceptual framework in Figure 1-1, where we previously presented the RSCs and their activities as the dependent variable. This part will focus on Industry 4.0 in detail and then focus on I4.0 technology (CPS, IoT, Cloud, Big Data, and Smart factory) in some detail, as they are the sub-dimensions of our independent variable, around which our research revolves, their role in supporting RSCs activities, and integration between them.

Industry 4.0 is a widely adopted concept that advocates a contemporary, technology-oriented, and interconnected approach to manufacturing (Masood & Sonntag, 2020; Sharpe et al., 2018). Industry 4.0 was first mentioned in a German government paper published in November 2011 as part of a high-tech plan for 2020. The essay outlined the fundamental principles of Industry 4.0 and laid the groundwork for an Industry 4.0 strategy (Kamble et al., 2018). Manufacturing organisations have adopted Industry 4.0 technologies in significant numbers in recent years. The objective was to assist firms in adopting ultra-precise, rapid technologies by leveraging interconnected goods, machinery, supply chains, and customers, while harnessing the advanced capabilities of Industry 4.0. Firms can enhance operations (e.g., greater flexibility and faster response times), thereby increasing their manufacturing sustainability and profitability. Performance levels once deemed unreachable can now be realised through the Internet of Things, cyber-physical systems, and cloud computing, among other technologies (Rosin et al., 2020). The fourth industrial revolution, known as Industry 4.0, is anticipated to yield a more agile, cognisant, efficient, intelligent, secure, and sustainable firm (Masood & Sonntag, 2020). I4.0 affects the satisfaction of commercial expectations and environmental standards.

The intelligent plant, embodying I4.0 concepts, employs technology to unify business and engineering processes, facilitating flexible, cost-effective, and resource-efficient production (Masood & Sonntag, 2020; Machado et al., 2019). I4 can be utilised to optimise value and sustainability while reducing waste. Industry 4.0 is also known as the Internet of Things (IoT), advanced manufacturing, or smart manufacturing (Pacchini et al., 2019). Intelligent networks based on CPS are a critical component of Industry 4.0, the fourth industrial revolution. Define CPS as "the merging of the physical and digital worlds by creating global networks for businesses that integrate their technology, warehousing

systems, and manufacturing facilities". The various operations of physical systems are integrated through biological functionalities using networking, computing, and communication infrastructures (Kamble et al., 2018). I4.0 results from the rapid adoption of new digital technologies, such as cloud computing and IoT. Smart connectivity among industrial units, process mobility, industrial process flexibility, interoperability, and integration with customers and suppliers are at the core of Industry 4.0 (Shaharudin et al., 2017).

Companies are pushing to implement Industry 4.0, and unsurprisingly, many academic articles discuss its benefits, aiming to persuade businesses to join the initiative. Furthermore, this self-proclaimed "Fourth Industrial Revolution" has prompted several academic papers to examine its global economic implications (Galati & Bigliardi, 2019). I4.0 aims to provide comprehensive customisation of products manufactured using information technology and to create a production chain based on customer feedback that automatically and flexibly adapts to changing conditions. Technology-driven businesses worldwide have shown interest in Industry 4.0 (I4.0) (Masood & Sonntag, 2020). Industry 4.0 encompasses technological advances such as autonomous manufacturing systems, the Industrial Internet of Things (IIoT), cloud computing, big data analytics, additive manufacturing, horizontal and vertical system integration, cybersecurity, augmented reality (AR), and simulation (Gunal, 2019). Industry 4.0 and sustainability are two important trends in contemporary manufacturing. Because of their intersections and interrelations, they can create a specific industrial wave that will completely transform the global production systems. Industry 4.0 can enable complete sustainability across industries, thereby contributing to a more sustainable future through its technologies (de Sousa Jabbour et al., 2020).

Industry 4.0 has numerous benefits for modern factories and society. Research has forecasted the effects of the fourth industrial revolution on a country's Gross Domestic Product (GDP) (Amara et al., 2019). I4.0 is an umbrella concept that integrates intelligent machines and systems with alterations to manufacturing processes to promote efficiency and enable more flexible adjustments (Hernes et al., 2020). Industry 4.0 is a novel paradigm in the industrial sector in which cyber-physical and intelligent systems collaborate with industrial processes to create value (Frank et al., 2019; Mueller et al., 2017). "Smart factory" was coined in Germany (Industry 4.0). It refers to a collaborative effort to develop solutions in agile manufacturing, responsive manufacturing, cloud manufacturing, holloing manufacturing, and grid or cloud computing (Rashid et al., 2018). Indeed, Industry 4.0 bridges the physical and digital worlds, laying the foundation for future intelligent factories (Diez-Olivan et al., 2019). Industry 0.4 has a large and forked field.

This study examines the potential of leveraging Industry 4.0 technologies to support reverse logistics, focusing on technologies, interoperability, and control to achieve resource efficiency, time and cost

savings, and sustainable production. Industry 4.0 has been a hot research topic for nearly a decade and is now a top priority for many manufacturing companies. (Maganha et al., 2021). On the Industry 4.0 side, sustainable manufacturing can be defined as “the integration of processes and systems that produce high-quality products and services with fewer and more sustainable resources (energy and materials)”. In addition, the safety of employees, customers, and the communities in which they operate, as well as the mitigation of environmental and social impacts throughout the product life cycle, are all essential considerations (Cerri & Terzi, 2016; Machado et al., 2020).

Studies (Kumar et al., 2021; Enyoghasi & Badurdeen, 2021) have supported sustainable manufacturing within the scope of Industry 4.0 from both product and process perspectives, analysing the obstacles to improving sustainability and identifying key steps to achieve sustainable processes. According to Machado et al. (2020) and Enyoghasi & Badurdeen (2021), Industry 4.0 has the potential to add value across all aspects of sustainability. These issues can help identify opportunities for industry development by examining innovative data-driven business models, new product and service offerings, and the closure of product life cycles. CPS-supported equipment also benefits SMEs by enabling the digital transformation of training and competency development through Industry 4.0 and communications technologies. Sustainable manufacturing offers cost savings through improved resource efficiency and regulatory compliance, an enhanced brand reputation, access to new markets, reduced labour turnover by creating attractive workplaces, and a long-term business approach through access to finance and capital (Machado et al., 2020).

2.3.1 Stages of industry development and the advantages of each stage:

The world witnessed several industrial revolutions, including the first (Industry 1.0). Compared with traditional methods, steam power and mechanisation of production increased output by a factor of eight between 1820 and 1840 (Vinitha et al., 2020). Mechanical production plants powered by water and steam typified Industry 1.0. Textile manufacturing, iron production, steam power, and machine tools emerged from the Industrial Revolution (Vinitha et al., 2020). The Second Industrial Revolution began (also known as Industry 2.0). The second phase was industrialisation, which lasted from the late 1800s to the early 1900s. The development of machine tools was central to the mass manufacturing revolution. New technologies were adopted, including electricity, telephones, internal-combustion engines, rail networks, gas, telegraphy, and sewage treatment (Vinitha et al., 2020). In addition, Industry 2.0 is characterised by mass production based on electrical energy (Kuo et al., 2019). In the 1970s, the third industrial revolution (Industry 3.0) began with partial automation in field engineering, enabled by advances in computing and automation. Electronics and computer-controlled devices are increasingly automated throughout their manufacturing processes. (Vinitha et al., 2020). Automated

production based on electronics and internet technologies is referred to as Industry 3.0 (Kuo et al., 2019), which has led to increased use of industrial robots (Vinitha et al., 2020).

Subsequently, the industry experienced a boom in the development sector as the Fourth Industrial Revolution rapidly became a global phenomenon centred on industrial transformation, revitalisation, and development (Ko et al., 2019). Industry 4.0 began in 2011 with the introduction of Cyber-Physical Systems (CPS) in production, which combine diverse data and knowledge to improve efficiency and productivity. As part of Industry 4.0, cyber-physical systems are emerging, and all systems are interconnected, communicate, and are processed using machine learning and cloud computing technologies. The Internet of Things supports manufacturing and service delivery. Advanced technologies in Industry 4.0 include smart manufacturing, high-end robotics, and augmented reality (Vinitha et al., 2020). The stages of industry development and their features are listed in Table 2-1.

Table 2- 1 shows the stages of the industry's development.

Industrial Era	Period	Changes	Notable industries	Societal impact
Industry 1.0	1760-1840	A steam or water-powered transition from hand production methods to machines.	Textiles, Iron, Agriculture, Mining.	Development of a stronger middle class.
Industry 2.0	1870-1914	Accelerated speed of movement of people and ideas, from steam and electricity.	Communications (telegraph), transportation (steam trains), and all Manufacturing.	High unemployment resulted from the replacement of workers by machines.
Industry 3.0	Late 20 th century	The “Digital Revolution” or the computer age.	New technology industries and the use of computer/communication technologies in production.	Widespread access to machines and communication reduced the need for labour.
Industry 4.0	2011	Cyber-physical systems	Artificial intelligence, high-end robotics, and augmented reality are examples of modern technologies in Industry 4.0	The Internet of Things (IoT) is closely linked to Industry 4.0, which enhances manufacturing and service delivery.

Table 2-1 presents the periods for each stage of industrial development and the most prominent changes at each stage, highlighting the key features of industry and its societal impacts.

2.3.2 Integration Characteristics of Industry 4.0:

Implementing the concept of "three-way integration" is a key approach. I4.0 End-to-end integration with horizontal, vertical, and circular integration in three directions (Oesterreich & Teuteberg, 2016). Horizontal integration entails tying the value chain together (Jonasdottir et al., 2021). It integrates ICT into manufacturing processes, business-planning mechanisms, and agents (Diez-Olivan et al., 2016).

Horizontal integration through value networks also enables closer collaboration with value chain partners across company borders by integrating IT systems, processes, and data flows (Oesterreich & Totenberg, 2016).

The corporate structure includes vertical integration (Jonasdottir et al., 2021). It integrates various ICT systems across hierarchical levels, from fundamental to advanced, for production management, execution, planning, and scheduling. This level of integration makes manufacturing processes more adaptable (Diez-Olivan et al., 2016). Vertical integration and networked manufacturing systems imply integrating IT systems, methods, and data flow, resulting in an intelligent manufacturing environment (Oesterreich & Teuteberg, 2016).

Vertical and horizontal integration connect the end user to the product life cycle, a process known as circular integration. This integration completes the production loop, resulting in end-to-end digitalisation from the planning and manufacturing stages (Diez-Olivan et al., 2016). End-to-end digital integration throughout the value chain enables highly customised products while reducing internal operating costs (Oesterreich & Teuteberg, 2016). Integration that spans a product's entire life cycle is known as end-to-end integration (Jonasdottir et al., 2021).

Based on what was stated by (Oesterreich & Teuteberg, 2016; Jonasdottir et al., 2021), in the triple integration of Industry 4.0, the researcher designed an explanatory diagram for the triple integration of Industry 4.0 according to what the researchers stated, as follows:

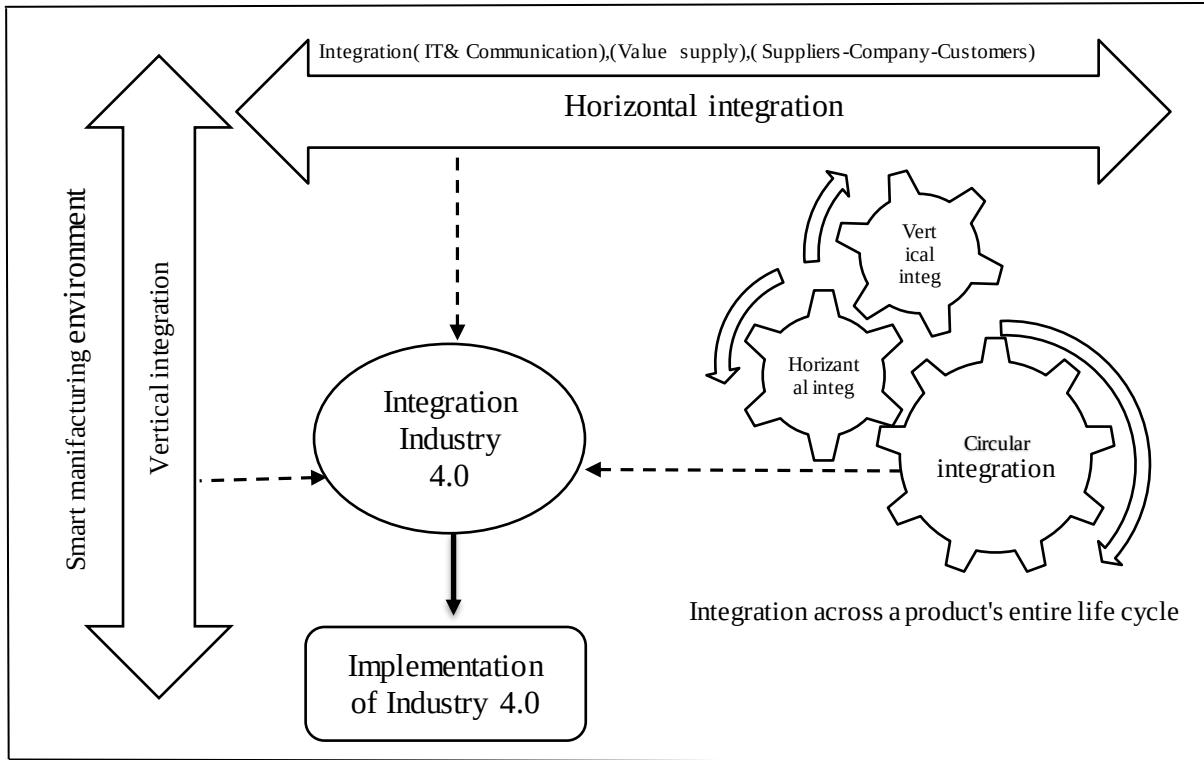


Figure 2- 4 Industry 4.0 Integrations (Source: authors).

The leading technologies of Industry 4.0 are cyber-physical systems (CPSs), the Internet of Things (IoT), cloud manufacturing, and smart devices. These technologies aid in forecasting future market trends and customer requirements (Maganha et al., 2021). Adopt new technologies to meet customer demands, such as low-cost, high-volume products that can be customised more (Bibby et al., 2018). Industry 4.0 features include shorter delivery times, more efficient and automated processes, higher quality, greater production agility, and profitable, customised products (Bongomin et al., 2021).

2.3.3 Approaches of Industry 4.0:

By reviewing the previous literature, it was found that there are three main approaches to Industry 4.0, namely:

The first approach emphasizes the technology, regardless of its purpose or manufacturing location (Li et al., 2017). It describes Industry 4.0 in terms of applications such as smart cities, users, intelligent enterprises, and innovative services, as well as industrial wireless networks (big data, databases, servers, and data mining). Devices such as machines, robots, mobile devices, and AGVs are examples of networks (cellular, wired, or wireless) (Bosman et al., 2019). I4.0 highlights semantic technologies, IoT, the Industrial Internet, Cloud computing, big industrial data, cybersecurity, product life cycle management, intelligent robotics, visual computing, and industrial automation (Masood et al., 2021).

The second approach focuses on the design principles, proposed motivation, and anticipated outcomes of a technology intervention, such as corporate social responsibility, product personalisation, service orientation, and intelligent products. The following topics discuss interoperability, modularity, horizontal and vertical integration, decentralisation, real-time capability, and virtualisation (Bosman et al., 2019).

Third approach: Industry 4.0 technology implementation can be analysed within specific areas or activities, such as product design and engineering, planning, supply chain management, and factory operations, to identify opportunities for improvement (Li et al., 2017). Based on the research presented in previous literature, an illustration of Industry 4.0 approaches can be depicted, as shown in Figure 2-6:

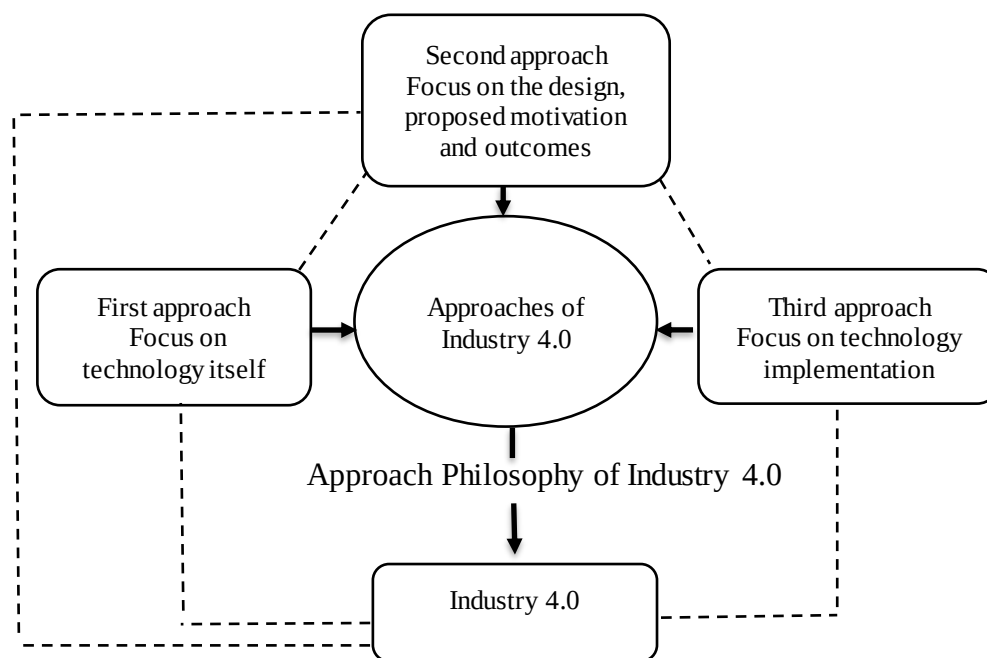


Figure 2- 5 Philosophical approaches to Industry 4.0 (Source: authors).

2.3.4 Industry 4.0 Technologies and Smart Manufacturing:

This chapter highlights the dimensions of one of the main research variables, Industry 4.0 technology. According to our research's conceptual framework, five main technologies in Industry 4.0 have been identified, each with sub-dimensions. These will be studied, and the extent to which such technologies affect reverse supply chain activities will be demonstrated. A brief presentation of each type is given below.

Industry 4.0 technology aims to network physical components to enhance the productivity, Quality, reliability, safety, and efficiency of manufacturing processes (Jamwal et al., 2021). Industry 4.0 technology effectively supports smart manufacturing (Bibby & Dehe, 2018). Therefore, to fully benefit

from Industry 4.0 technologies, it is necessary to integrate the physical components of manufacturing and other Industry 4.0 technologies into the automation system. Industry 4.0 technologies have demonstrated a remarkable ability to enable and realise smart manufacturing, encompassing improved value chain integration, security, trust, and dependability (Dornelles et al., 2022). The core idea of Industry 4.0 is to integrate contemporary digital technologies into physical processes and production, with a focus on interconnectedness, machine learning, and real-time monitoring and control (Guo et al., 2021). Moreover, an emphasis on networked machinery in manufacturing settings that can autonomously exchange data and regulate one another signals a dramatic change in the manufacturing landscape (Morgan et al., 2021). Below are several Industry 4.0 technologies.

2.3.4.1 Cyber Physical Systems (CPS):

One of the most essential parts of Industry 4.0 systems, CPS enables the integration of the physical and virtual realms, combines computational and communication processes with biological ones, and upgrades physical systems with new capabilities (Rossit et al., 2019). A cyber-physical system is a complex system that integrates sensing, computing, control, and networking within physical processes and objects over the Internet. Consequently, it plays a vital role in modern industry by linking the physical and digital worlds. In addition to its ability to meet changing industrial needs, its structure and functions are continuously being improved. As a result, researchers and practitioners have gained increasing attention (Duo et al., 2022). CPS is a collaborative platform that connects industrial business processes and networks, making smart manufacturing systems, storage facilities, supplier organisations, and final demand points readily accessible. CPS includes intelligent machinery, processes, factories, and storage systems that can exchange information and operate independently to perform tasks such as running, replenishing, ordering, and transferring tangible goods (Kagerman et al., 2019).

Therefore, CPS facilitates the sharing, integration, and collaboration of information, along with real-time monitoring. This technology can also be used to manage customer feedback in reverse supply chains (Chang et al., 2014). The study by Dev et al. (2020) showed how Industry 4.0 technologies benefit reverse supply chains. It involved investing in cyber-physical systems (CPS) technology for remanufacturing and recycling returned household products, and integrating CPS with a web-based resource planning system to handle data in real time. This enabled the determination of reorder points using inventory measurement sensors and guided the selection of reorder levels. With the rapid growth of modern industry, the demand for CPS integration is rising to address deficiencies across networks, technologies, tools, and devices. Combining systems and technologies in CPS is complex and diverse, creating a compatible, open system that allows integration with various activities, such as RSC (Perez

et al., 2022). Additionally, the Cyber- Physical System serves as the foundation for IoT deployment. In this context, the Smart Factory embodies key features of Industry 4.0 (Mueller et al., 2017).

2.3.4.2 Internet of Things (IoT):

The Internet of Things (IoT) refers to a network of physical objects equipped with sensors, software, and other technologies that enable them to communicate and exchange data with other devices and systems over the Internet (Khodadadi et al., 2016). In addition, the Internet of Things (IoT) connects people and things by transforming today's information and network technologies. (Shaev, 2014). It optimises connectivity, not just for people but also for machines and devices (Bibby & Dehe, 2018). IoT allows objects and humans to communicate (Alcácer & Cruz-Machado, 2019). In the context of Industry 4.0, there appears to be agreement on the term (IoT) (Gilchrist, 2016). The ability of IoT aggregates to autonomously gather information about the natural world, potentially using a large number of sensors embedded in objects or deployed ad hoc, is a crucial component (Mangia et al., 2018). The Internet of Things (IoT) refers to the digital interconnection of everyday objects.

On the other hand, the Internet of Things refers to more "things or objects" connected to the Internet than people (Ali et al., 2019). The study by Garrido-Hidalgo et al. (2020) contributed to IoT investment in support of RSC by integrating IoT communication standards for machine-learning-based management of WEEE. His contribution introduces a new end-to-end IoT framework for Industry 4.0 to manage electrical and electronic waste. He proposed a heterogeneous IoT network that enables low-energy, low-cost supply chain management. To achieve this, he focused on cooperation among emerging IoT technologies for reverse supply chain management to recover electrical and electronic waste. IoT is highly beneficial in reverse supply chains, as it increases visibility, streamlines manual processes, improves inventory management, and supports tracking of product life cycles. This helps ensure regulatory compliance and promotes sustainability (Manavalan & Jayakrishna, 2019). Moreover, IoT technology can be used to collect, monitor, and process data in real time, allowing companies to implement more efficient, transparent, cost-effective, and time-saving reverse logistics processes and enhance manufacturing sustainability (Ghobakhloo et al., 2023). In summary, the Internet of Things will transform physical elements into intelligent systems that communicate with other devices and humans, thereby advancing manufacturing sustainability across various fields (Khodadabi et al., 2016).

Industrial Internet of Things (IIoT) is often used to denote the application of the Internet of Things in industrial settings (Boyes et al., 2018). It seeks to create efficiencies, enhance safety, and reduce costs in industrial operations. Besides that, IIoT applications span numerous areas within the industrial sphere, such as predictive maintenance, where real-time data from IoT sensors is used to monitor

equipment condition and health. Thus, this signals the need for maintenance, enabling machines to be maintained based on data-driven insights rather than fixed schedules, thereby reducing downtime and maintenance expenses (Javaid et al., 2021). It is also used to trace and control the flow of materials throughout the production and distribution chain, thereby enhancing inventory management, preventing theft or loss, and ensuring efficient asset utilisation (Ilure et al., 2020). Similarly, the Internet of Things enhances logistics services by improving the monitoring of goods' movement from the manufacturing plant to the distribution centre, optimising routes and ensuring high delivery accuracy (Javaid et al., 2021). Conversely, the Internet of Things could facilitate reverse logistics by monitoring and tracking returned materials via embedded sensors. This information helps firms decide whether to resell, repair, or recycle returned products. It is also effective for the automated sorting and inspection of returned materials (Thürer et al., 2019).

The Internet of Things has benefited reverse supply chain operations by providing more detailed information, facilitating easier tracking, enhancing resource management, and supporting the implementation of sustainability programs (Garrido-Hidalgo et al., 2019). The adoption of the Internet of Things (IoT) in the industrial sector, particularly in reverse supply chains, will enable the company to create a more adaptable, efficient, and sustainable supply chain (Manavalan et al., 2019).

2.3.4.3 Big data:

Two of the most important factors in Industry 4.0 relate to the availability and manipulation of big data (Gu et al., 2015). The more effective the technology, the higher the likelihood of generating large volumes of data (Patnaik, 2020). Big data has transformed manufacturing and reverse supply chain operations by improving process effectiveness and supporting operational sustainability. It does so by enabling information-based understanding across all aspects of the production and post-production lifecycle (Awan et al., 2021). Additionally, the 5Vs are widely used in the literature to characterise big data (variety, veracity, volume, velocity, and value) (Wamba et al., 2015; Xu & Duan, 2019). The term big data refers to massive, diverse volumes of information that can only be stored, processed, and analysed using advanced technologies, enabling users to extract valuable insights across various domains (Grover et al., 2018).

Industry 4.0 highlights the potential of using big data to improve resource efficiency. The CPS will generate large volumes of data, and big-data technologies will be necessary to process this information, improve system development, and clarify the relationship between cyber systems and big data. Digitisation has become a priority for nearly all organisations today (Patnaik, 2020). Industry 4.0 can derive valuable insights from supervised assets. Unusual industrial equipment, tools, and operational behaviours can be accurately forecast using information science, enabling prediction of severe events

and damage (Plumpton, 2019). They developed Big Data techniques to extract meaningful insights, helping businesses understand past and present market behaviour and forecast future trends and needs. As a result, data becomes more practical and accessible to service providers and customers, increasing value and competitive edge (Mohammed, 2018). Big Data is crucial to Industry 4.0, and managing it presents several important challenges (Patnaik, 2020). Extensive data analysis also involves extracting knowledge from large datasets, thereby supporting data-driven decision-making (Ivanov et al., 2019). In summary, big data gives manufacturing and reverse supply chain operations insights that support productivity, enhance sustainability, and increase responsiveness to consumer and market demands (Edwin et al., 2022). This research uses customer data to evaluate Industry 4.0 performance, drawing on feedback from reverse supply chains that emphasise recycling, environmentally friendly disposal, and customer information management.

2.3.4.4 Cloud:

The “cloud” is a network of servers accessible via the Internet that store, manage, and process data. The term “cloud” is often associated with cloud computing, which provides on-demand access to shared computing resources, including storage, servers, databases, and applications (Malik et al., 2018). “Cloud manufacturing” refers to a set of IT services, such as internet access, web-based services, and system management (Helo et al., 2014). Consequently, cloud-based solutions are web applications that store data on external servers and are mainly accessed through the Internet (Bibby & Dehe, 2018). Cloud manufacturing is also described as a networked manufacturing system providing open access to a broad and varied collection of manufacturing resources; these resources enable temporary cyber-physical production lines to adapt quickly to customer demands, offering higher efficiency, lower unit costs, and better utilisation of physical assets (Schuh et al., 2014). Users depend on large data centers for services and store personal information and software on systems they do not control (Marinescu, 2013). The cloud, an Industry 4.0 technology, can support reverse supply chains by enabling the recovery of end-of-life materials for recycling, remanufacturing, or disposal (Dev et al., 2020). Its real-time data-tracking and analysis capabilities enable it to monitor material returns. The integration of various technologies, including the Internet of Things and sensors, helps companies track returned goods and support decision-making (Javaid et al., 2021).

Additionally, cloud platforms can enable interconnected supply chains, bringing stakeholders together and streamlining processes such as permit returns, renewals, and the recycling of goods by automating workflows and increasing visibility (Esmaeilian et al., 2020). The cloud can support varying return volumes, flexibly manage reverse logistics services without requiring extensive IT infrastructure, and provide secure, transparent visibility into returned materials (Garrido-Hidalgo et al., 2019). Reverse

supply chains are supported by cloud computing to enable more intelligent, faster, and more sustainable logistics, which is paramount to the future of Industry 4.0 (Sun et al., 2022). Furthermore, cloud computing has become one of the most prominent IT trends, offering unlimited resource sharing and an enhanced user experience. Its substantial commercial value is gradually emerging (Xu & Buyya, 2019). Cloud computing is widely regarded as the next significant step forward in application development. Typically, cloud computing is homogeneous and targets enterprise computing (Rountree et al., 2014).

2.3.4.5 Smart factory:

Smart technology supports complex systems and processes, enabling an intelligent factory to operate efficiently. Machines, products, people, and other resources communicate with one another. It also interacts with customers through smart factory facilities and the supply chain (Simona et al., 2014). Indeed, by incorporating concepts such as the Internet of Things and cyber-physical systems, the smart factory concept aims to enable highly flexible, self-adaptive production processes, with machines and products that act intelligently and autonomously (Syberfeldt et al., 2017). As a result, these paradigm shifts and a new manufacturing method will drastically change operators' working conditions (Syberfeldt et al., 2016). Add the 'Smart Factory,' a key feature of I4.0 (Drath & Horch, 2014).

Factory operations become more intelligent, efficient, safer, and environmentally sustainable as efforts are made to integrate production technologies and devices, information and communication systems, data and service network infrastructures, and environmental sustainability (Strozzi et al., 2017). The smart factory is a concept that entails a flexible production system connected to processes and operations via CPS and advanced digital technologies, which can self-optimize performance, adapt to and learn from new conditions in real-time, and run production processes autonomously (Sufian et al., 2021).

Customising goods and services at the same cost-efficiency level as mass production (mass customisation) is achievable in a Smart Factory, for example, thanks to production flexibility, configurability, and customer interaction to understand their needs (Strozzi et al., 2017). Advanced industrial digital technologies provide beneficiaries with information, enabling them to improve their manufacturing processes. Operations visibility, often associated with smart factories, relies on digital manufacturing (Ahuett & Kurfess, 2018). The smart factory uses advanced Industry 4.0 technologies, such as the Internet of Things, artificial intelligence, and robotics, to enable highly automated, data-driven, flexible manufacturing (Soori et al., 2023). These features improve the performance of reverse supply chains by facilitating the reuse of goods for recycling, refurbishment, or disposal (Shaharudin et al., 2017). Smart factory technology can support reverse supply chains by automatically sorting and

processing returned products, as smart factories are equipped with sensors, IoT devices, AI, and robotics to categorise items by condition (Mehrpooya et al., 2019). This helps in decision-making about whether to renew, recycle, or dispose of items in an environmentally friendly way. Additionally, smart factories contribute to the circular economy by promoting material reuse and rationalising material use (Lin, 2018), thereby reducing waste and supporting environmentally sustainable reverse supply chains.

In addition, Dev et al. (2020) indicate that smart factories are equipped with flexible manufacturing systems that can quickly adapt to changes in the quantity and quality requirements of reverse logistics. Smart factory implementation will help sustain Industry 4.0, enhance efficiency, reduce waste and reverse supply chain operations, and improve waste management and recycling (Bag et al., 2021). The smart factory is a multifaceted system that integrates core Industry 4.0 principles to enhance manufacturing competitiveness, efficiency, flexibility, and sustainability (Benotsmane et al., 2019). Smart manufacturing and smart factories are the most important aspects of Industry 4.0, and this paper examines them in depth.

2.4 Concluding remarks:

In the chapter abstract, the researcher provided background information on the study, including an introduction to the relationship between the variables. Next, a comprehensive theoretical framework for the research variables and their sub-dimensions was presented in a logical order, offering a clear and organised presentation.

Chapter 3

Systematic Literature Review and Analysis

3.1 Introduction:

This chapter reviews the literature to better understand how Industry 4.0 technologies support reverse supply chains. To do this, it examines prior studies on the research variables and their sub-dimensions through a deliberate literature review.

The reviewed literature is analysed, discussed, and critically examined in depth, focusing on the main research variables: Industry 4.0, reverse supply chains, and their sub-dimensions. The literature review is organised into two main sections. The first section covers traditional reverse supply chain activities, such as recycling, recovery, remanufacturing, and reuse, and examines how Industry 4.0 technologies contribute to them. The second category takes a more modern approach, integrating Industry 4.0 technology with a contemporary vision of reverse supply chain activities, emphasising customer preferences, the rational use of raw materials, and manufacturing ethics.

3.2 Searching:

According to the search protocol outlined in Table 3-1, to ensure consistency, objectivity, and reliability, users use the Scopus and Google Scholar databases to retrieve potential data, as well as other approved databases relevant to our research topic, for the literature review.

All references for this research are selected from accredited international scientific publishing databases, including Scopus and Google Scholar. Keywords related to the research topic, such as reverse supply chains and Industry 4.0, were used to find relevant studies. The focus was on research papers that explore the relationship between these areas. The researcher encountered challenges due to the limited number of studies combining RSCs and I4.0. This motivated the researcher to develop a framework for their integration. This represents a new contribution to supporting and strengthening the industrial sector, ultimately benefiting the consumer.

Table 3 - 1. Protocol of systematic literature review.

Research Protocol		Description
The base plan of Search	Databases	Scopus database and Google Scholar.
	Publication type	Journals indexed by Scopus and Google Scholar.
	Language	English.
	Years Publication	Focus on published in the last decade.
Search features	Search terms	Titles, abstracts, keywords.
	Search terms in titles,	Reverse supply chains, and industry 4.0.
	Keywords	Industry 4.0, Reverse supply chain.
The research	inclusion criteria, research	variables and their relationship.
Sample Exclusion		Criteria Articles do not focus on the content of the topic.
Data collection,	Detailed analysis and statement of relationship, linkage, and integration.	
Analysis, synthesis.		

3.3 Publications in Journals:

Several journals on the subject have been published in the Scopus database, which was used for the search. Searched using the keywords and the article title. Moreover, it is used to search for documents (Reverse Supply Chains and Industry 4.0). The topic is to determine the scope of the selected topic in business, management, accounting, computer science, environmental science, and materials science; define relevant articles; and specify English as the publication medium. Articles not applicable to the research topic are considered for exclusion. The results were ten journals that published the research. The journals that have published articles on this topic, along with the number of research studies, are listed in Table 3-2.

Table 3- 2 Publications in journals.

Sequence	Sources
1	Computers in Industry.
2	Resources, Conservation, and Recycling.
3	Sustainability.
4	Applied Sciences.
5	International Journal of Physical Distribution and Logistics Management.
6	International Journal of Logistics Research and Applications.
7	International Journal of Production Research.

8	Journal of Manufacturing Technology Management.
9	The South African Journal of Industrial Engineering.
10	Journal of Industrial Information Integration.

3.4 Approach for Systematic Literature Review:

A systematic literature review was conducted to deepen understanding of prior researchers' contributions within the scope of the research. The researcher conducted a literature review primarily using the Scopus database, supplemented by Google Scholar, to ensure scientific consistency, methodological rigor, and comprehensive coverage of relevant literature. Scopus was chosen as the primary database because it indexes high-quality peer-reviewed journals and provides standardised bibliographic and citation data, thus enhancing the reliability, transparency, and reproducibility of the review process. Google Scholar was used as a supplementary source to identify additional relevant studies and minimise the potential for overlooking recent or interdisciplinary publications. The combined use of these databases supports a systematic, academically rigorous literature review methodology that aligns with established standards.

This method involves identifying and selecting literature relevant to the research topic and systematically analysing research papers, while ensuring accurate article selection within the research scope. The Scopus and Google Scholar databases were used to identify published research papers on the research topic, as these databases are widely available and commonly used to review literature in the areas of RSCs and Industry 4.0, and are regarded as robust resources for scientific studies. In this section, we review the literature on the research variables identified through selected database searches to extract topic-related findings pertinent to the aims of our present study. I used related keywords, including Industry 4.0 and reverse supply chains, to identify papers that addressed the connections between the research topic and its branches. Relevant keywords and titles were also used as the main way of searching. The focus has been on papers and books published within the last decade. In addition, the search strategy was combined with the “snowball” technique of “searching” for the most relevant references to the topic to expand the scope and comprehensiveness of knowledge.

Using this systematic research method, 366 research papers were identified and used as references for the dissertation. To improve the transparency and reliability of the findings, the researcher supplemented the Scopus database results with figures directly from the search results. Scopus offers visual summaries, such as the distribution of research papers by year and publication trends, enabling the researcher to present bibliometric information. Conversely, Google Scholar does not provide such visual summaries, offering only textual search results.

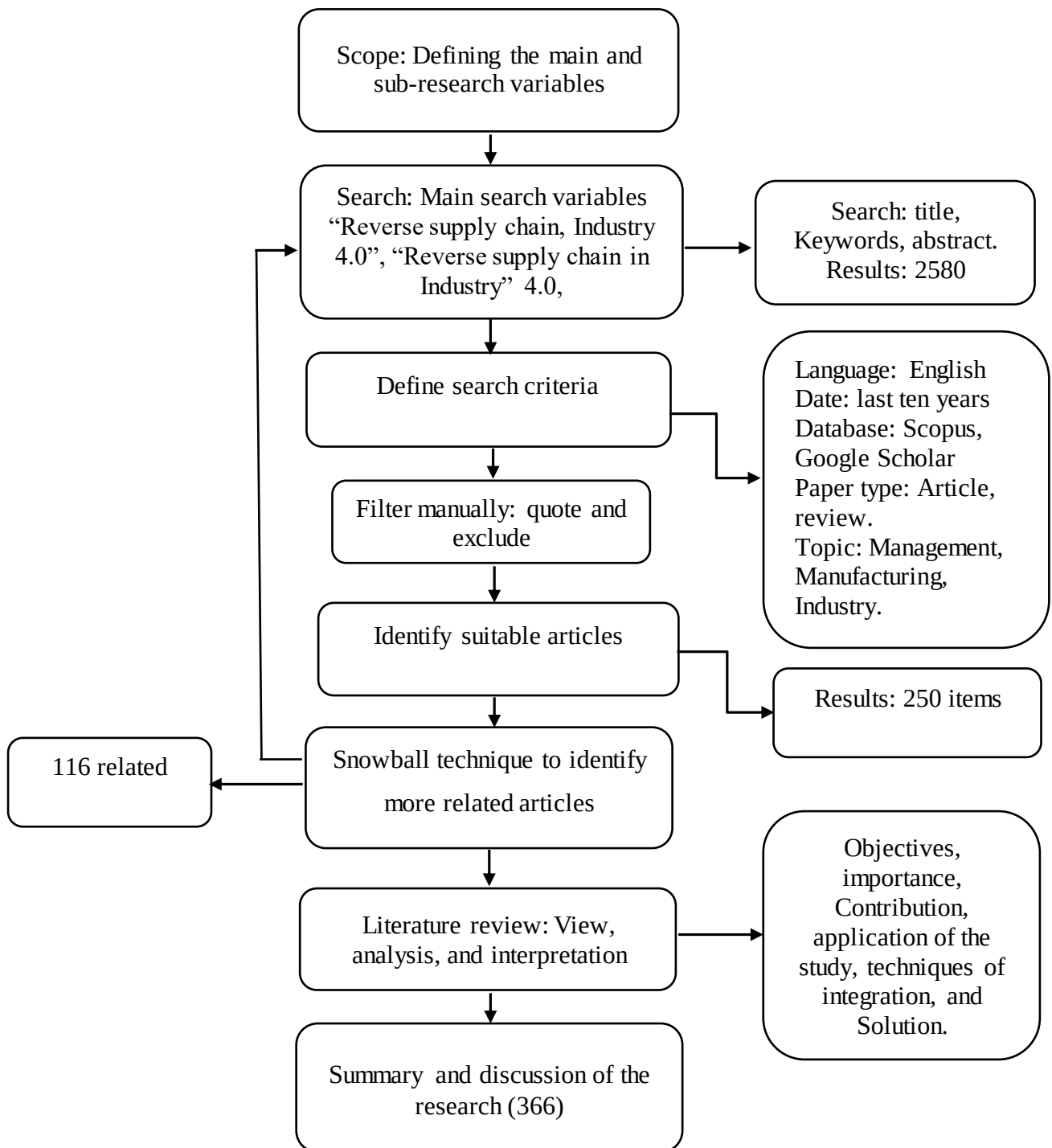


Figure 3- 1 Systematic of literature review layout (Source: authors).

Based on the searches shown in Figure 3-1, the study utilised the Scopus and Google Scholar databases. After filtering and selecting the most relevant articles to our research topic and removing duplicates, 366 published articles and research papers remained. The researcher then reviewed the specified literature. Using both electronic and manual methods, a set of articles closely related to our research scope was identified, reviewed, and analysed in detail. Tables and analytical summaries were provided

for each article and categorised according to the pathways of our current research. Additionally, the researcher examined other articles focusing on abstracts, research methodologies, and results. The researcher also drew from previously published articles and research papers to strengthen the theoretical framework and research methodology, including the quantitative and qualitative approaches used to generate our current research results.

3.5 Search Results and Overview:

This section provides schematic diagrams and details of the studies collected based on various criteria, including year of publication, author, journal, and other factors. According to specific searches, “Reverse supply chain and Industry 4.0,” 319 research papers were identified in the Scopus database.

3.5.1 Distribution of Papers over the Years:

The searches were conducted over the past 10 years. We have observed growing interest among researchers in publishing on Industry 4.0 and reverse supply chains, reflecting a contemporary trend of investing in Industry 4.0 technologies to improve reverse supply chain operations. We notice a peak in publishing in 2023, followed by a decline in 2024, as shown in the figures. This is because the year is not yet over, since the searches were conducted in the second half of 2024.

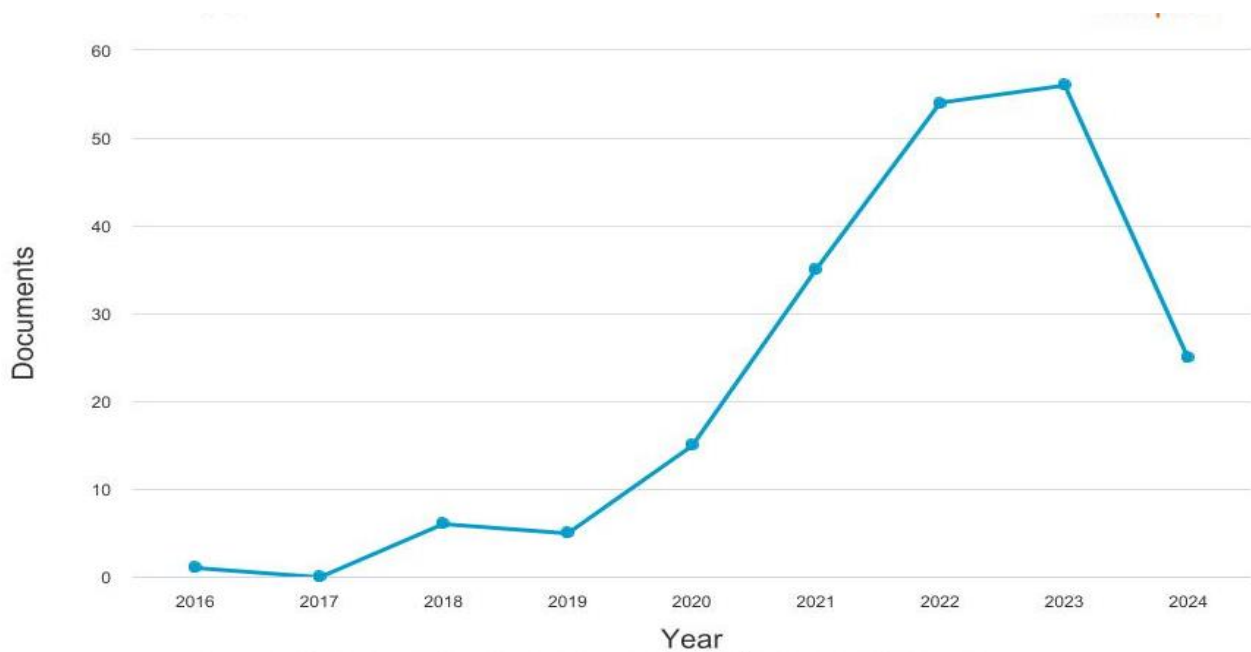


Figure 3- 2 Distribution of Papers over the Years (Source: Scopus database).

3.5.2 Contributions Classified by Author:

Contributions by Author: The chart below shows the top contributors to publications on Industry 4.0 and reverse supply chains, ranked by publication count. Govindan, K., published 10 publications, followed by Kumar, A., with 8, and Reyes, J. A., with 7. All of the publications were in peer-reviewed academic journals.

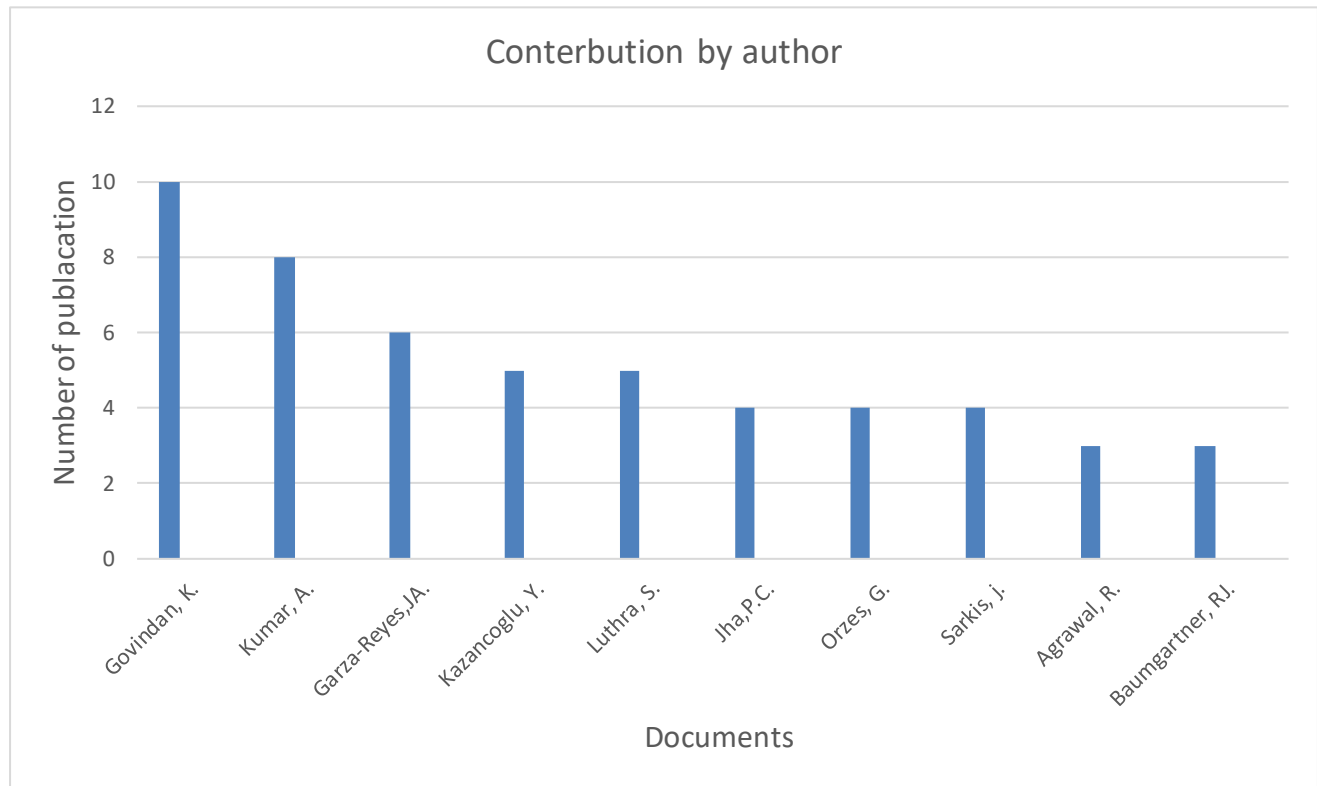


Figure 3- 3 Contributions classified by Author (Source: Scopus database).

3.5.3 Classification of contributions by subject area:

Given the subject's importance and the attention it has received in the literature across several fields, researchers have addressed it in areas including engineering, management, business, environmental aspects, and related fields, as it connects these domains.

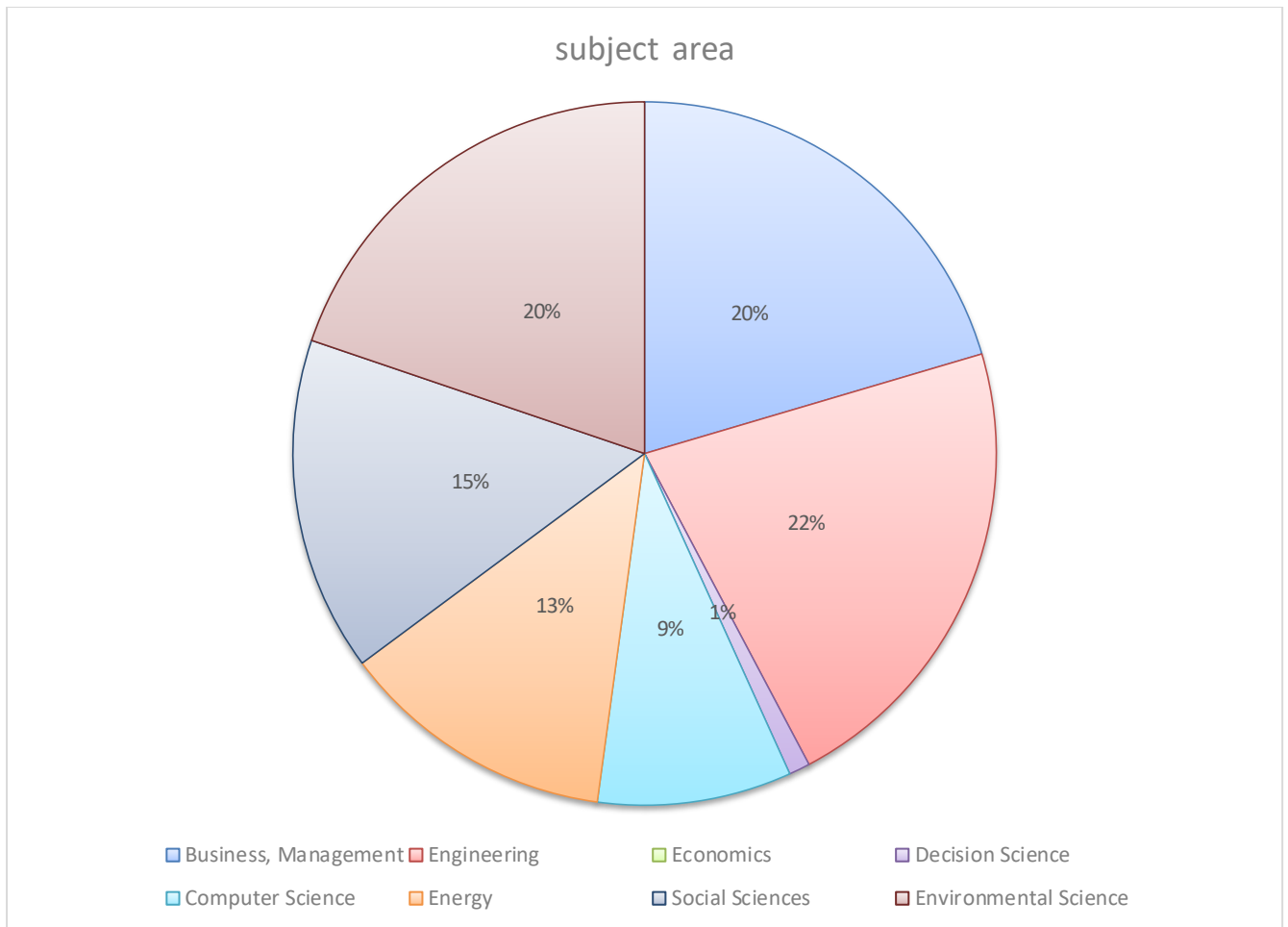


Figure 3- 4 Classification of contributions by subject area (Source: Scopus database).

3.5.4 Document by type classification:

The researcher defined articles and reviews in the search process definition, a method often used to review prior literature. From the figure below, we see that the percentage of published articles was 76.1% and the review rate was 23.9%.

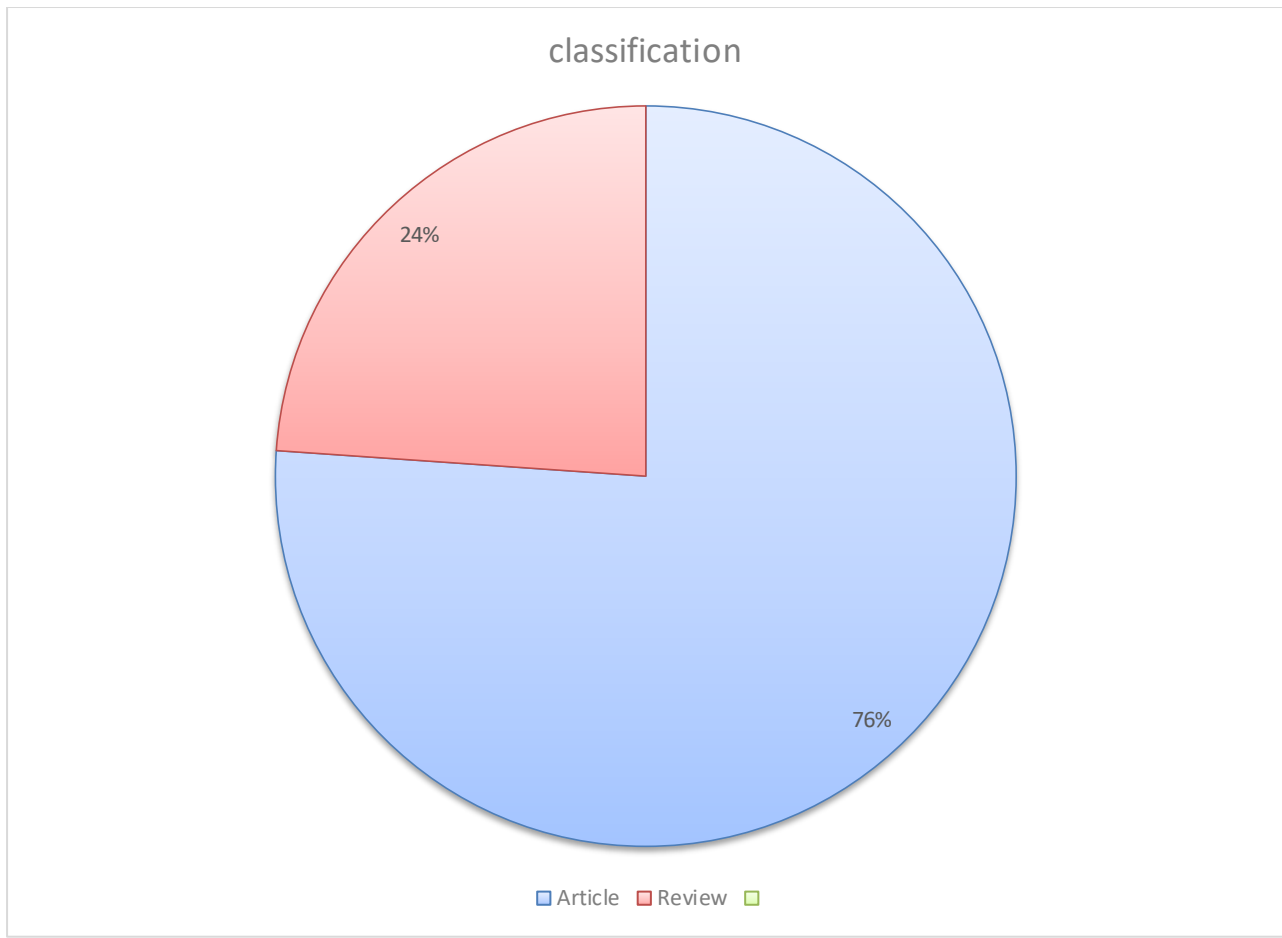


Figure 3- 5 Document by type classification (Source: Scopus database).

3.6 Literature Review: View of previous studies:

Using predefined search criteria, articles relevant to our research topic were identified through systematic searches. This helps understand the contributions of previous researchers to the current analysis and discuss them. Moreover, this helps leverage the achievements of earlier studies in this field and provide a clear direction for the researcher's ongoing research. By highlighting the contributions of previous researchers in the field of Industry 4.0 and reverse supply chains and analysing them with a clear view of the trends in their research paths, the researcher can better identify their own research direction, build on previous work, and utilise research recommendations in this field. The specific searches yielded several articles closely aligned with the researcher's focus for review and analysis.

3.6.1 Classification of studies:

This section offers a classification of studies based on problem context, objectives, research significance, and researchers' orientations, as reviewed in the literature on Industry 4.0 and manufacturing research supporting reverse supply chains. Through manual screening, the researcher

identified a set of prior studies that, in their judgment, most closely align with our current research path. Additionally, it provides insights into the directions of previous researchers. Based on their research paths, they employed different models and methodologies to achieve their results. As a result, the researcher classified the studies in our current research according to the nature of the relationships between the variables to broaden understanding and address existing gaps in the topic. Furthermore, the researcher presented tables summarising prior contributions, categorised by research orientation, along with analyses of key aspects of each study to highlight recent findings in this field. In line with the focus of our current research, previous studies were divided into two groups based on the conceptual framework shown in Figure 1- 1, which encompasses two aspects of reverse supply chain activities within Industry 4.0: traditional activities and the contemporary vision of reverse supply chain practices.

We can consider both as traditional reverse supply chain activities that focus on returning goods from consumers to manufacturers or recyclers through operations that companies either manage themselves or outsource to third parties (Wilson & Goffnett, 2022). The tasks include handling customer returns, conducting inspections and processing, and determining whether products can be refurbished, recycled, or disposed of (Sangwan, 2017). Remanufacturing is the process of restoring used products to like-new condition, while recycling involves disassembling used materials for reuse. These processes can be improved through data collection and analysis, and responsible disposal and recycling are maintained by complying with environmental regulations (Sharma et al., 2016). Conversely, both Taghikhah et al. (2019) and Bag et al. (2023) emphasise the role of reverse supply chain activities in rationalising material consumption, gathering customer information to meet preferences, and promoting ethical manufacturing. This includes designing durable, recyclable products, implementing take-back and exchange programs to increase returns, and using sustainable materials to reduce waste (Frei et al., 2020). The supply chain aims for transparent and ethical practices, including responsible management of returned goods and open communication with customers about environmental impacts. Additionally, these goals are achieved through eco-friendly packaging, collaboration with ethical suppliers, and measuring and reporting impacts to demonstrate a commitment to sustainability and ethics (Paulraj et al., 2017). The contributions of previous researchers are outlined as follows:

3.6.1.1 Traditional activities of RSCs in I4.0 and manufacturing:

2.6.1.1.1 Recovery, recycling in I4.0 and manufacturing:

Recycling involves gathering, separating, and sorting materials to create new products or raw materials. These activities include sorting and recycling materials for reuse or eco-friendly disposal, which helps reduce the use of raw materials and minimise the ecological footprint of waste (Sangwan,

2017). Additionally, we will highlight the concept of recovery. Recovery is the process or mechanism of reclaiming expired materials to prepare them for subsequent recycling or environmentally friendly disposal (Augustine et al., 2019).

The table below presents the contributions of previous researchers in the field of Industry 4.0 and manufacturing, along with the support mechanisms they propose for reverse supply chains in recovery and recycling activities.

Table 3 - 3. Studies of RSCs (recovery, recycling) in I4.0 and manufacturing:

Authors	Objectives	importance	Techniques of integration	solution	Application of the study
Nuss et al., 2015	Aims to identify planning problems systematically	Interconnecting planning problems within an integrated framework	reverse supply chain planning matrix (RSCPM)	Reverse Supply Chain Planning Matrix	Germany
Shaharudin et al., 2017	Product returns motivate manufacturing firms	provides valuable prudence to an essential predictor of company performance in RSCs	institutional forces	Significance of product return in the assumption of RSC activities	firms in Malaysia
Habibi et al., 2017	The gathering and disassembly of end-of-life product requirements are to be optimised	tackling the load of waste, electric and electronic tools	Collection-disassembly	optimisation of collecting and disassembly improves the international execution of the RSCs	Franc
Doan et al., 2019	risk factors	responsibility end-of-life products	A fuzzy approach	flexibility for decision-makers	Vietnamese electronics industry
Enyoghasi & Badurdeen, 2021	Implementation of sustainable manufacturing facilitated or enhanced by using I4.0.	Role Illustration of individual I4.0 technologies and their potential impact on sustainability.	Product, process, and system integration.	Comparative analysis	German
Garrido-Hidalgo et al., 2019	Solutions for Industry 4.0 in R-SCM are based on IoT networks and align with DSC objectives.	Deploying the communications infrastructure can manage data gathered during the recovery of WEEE.	ICT, IoT	Identify various communication bottlenecks that must be addressed to enhance the reliability of Industrial Internet of Things (IIoT) networks.	Recovery of computer-based products.
Pourmehdi et al., 2021	Integration 4.0 with RSC is sustainable in the steel industry.	Identify and analyse the challenges to integrating I4.0 with RSC.	Fuzzy analytical network process	The capability of Industry 4.0 to create an efficient reverse logistics system.	steel industry
Mohajeri et al., 2021	Evaluating several methods with different	Maximising recycling utilisation and	A multi-stage fuzzy model of the RSC.	Providing a comprehensive RSCM solution	Iran

Authors	Objectives	importance	Techniques of integration	solution	Application of the study
	technologies for recycling food waste based on the indicators of the Industry 4.0 revolution.	customer responsiveness and minimising the harmful effects of environmental pollution and transportation costs.		for household waste recycling based on I4.0 technology.	

According to what is shown in Table 3-3, the researcher analysed each study separately, including the essential main aspects of the study, as shown below:

Nuss et al. (2015) present a conceptual framework for reverse supply chain planning that systematically identifies the problems involved in product recovery. A classification system, the Reverse Supply Chain Planning Matrix (RSCPM), is proposed to categorise planning problems and demonstrate their interconnectedness within recovery processes. The study offers an integrated and systematic perspective on the planning challenges of reverse supply chain management. By proposing potential solutions for end-of-life product recovery mechanisms in manufacturing, the study provides a foundational framework for future research in reverse logistics. The researcher identifies areas for further research to develop new models and strategies to address these issues.

Moreover, Shaharudin et al. (2017) examined the motivation of manufacturing companies to implement closed-loop supply chain activities in response to product returns, thereby influencing the efficiency of reverse supply chains. The research findings recommended that manufacturing firms implement reverse supply chain operations based on product returns received through closed-loop operations. In the study, a critical realist mixed-methods approach was used, employing a five-point Likert scale in the questionnaire's quantitative component. He employed a semi-structured interview method to collect and analyse qualitative research data. His work was consistent with prior findings in the literature, which suggest that recovery operations within reverse supply chains are currently used to generate revenue rather than incur additional expenses. This reflects the company's performance in the reverse supply chain. His work also provided insights into the variables that can enhance the outcomes of adopting reverse supply chain activities by intensifying the scale of involvement with product returns, an important indicator of the company's performance in reverse supply chains.

Highlighting the studies of Nuss et al. (2015) and Shaharudin et al. (2017), note that these studies addressed a research gap by focusing on reducing waste through mechanisms to recover expired materials via reverse supply chain activities and utilising recovered materials for recycling as a source of raw materials. Thus, companies invested in recovered materials as an additional revenue stream. In

addition, the studies demonstrated how they could help address a research gap, specifically by reducing waste and optimising investment.

Furthermore, Habibi et al. (2017) also sought to develop a model to improve waste treatment from electrical and electronic equipment. The research revealed that waste from electrical and electronic equipment is the most common type and should be treated, as the raw materials can be reused in production. The research shows that integrating assembly and disassembly processes enhances the functioning of the global reverse supply chain, for example, by reducing total costs. Within this research gap, Habibi et al. (2017) investigated methods to reduce electronic and electrical waste. Their input was to develop a model and mechanisms to enhance waste treatment. The works of Habibi et al. (2017) and Shahreddin et al. (2017) are similar in principle, as both focus on decomposing the reverse-processing chain in recycling and on coordinating among departments to enhance the process and minimise costs. The two studies concluded that recycling activities are cost-effective for firms.

Doan et al. (2019) adopted a fuzzy approach to help companies organise recovery systems in their factories and facilitate the flow of expired products into their facilities. The study employed a mathematical model to analyse the research data and recommended establishing unique, more effective reverse supply chain centres. This study proposes a multi-product, multi-level e-waste management model that accounts for risk and uncertainty, critical issues in waste management systems. To illustrate the model's effectiveness and the proposed solution, a case study was conducted for an electronics manufacturing company in Vietnam. The main findings of the study were that risks and uncertainty significantly affected the overall cost and structure of the waste management network. Therefore, these issues should be integrated into the design stage of waste management networks. The results also show that the proposed model yields a better network structure and a lower total cost.

Similarly, Enyoghasi & Badurdeen (2021) use analytical comparisons to demonstrate the magnitude of I4.0 technology's influence on manufacturing sustainability. A work plan was developed to create a scale for estimating the sustainability of products, processes, and systems, enabling evaluation of their impacts. The scholar employed a qualitative research approach, conducting a comparative analysis to assess sustainable manufacturing. The paper also investigated processes that Industry 4.0 can support to enable sustainable manufacturing grounded on the 6Rs (reduce, reuse, recycle, redesign, remanufacture, and recycle). In addition, the study addressed a research gap in waste reduction and the potential for optimal investment to enhance manufacturing. The study results showed that many sets of sustainability metrics at the product, process, or system levels have not been examined in the literature in the context of Industry 4.0 technologies, underscoring the need for further research. The study presents the prior literature effectively and systematically but does not employ a quantitative approach supported by numerical data to strengthen the research findings.

In highlighting the research gaps identified by previous researchers, the researcher primarily selected contributions that align with the research gap of our current study. Doan et al. (2019) address waste reduction and investment optimisation for manufacturing sustainability by adopting a fuzzy approach to the recovery of end-of-life materials. The study presented a mathematical model for waste management, which the researcher contributed to reducing waste. Enyoghasi & Badurdeen (2021) showed, in their general framework, the potential of Industry 4.0 technologies to support the 6R principles (reduce, reuse, recycle, redesign, remanufacture, and recycle), which essentially aim to reduce waste and invest waste in ways that enhance manufacturing sustainability.

A study by Garrido Hidalgo et al. (2019) highlighted the growing need for effective management of recovered materials. It demonstrated the need for more sophisticated ICT-based solutions to track and control these materials. IoT-managed network technologies can address these issues. His studies suggest a system of full RSC management (R-SCM) that incorporates IoT communication standards and enables cloud-based monitoring of electrical and electronic waste inventory using embedded sensors. The study employed a quantitative research method by designing an IoT-based system for integration. This was supported by a practical analysis using quantifiable data to assess the system's overall performance. Therefore, the researcher's work is a step toward the transition to electronic reverse supply chains through the integration of I4.0 technologies. The paper presents a sound theoretical model, supported by a case study, and adopts an empirical, scientific perspective. It is, however, neither comprehensive nor broadly scoped.

Furthermore, as demonstrated by Pourmahdi et al. (2021), Industry 4.0 is a complex technology, and developing nations will struggle to adapt to it and transition to more sustainable manufacturing methods. Their research concentrated on steel manufacturing plants, where steel is a vital factor in the industry's development and can be recycled extensively, thereby increasing the importance of RSCs. Pourmahdi et al. (2021) identify barriers to the adoption of Industry 4.0 and reverse logistics.

Additionally, Mohajeri et al. (2021) propose an innovative solution for managing food waste by integrating Industry 4.0 technologies into the reverse supply chain. The study aims to address food waste management issues at the consumer level, making the process more sustainable and efficient. It offers a practical contribution by introducing advanced technologies, including the Internet of Things, artificial intelligence, and big data, into reverse supply chains, enabling real-time integration and monitoring of food waste management. The paper also presents a small, domestic recycling machine for household waste that converts food waste into compost, reducing waste in line with circular economy principles. The study uses a multi-stage fuzzy model of the reverse supply chain.

The study by Garrido Hidalgo et al. (2019) addressed a research gap in the treatment of electrical waste, utilising Industry 4.0 technologies to track the recovery of end-of-life materials through reverse

supply chain management. The study by Mohajeri et al. (2021) also proposed a solution for waste treatment by developing a machine for recycling household waste.

Studies by Garrido-Hidalgo et al. (2019), Mohajeri et al. (2021), and Bourmahdi et al. (2021) specifically examine the development of reverse supply chain management frameworks in the context of Industry 4.0 technologies. Although each study focuses on a different industrial sector, they share a common theme: Industry 4.0 technologies, particularly the Internet of Things (IoT), cyber-physical systems, and the smart factory, redefine traditional reverse supply chain processes. Their work marks the initial efforts to modernise traditional reverse supply chain activities. Building on previous research, our study will propose an approach to developing reverse supply chain activities based on contemporary perspectives to improve manufacturing sustainability.

Studies, in particular, highlight the multifaceted aspects of integrating Industry 4.0 technologies and reverse supply chains. This highlights the urgent need not only for technological solutions but also for strategic frameworks that foster adaptability and address the challenges that impede integration, despite the potential of such solutions to support the integration of Industry 4.0 technologies and reverse supply chains. Therefore, new mechanisms must be explored using contemporary methodologies to enhance their integration and promote manufacturing sustainability.

3.6.1.1.2 Reverse supply chain alliances in I4.0 and manufacturing:

Reverse supply chain alliances are agreements or contracts that industrial companies establish with secondary parties to manage product collection and recovery through mechanisms specifically designed for this purpose (Sheu & Gao, 2014).

The following table presents reverse supply chain alliances in Industry 4.0 and manufacturing contexts, demonstrating optimal contracting mechanisms with secondary parties to support recovery operations.

Table 3- 4 Reverse supply chain alliances in I4.0 and manufacturing:

Authors	Objectives	importance	techniques of integration	solution	application of the study
Sheu & Gao, 2014	seeks to find equilibrium negotiation solutions	Profit improvement from recycled products.	bargaining power	The RSCs provider alliance increases the bargaining power of the RSCs	manufacturers in Taiwan
Sun et al., 2019	new products returned	Increasing profit from RSCs	mathematical modelling	Revenues rise as agents' effort rises	Two competing dealers

Table 3-4 presents two contributions by researchers (Sheu & Gao, 2014) and (Sun et al., 2019) on reverse supply chain alliances with secondary suppliers to manage the recovery of expired materials

and new goods. The researcher presented a brief analysis of both studies, including the most critical aspects of the research, as follows:

Sheu & Gao (2014) examined interactions between competing electronics manufacturers and reverse logistics service providers. Using a three-stage approach based on two scenarios, one involved a reverse alliance with logistics service providers, while the other involved no reverse partnership. The study also used mixed-methods research to gather and analyse data. It showed how bargaining power influences negotiations between manufacturers and reverse logistics service providers in reverse supply chains. The findings suggest that an alliance with a reverse logistics service provider increases the provider's bargaining power and warrants further study. The research focuses on the decision-making processes of competing retailers in reverse supply chains. It analyses how the bargaining power of retailers and manufacturers affects retailers' decisions to cooperate and the resulting competitive dynamics. The paper offers a framework for evaluating whether forming a retail alliance is strategically viable. It also helps understand vertical and horizontal relationships in reverse supply chains, and when strategic cooperation among retailers is more advantageous than direct competition. Overall, the study fills a research gap by examining how competitive strategies interact in material recovery within reverse supply chains.

Sun et al. (2019) examined, using mathematical modelling, how manufacturers can motivate their dealers to handle and sell newly returned products. The study relied on each manufacturer contracting with two dealers to return materials. By considering dealers' rationality, the study designed optimal incentive contracts that account for dealers' efforts in handling cases under the company's approved return policy. In addition, creating competition among dealers intensifies their efforts. In contrast, each dealer's revenue share from the manufacturer declines, and the risks, incentives, and total agency costs across the entire supply chain tend to decrease. The dealers' revenue share is inversely related to return uncertainty. That is, the fewer new materials that the dealer has, the higher his revenue. The study's results showed that dealers, through their collective efforts, helped reduce material returns. The research issue addressed by Sun et al. (2019) concerns the correlation between manufacturers (agents) and retailers (agents). The manufacturer uses competitors in other retail channels to recall its products. This adds complexity to the process, as the manufacturer cannot directly observe the number or quality of returns. The study contributes by developing a mathematical model of dynamics under asymmetric conditions and proposing contractual mechanisms to improve the performance of reverse supply chains. The study addresses a research gap in multi-agent competitive environments by modelling agents' strategic behaviours under information asymmetry.

Studies by Sun et al. (2019) and Sheu & Gao (2014) converge in exploring the performance of reverse supply chains under competitive conditions. However, each study approaches the topic from different

perspectives. The study by Sun et al. (2019) focuses on the principle of contractual compatibility, which is ideal when a company faces challenges in monitoring and implementing its commitments. Meanwhile, the study by Sheu & Gao (2014) focuses on strategic alliances, which are a beneficial option when a company can negotiate in parallel while pursuing cooperation.

3.6.1.1.3 Studies of RSCs activities based on I4.0 technology:

Previous researchers have made many contributions to the support of Industry 4.0 technologies in reverse supply chains. Within the context of the circular economy, the researcher has identified a group of these studies to present and analyse, as they are most in line with the directions of our current research. Table 3-5 summarises the studies.

Table 3- 5 Studies of RSCs activities based on I4.0 technology.

Authors	Objectives	importance	techniques of integration	solution	application of the study
Gu & Tagaras, 2014	sorting the collected, used products	Remanufacturing	The collector and the remanufacturer	Comparison between assembly and remanufacturing	China
Abdul Hamid et al., 2020	Investigate how to address Industry 4.0 challenges in the circular economy.	Address challenges as a basis for operational decision-making.	The fuzzy Delphi Method is applied to address the qualitative information and translate the linguistic preferences.	Identification of 18 essential challenges in I4.0 in the CE.	Malaysian palm oil industry
Zhou et al., 2020	Limitations the most suitable path for technological progress and structural change	Identify the joint effects of energy- and environment- biased technological progress.	The integration of the CE and Industry 4.0.	Technological and backstop technological progress are the main drivers of sustainable economic growth.	China
Yadav et al. (2020).	Explore the enablers that facilitate the adoption of sustainability.	Explore the enablers that facilitate the adoption of sustainability.	The RBWM method determines the intensity of each enabler's effect.	Managerial, economic, and environmental enablers play a role in the adoption of sustainability.	Indian
Saniuk et al., 2021	Identify the critical knowledge and skills employees must possess to implement the I4.0 concept.	Human Resource Development in Industry 4.0	Adequate education, learning and training.	This is particularly important for adapting the employee training system and the student education process.	Poland

Authors	Objectives	importance	techniques of integration	solution	application of the study
Mastos et al. (2021)	Industry 4.0 waste-to-energy solution is developed	A circular approach develops in the supply chain.	Resolve model	Redesigning SC for a CE using I4.0 technologies can enable circular supply chain management.	European Connected Factory Platform for Agile Manufacturing
Rajput & Singh, 2021	Integrate the CE and RL into the supply chain to promote environmental and economic growth.	Lowering costs and maximising product end-of-life.	(MILP) model	The proposed MILP model jointly integrates the CE and RL network problems in Industry 4.0.	UK, India
Krstić et al., 2022	By assessing their applicability, determine which I4.0 technologies are most suitable for the RL sectors.	Proper performance of reverse logistics (RL) activities.	The best-worst-best method (BWM) to determine the weights of the criteria in a new multi-criteria decision-making model (MCDM)	Mobile e-markets, cloud computing, and the Internet of Things are the most valuable technologies.	Turkey, the United Kingdom, the USA, and China

After reviewing the eight contributions in the table above, the researcher analysed the studies individually to clarify the researchers' orientations, methodologies, and contexts related to the research problem, objectives, and significance. Below is a summary of each study.

Gu & Tagaras (2014) argue that the reverse supply chain within companies comprises two distinct activities: assembly and remanufacturing. Each company is responsible for its assigned work and for transferring materials to other companies through centralised decision-making, comparing optimal assembly quantities for the reverse supply chain. The research problem in this study is to maximise material recovery, regardless of sorting accuracy, to enhance a greener environment. The study proposes investing in the Internet of Things to enable rapid assessment and sorting of recovered materials and to indicate their remanufacturing potential. Using the product code, the Internet of Things can identify radio frequencies, enable real-time monitoring of all forward, and reverse logistics links. This technology will enable supply chain assessors to quickly and cost-effectively evaluate the quality of recovered products.

The essence of the study lies in addressing a research gap arising from the study problem, namely, the mechanisms for collecting as much recovered material as possible to promote a green environment. The study examined the potential of investing in Industry 4.0 technology (the Internet of Things) to sort and evaluate recovered materials and demonstrate their recyclability. Thus, this study can be

classified as one of the researchers' contributions to reducing waste and investing it in ways that enhance manufacturing sustainability and environmental conservation.

Abdul Hamid et al. (2020) present a model to understand the challenges facing Industry 4.0 and its integration with the circular economy in the palm oil industry. The Fuzzy Delphi method was used to analyse qualitative data. The study identified 18 of the most significant challenges facing Industry 4.0 in linking with the circular economy. The main issues include insufficient investment in virtualising automation systems in Industry 4.0, poor process design, and unstable communication among companies. The findings highlight issues related to Industry 4.0 and the circular economy, ways to address these challenges as a basis for informed operational decisions, and the potential to utilise Industry 4.0 technologies to support the circular economy. The study also notes limitations and suggests directions for future research to tackle the identified challenges.

By conducting a more in-depth analysis of the research gap, the study developed a model to understand better the challenges hindering the integration of Industry 4.0 and circular practices. It also aimed to create a cohesive model that facilitates the combination of both, leading to benefits such as increased manufacturing sustainability and improved waste management. Despite its thoroughness, the study lacks empirical analysis, which may limit its implementation. However, the paper examines the potential of Industry 4.0 technologies to facilitate the circular economy. In addition, it talks about limitations and future research directions.

Furthermore, Zhou et al. (2020) discuss integrating the circular economy (CE) with Industry 4.0 to achieve sustainability by adopting Industry 4.0 technologies that enable smart manufacturing. This enables a transition through the most suitable channels of technological advancement and structural change to enhance economic growth, depending on China's business environment. The researcher used a quantitative approach for data collection and analysis, in line with the research hypotheses and objectives. Additionally, the research problem focuses on the optimal investment in Industry 4.0 technologies to support the CE's transition to a circular economy aligned with sustainability goals in manufacturing. Abdul-Hamid et al. (2020) align their study closely with this work, as both papers analyse the mechanisms for integrating Industry 4.0 technologies to support the circular economy and share visions for improving sustainability and economic growth.

Within the framework of a more analytical treatment of the research gap. The article by Abdel Hamid et al. (2020) aimed to identify the mechanisms of connecting Industry 4.0 with the circular economy by creating a model that would help comprehend the challenges that impede the integration of both of them, minimise the challenges, and construct an integration model between them to obtain multiple economic, social, and environmental benefits. Similarly, Zhou et al. (2020) investigated the application of a model for investing in smart manufacturing technologies to support a successful transition to a

circular economy. It is important to note that the two studies focused on investment in Industry 4.0 technology to promote recycling and optimise the use of raw materials, ensuring the sustainability of manufacturing and the transition to the circular economy.

Yadav et al. (2020) examine the contributions of Industry 4.0 technologies, including the Internet of Things, Big Data Analytics, Blockchain, and Machine Learning, to manufacturing and to manufacturing sustainability. The study will provide a roadmap for enhancing the implementation of sustainability initiatives in manufacturing organisations in the developing world by adopting Industry 4.0 technologies. This paper employed a mixed-methods approach to gather and analyse data, using a five-point Likert scale to assess the research sample. This paper identifies the drivers of reverse logistics and the circular economy that influence manufacturing sustainability within Industry 4.0. The study's findings revealed that administrative, economic, and environmental enabling factors are significant determinants of sustainability adoption. This study may be useful to specialists in this domain.

Additionally, the research by Saniuk et al. (2021) differs from prior studies by evaluating the skills and knowledge required of workers in Industry 4.0. The technology is applicable across numerous sectors, including those related to customer needs. Given this technology's flexibility in responding to customer requirements, it requires qualified support staff. These qualifications were identified through an analysis of prior literature and surveys conducted within specific industrial companies. In addition, the study employed a mixed-methods approach to collecting and analysing research data, as well as conducting personal interviews via electronic communication. The study results indicated the need to update employee training systems and lay the foundation for learning.

Furthermore, Mastos et al. (2021) explore the potential of circular economy models and solutions that use Industry 4.0 technologies to transform end-of-life products into new, multi-use items. The study develops and tests solutions for using waste and converting it into energy within Industry 4.0, demonstrating their application through a case study applied to the supply chain to assess the performance of circular supply chain management (CSCM). The researcher used qualitative methods in the case study. The results indicate that redesigning supply chains for the circular economy with Industry 4.0 technologies can enable circular supply chain management to provide clear benefits by applying the proposed solution across the six dimensions of the circular economy (renewal, sharing, optimisation, replication, virtualisation, and exchange) based on the Resolve model. Although the study offers a practical example of Industry 4.0 in reverse supply chains, its generalisability is limited because it relies on a single case study. It also has not been evaluated over the long term and cannot be extended to different industrial sectors.

Moreover, Rajput & Singh (2021) showed that integrating circular economy and reverse logistics services into the existing supply chain is crucial for enhancing environmental sustainability and economic growth. The study employs a Mixed-Integer Linear Programming (MILP) model to achieve a circular economy within Industry 4.0, leveraging reverse logistics and IoT sensors that capture real-time production data to improve transparency and accuracy. The research will lower costs and extend product shelf life, developing an Industry 4.0 facility with a circular economy and reverse logistics network.

Krstić et al. (2022) discuss the circular economy (CE), which maximises the value of goods, components, and materials. The study highlights the importance of effective reverse logistics (RL) operations. Traditional RL methods are inadequate for modern supply chains and require Industry 4.0 technologies to improve efficiency. This paper assesses the suitability of I4.0 technologies for RL industries. A new multi-criteria decision-making (MCDM) model was developed using the best-worst method (BWM). Technologies were classified with the COBRA method, which was also validated. Results show mobile e-markets, cloud computing, and IoT are the most valuable technologies, driving machine learning and education programs to realise their full benefits. Though the COBRA methodology for evaluating Industry 4.0 in reverse logistics is outlined, it remains theoretical and untested across industries.

3.6.1.1.4 Comparative Analysis Matrix:

To shed more light on a set of selected previous studies that focus on the integration of Industry 4.0 technology with reverse supply chains within the circular economy framework. The researcher identified a set of studies that address the topic from several perspectives, including specialisation, geography, and operations, and compared them, focusing on aspects such as the research problem, research contribution, and research gap.

Table 3- 6 Comparison matrix:

Study	Research Problem	Research Contribution	Research Gap
Abdul-Hamid et al. (2020)	Challenges of Implementing Industry 4.0 Technology in the Context of the Circular Economy in the Malaysian Palm Oil Industry.	Highlighting specific technological and regulatory barriers, it provides an analysis in the context of developing countries.	Limited studies address strategies for overcoming barriers to the integration of I4.0 technology and the circular economy
Zhou et al. (2020)	Exploring the key drivers of China's economic development in the context	Providing a comprehensive economic vision and utilising empirical data to	There is a limited number of studies that address the impacts or partial factors in

Study	Research Problem	Research Contribution	Research Gap
	of I4.0 and the Circular Economy.	distinguish between the effects of different development forces.	implementing the principles of I4.0 and the circular economy.
Mastos et al. (2021)	How to effectively implement Industry 4.0 solutions in reverse supply chain management.	Develop and optimise the operation of a practical application that integrates the Internet of Things, blockchain, and RSC.	A comprehensive presentation of an I4.0-based platform designed to enhance transparency, traceability, and sustainable integration with RSCs.
Krstić et al. (2022)	Demonstrates the feasibility and effectiveness of Industry 4.0 technology in the context of reverse logistics.	Introducing the Cobra methodology for multi-criteria decision making to demonstrate the feasibility of implementing the technology.	Lack of studies addressing the systematic evaluation of Industry 4.0 technologies in the context of reverse logistics.

Each study in Table 3-6 identifies and addresses a specific challenge related to the research gap in integrating Industry 4.0 technologies into reverse supply chains within the circular economy framework. Abdul Hamid et al. (2020) study focuses on the challenges of integrating Industry 4.0 technologies and RSCs in the Malaysian palm oil industry, with an emphasis on structural and organisational barriers. Although the findings provided valuable contextual information relevant to developing countries, the analysis was primarily descriptive and further sector-focused, with very limited consideration of mechanisms for organisational integration or sustainability-driven RSCs activities. The study also does not explore how digital technologies could be used to facilitate customer-oriented processes or ethical manufacturing elements in reverse systems. As a result, there is limited knowledge about the strategic adoption of I4.0 practices within current RSCs activities. Zhou et al. (2020) adopt a comprehensive economic perspective to examine whether technological innovation or structural change is the primary driver of economic development in China under Industry 4.0. The study offered a wide-ranging overview of macroeconomic data-supported indicators; its main focus was national economic development rather than sustainability practices within organisations or supply chains. RSCs activities, customer integration, manufacturing ethics, and resource recovery processes were also given less attention in the research conducted. As a result, there remains little literature explaining how Industry 4.0 affects environmental change and firm performance. Industry 4.0 cultures create opportunities for sustainability-oriented RSCs at both the operational and organisational levels. Mastos et al. (2021) shift the focus to the reverse supply chain level, exploring the potential integration of Industry 4.0 technologies, such as the Internet of Things and blockchain. Despite this practical contribution, the study mainly emphasised technological integration and operational efficiency without providing a comprehensive theoretical explanation of how these

technologies contribute to scope sustainability objectives. Moreover, customer feedback and recycling were not examined as strategic mediating mechanisms within the relationship between I4.0 technologies and RSCs activities.

Kristic et al. (2022) examine reverse logistics and assess the appropriateness of each Industry 4.0 technology based on its impact on reverse logistics. A structured framework is provided to assist in decision-making. The study, however, focused mainly on technical and operational assessments of reverse logistics processes, without a clear distinction between RSCs activities in general and those undertaken under the full umbrella of reverse logistics. Further, theoretical insights into sustainability-specific dimensions such as customer responsiveness, the rational use of raw materials, and ethical manufacturing were also minimal. As a result, previous research has not advanced comprehensive frameworks to explain how I4.0 technologies expand the contemporary vision of RSCs activities beyond mere reverse logistics functions. Regarding their research contributions, the selected studies employ a wide range of empirical approaches to methodological innovation. The contextual barriers to integrating Industry 4.0 technologies into reverse supply chains are particularly salient in developing countries, as noted by Abdel Hamid et al. (2020). The study by Zhou et al. (2020) is added to the analysis of macro-level economic drivers, thereby further informing the discussion of policies and strategies. Another practical application of Industry 4.0 technologies in reverse supply chains, as reported by Mastos et al. (2021), serves as a concrete illustration of their potential. The study by Krstic et al. (2022) is part of a new decision-making process (COBRA) that helps to evaluate the truthfulness of judgments when adopting the technology.

Within the framework of the research gap. The scarcity of literature offering in-depth insight into the practical impediments to the introduction of Industry 4.0 technologies in the transition to the circular economy, specifically in the palm oil industry. The study by Abdul-Hamid et al. (2020) addressed a research gap by identifying key issues in the adoption of Industry 4.0 technologies in Malaysia's palm oil industry, thereby advancing understanding of technology adoption and contributing to the body of knowledge on the topic. Research on the relative effects of technological innovation versus structural economic change in fostering sustainable development in Industry 4.0 and the circular economy remains limited, particularly in the Chinese manufacturing sector. Thus, Zhou et al. (2020) have filled this knowledge gap by conducting an empirical investigation into the drivers of Chinese economic development, grounded in a deep understanding of the focus of innovation policies. Moreover, because few studies investigate the integration of Industry 4.0 technologies, i.e., the Internet of Things, blockchain, and big data, into the reverse supply chain; most research has focused on these technologies separately. At times, it has focused on linear rather than cyclical supply chains.

Mastos et al. (2021) addressed this research gap by proposing and illustrating a technical platform based on Industry 4.0 technologies to promote transparency through continuous traceability, enhance sustainability in reverse supply chains, and support the digital transformation of the circular economy. Moreover, as systematic studies comparing Industry 4.0 technologies and their implementation with reverse logistics are absent, prior research has examined only single-technology Industry 4.0 approaches, which have not provided a systematic decision-making framework. Thus, Krstic et al. (2022) used the COBRA method to address this gap by assessing and categorising the potential applications of reverse logistics in Industry 4.0 technologies, defining their priorities, and evaluating their effects.

In general, prior literature has focused primarily on operational efficiency, technological applications, and macro-level sustainability perspectives, with limited attention to the integrated roles of customer feedback, recycling, resource utilisation efficiency, and ethical manufacturing within digital RSCs. These limitations justify our research vision, which examine to develop a comprehensive framework that explains how Industry 4.0 technology supports the contemporary vision of RSCs activities through strategic mediation factors and sustainability-oriented organisational practices.

3.6.1.2 A group of studies that include a contemporary vision of RSCs activities in I4.0:

3.6.1.2.1 Studies of contemporary RSC activities (rational use of raw materials) and I4.0 technology:

Industry 4.0 technology promotes the efficient use of raw materials. Improving process efficiency and resource utilisation cuts down waste. Using the Internet of Things, advanced sensors, and real-time data analysis, manufacturers can easily monitor material flow (Stock & Seliger, 2016). Additionally, cyber-physical systems in the smart factory improve the flexibility to adjust production processes, thereby reducing overconsumption and material waste, aligning with the principles of mass customisation and the circular economy (Bagh et al., 2021). Moreover, simulation and digital twin systems enable virtual process prototypes, decreasing the need for physical experiments and rationalising resource use (Campbell et al., 2018).

The literature review showed that Industry 4.0 technologies could improve processes, reduce raw material consumption, and rationalise resource use. Previous studies have also shown several other advantages of Industry 4.0, including enhanced manufacturing processes and environmental preservation. The following table shows some contributions by researchers in this field.

Table 3- 7 Studies of contemporary RSCs activities (rational use of raw materials) and I4.0 technology.

Authors	Objectives	importance	techniques of integration	solution	application of the study
Bag et al., 2023	Shows the role of I4.0 technology in achieving sustainability in SC operations.	Show the role of I4.0 in enhanced operational capabilities.	Organisation Information Processing Theory (OIPT)	adopting Industry 4.0 technology to improve resource consumption rates (rationalisation of raw materials use)	South African
Jena et al., 2020	Investing in Industry 4.0 technologies to reduce and rationalise the consumption of raw materials	Reduce material waste and save energy.	Case Study, Using Smart Factory Technology to Measure Rationalisation	Vertical integration of I4.0 technology reduces raw material consumption and saves energy.	Cement factory in Jharkhand, India

In Table 3-7, two studies (Bag et al., 2023) and (Jena et al., 2020) include a statement on the role of Industry 4.0 in rationalising the consumption of raw materials. Given the topic's relevance to our current research, the researcher conducted a simplified analysis of both studies, as shown below.

Bag et al. (2023) examine the role of Industry 4.0 technology in achieving sustainability in supply chain operations. Organisation Information Processing Theory (OIPT) suggests that Industry 4.0 tools should enhance operational capabilities. South African manufacturers were surveyed, and 200 responses were received. Partial Least Squares Structural Equation Modelling (PLS-SEM) is used to test the conceptual model. The study adopted a mixed-methods approach and used a five-point questionnaire to collect data from the research sample. The study results showed that adopting Industry 4.0 technology improves resource utilisation (rationalisation of raw material use), reduces waste and pollution, enhances manufacturing processes, reduces raw material consumption, saves energy, and contributes to sustainable manufacturing operations.

The research gap in the study by Bag et al. (2023) is the need to rationalise the use of raw materials, minimise waste, and ensure sustainable manufacturing. The research aims to demonstrate that Industry 4.0 technology can facilitate supply chains that improve operational performance and manufacturing sustainability.

Jena et al. (2020) mention the use of cyber-physical systems, also known as Industry 4.0. This paper demonstrates the architecture of a smart factory by virtualising functions, including industrial networks, cloud, supervisory control stations, and production, maintenance, and energy consumption. The study employed a quantitative approach to data collection and analysis. The experiment was conducted in a factory to optimise resource use and reduce waste, thereby enhancing sustainability in the manufacturing process. In addition, this self-organising system will help the factory achieve greater

efficiency, fewer environmental impacts, and other essential performance measures. A case study at a cement factory was used to evaluate the model's results. It is clear that applying the sustainable manufacturing system model improved critical environmental performance indicators, such as specific energy consumption, carbon footprint, specific water consumption, and process waste, and increased productivity.

Table 3- 8 Synthesis matrix

Aspect	Bag et al. (2023)	Jena et al. (2020)
Research Problem	Explores how I4.0 technologies can enhance the circular economy and sustainability.	How can I4.0 technology be leveraged to enhance sustainable manufacturing operations?
Research Contribution	Present a comprehensive conceptual framework for integrating I4.0 technologies (IoT, Big Data analytics) with circular economy strategies to enhance sustainability.	A systematic literature review, specifically on I4.0 technology and its potential effect on green and lean manufacturing.
Gap in research	There are limited studies linking I4.0 to the circular economy and sustainable supply chains, particularly with empirical validation.	There is a lack of a comprehensive view of the I4.0 contribution to sustainable manufacturing, and research in this area is fragmented.

In a comparative analysis, the two studies explore the role of Industry 4.0 technologies in making manufacturing more sustainable, despite differences in focus and scope.

The research problem of the Bag et al. (2023) study was the strategic implementation of Industry 4.0 technologies to facilitate the circular economy practices. Their work has highlighted the need to integrate digital technologies to facilitate sustainable reverse supply chains. On the contrary, the study by Jena et al. (2020) was aimed at discussing the contribution of Industry 4.0 to the idea of sustainable manufacturing, which involves better ways of producing items in order to decrease the negative effects on the environment and justify the waste of raw materials.

In their research contribution, Bag et al. (2023) proposed a methodological framework that connects Industry 4.0 tools such as the Internet of Things, cyber-physical systems, and big data analytics to the circular economy strategy and demonstrated their ability to deliver sustainable performance. Similarly, Jena et al. (2020) presented a systematic literature review to categorise Industry 4.0 technologies and demonstrate their role in green and lean manufacturing practices, a highly valuable contribution for future studies.

Regarding the research gap, Bag et al. (2023) found a lack of empirical studies on the support of Industry 4.0 technologies for the circular economy, underscoring the need for further research through case studies and practical applications. The assessment of current studies on Industry 4.0 and sustainable manufacturing presented by Jena et al. (2020) also highlights fragmentation in the literature, as it lacks a comprehensive study that integrates technological, environmental, and operational aspects.

3.6.1.2.2 Studies of contemporary RSCs activities (Manufacturing Ethics) and I4.0 technology:

We built upon previous researchers' contributions when reviewing the existing literature. Further studies on Industry 4.0 technologies are needed to support manufacturing ethics, despite the field's importance. In recent years, rapid technological advances in the industry and the increasing diversity of products and their customisations, in both quantity and quality, have created a need to keep pace with standards that govern these areas. Previously, in the context of our current research, the term "manufacturing ethics" referred to producers' responsibility to provide goods and services that meet customers' actual needs in terms of quantity and quality, rather than burdening them with products that do not benefit them. Additionally, producers have responsibilities toward the environment and social welfare. Recently, the term "manufacturing ethics" has emerged as a contemporary concept reflecting the acceleration of technological change. This concept includes protecting and preserving customer data across various applications and fields, as well as imposing restrictions on modern technologies that could be used for illicit purposes. The following table shows the contributions of two researchers.

Table 3- 9 Studies of contemporary RSCs activities (Manufacturing Ethics) and I4.0 technology.

Authors	Objectives	importance	techniques of integration	solution	application of the study
Kumar et al., 2020	I4.0 technologies to support ethical and sustainable operations in the manufacturing	Analyse challenges faced by I4.0 technologies in supporting ethical manufacturing and sustainable operations in SMEs.	The DEMATEL approach was used as the research stream.	Identify challenges and provide recommendations to enhance manufacturing ethics within the context of Industry 4.0.	India
Anderson & Fort (2024).	Integrating AI services into work environments in heavy industry.	The AI ethics approach developed for the research included an integrated ethical analysis of work contexts and design solutions.	AI techniques according to pre-prepared questions for research purposes	Providing recommendations and proposals for each case and monitoring them	France, Belgium, and Germany

The study by Kumar et al (2020) investigated the potential of Industry 4.0 technologies to support ethical and sustainable operations in manufacturing. Studies in this area remain limited for SMEs. Therefore, the researchers analysed the challenges posed by Industry 4.0 technologies to the support of ethical manufacturing and sustainable operations in SMEs. Fifteen critical challenges were identified through a literature review. In addition, to further categorise these challenges, the DEMATEL approach was employed within the research stream. The study employed quantitative methods to collect and analyse data. The study results showed that manufacturers' lack of motivation to adopt ethical and sustainable operations was the most significant challenge. Other critical challenges include SMEs' lack of long-term planning when adopting Industry 4.0 technologies for production to address ethical and sustainability issues in manufacturing; limited awareness of Industry 4.0 contributions to manufacturing ethics; and the high upfront costs of these technologies required to support sustainable manufacturing ethics.

Anderson & Fort (2024) introduce a methodology used in the European AI-PROFICIENT Horizon 2020 project to evaluate the integration of the ethical dimension into industry. The project was a three-year collaboration involving a university partner and industry and technical partners. The study adopted an AI ethics approach specifically developed for the research, which included an integrated ethical analysis of work environments and design solutions, along with targeted, nuanced ethical recommendations for partners who participated in ongoing evaluations. The results were categorised to make them easier to apply within a specific part of the broader industry. The researcher also highlighted the lack of literature on this topic, emphasising the need for further research. Additionally, the study used a mixed-methods approach, combining quantitative data analysis with expert opinions to support the findings.

3.6.1.2.3 Research of contemporary vision (Customer preferences) and I4.0 technology:

Cyber-physical systems, Internet of Things, big data analytics, and the smart factory are part of Industry 4.0 technologies that are radically transforming the manufacturing environment. Using these technologies, companies are better positioned to respond more quickly to customer preferences. With the help of real-time collection and analysis of customer data, companies are now capable of creating products in ways never seen before, custom-made to meet customers' needs and desires (Kagermann et al., 2013; Liao et al., 2017). Moreover, the mass production is being replaced with mass customisation, which is becoming possible through advanced analytics and digital integration and improves customer satisfaction and competitive advantage (Frank et al., 2019). Moreover, big data analysis, including predictive analytics, supports proactive decisions in product design and customer

information management by leveraging customer responses to better align products with evolving consumer preferences (Xu et al., 2018).

Table 3- 10 Studies of contemporary RSCs activities (Customer preferences) and I4.0 technology.

Authors	Objectives	importance	techniques of integration	solution	application of the study
Silva et al., 2018	Suggest a customer feedback platform for vehicle manufacturing in the context of I4.0, capable of collecting and analysing data through the OBD-II scanner.	Help to manage, prevent, and mitigate various vehicle problems.	OBD-II scanner (on-board diagnostics).	Improve vehicle manufacturing through an efficient electronic reverse-processing chain integrated with Industry 4.0 technologies.	Brazil and Italy
Naeem & Di Maria, 2022	Explore how adopting I4.0 affects customer participation (CP) in the new product development (NPD) process through customer information management.	Leveraging Industry 4.0 technologies in product development through customer involvement.	I4.0 Technology	I4.0 technology has increased customer involvement in the product development process.	Industrial companies in northern Italy
Dev et al., 2020	Examining the extensive reverse logistics simulation that backs up I4.0 virtual factory component.	Linking I4.0 technology, represented by virtual reality, simulation models with the RSC, ERP systems using a modified model.	Simulation, VR	1- Focusing on the cost of socially influenced operations is necessary. 2- The results are context-specific and deserve more detailed analysis.	A refrigerator company is situated in Pondicherry, India.

Silva et al. (2018) highlight the so-called Internet of Intelligent Vehicles (IoIV) as an evolution of the Internet of Things (IoT) applied to the automotive sector. IoIV is closely related to the Industrial Internet of Things (IIoT), a key component of Industry 4.0. Through it, value can be created across the product life cycle, enhancing customer feedback by obtaining information about the product's history. In this way, automatic communication between the vehicle (and its owner) and the manufacturer is facilitated, enabling analyses of vehicle-related data, such as historical driver usage patterns, fuel consumption, and maintenance indicators. Thus allowing the prevention of critical problems and unwanted issues. Therefore, the study aims to propose a customer feedback platform for vehicle manufacturing in the context of Industry 4.0, capable of collecting and analysing data from vehicle sensors via the OBD-II (on-board diagnostics) interface to help manage, prevent, and mitigate various vehicle problems. The study's results, which examined the platform's application in automotive factories in Brazil and Italy, demonstrated its feasibility and potential to enhance the vehicle

manufacturing process through an efficient electronic reverse-processing chain integrated with Industry 4.0 technologies.

Naeem and Di Maria (2022) demonstrated that the application of modern Industry 4.0 technologies has significant potential for product customisation. Therefore, the study examined whether the adoption of Industry 4.0 technologies influences customer participation (CP) in the company's new product development (NPD) process. The research used a mixed design, employing a questionnaire developed for the study and online personal interviews. Data were collected from industrial companies in northern Italy. Additionally, the results showed that companies using more I4.0 technologies enable greater customer participation in product design and production. This positive effect is stronger in product design than in production. It indicates that manufacturers engage in the company's operations by gathering customer feedback and comments, allowing customers to express their preferences in detail and have them effectively met.

Dev et al. (2020) propose developing a roadmap for excellence in sustainable reverse supply chain operations by integrating Industry 4.0 principles with the Resolve model of the circular economy (CE) approach. The relationship between I4.0 and RSCs is examined using a processing model grounded in economic performance across two main dimensions: information exchange with the reverse logistics system and the diffusion of green products in the market. The role of virtual reality technology in Industry 4.0 is explored using a reverse logistics simulation model that incorporates processes such as inventory policy, production planning, and the utilisation of recovered materials for customised manufacturing. The remanufacturing model simulates the trade-off between setup delays and green transportation availability. The research proposes sharing the required information with customers to confirm their actual needs and desires and to achieve them by analysing trade-offs between economic and environmental performance. Therefore, the study demonstrates the potential to integrate Industry 4.0 and sustainable RSCs through advanced technologies, such as augmented reality and a simulation model that connects consumers to products.

Based on a review and classification of previous studies, the researcher aimed to highlight existing knowledge relevant to our research scope. A brief analysis of each study was provided, emphasising its importance, objectives, conceptual frameworks, and methodologies. A simplified overview of each study was also presented, showing a variety of approaches among the researchers. The methodologies used varied, indicating that multiple methods can be applied in this field. Additionally, the research objectives, contributions, and significance differed. Researchers also employed different methods for data collection and analysis. The most common approach was mixed methods, as it was best suited to this type of research. The researcher mainly examined studies on the role of Industry 4.0 technology in supporting reverse supply chain activities and related frameworks. Furthermore, most studies have

addressed gaps in research on the integration of Industry 4.0 technologies, reverse supply chains, sustainability, and waste reduction, all of which are relevant to our current study.

In Chapter 2, we present the background of the research variables and review previous literature. We found that most earlier work on reverse supply chain activities has centred on recycling and material recovery processes that flow from customers to factories. Additionally, integrating Industry 4.0 technologies into reverse supply chain activities remains a challenge. Therefore, our research aims to deepen understanding by exploring how to integrate Industry 4.0 technologies more effectively into reverse supply chain activities. This perspective adopts a contemporary understanding of what can be achieved through reverse supply chains, extending beyond recycling and recovery to include activities that address customer preferences, the rational use of raw materials, and manufacturing ethics. Figure 3-6 illustrates our research vision, which will develop into a conceptual framework to improve sustainable manufacturing and environmental conservation.

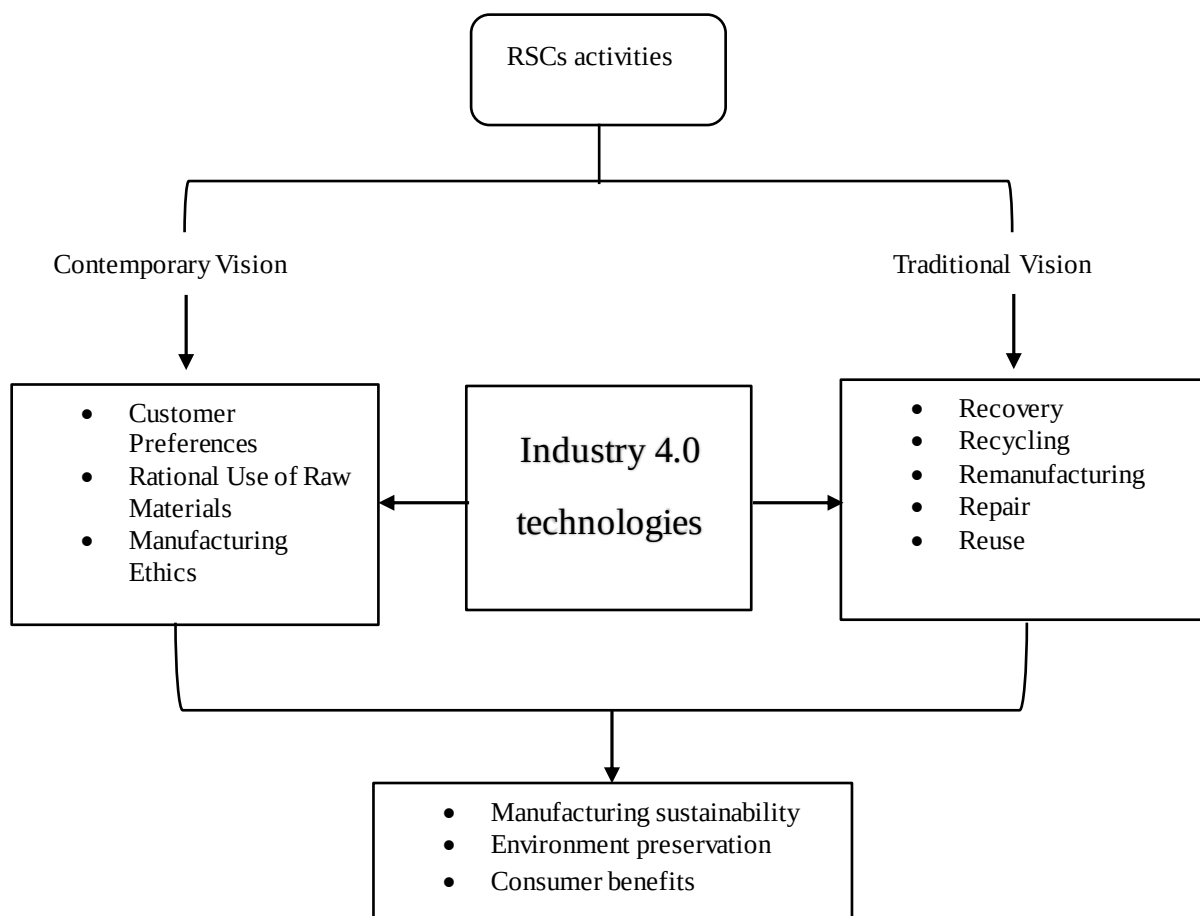


Figure 3- 6 Industry 4.0 technology supports RSCs activities with a contemporary vision (Source: authors).

We examined the integration of Industry 4.0 technology with reverse supply chain activities to further develop the research idea. Previous literature indicates that traditional reverse supply chain activities include collecting products from customers, inspecting them for residual value, and transporting them to a remanufacturing facility (Kushwaha et al., 2020). Additionally, prior literature highlights the potential of supply chain activities to support customer preferences, the rational use of raw materials, and manufacturing ethics, as shown in Tables 3-7, 3-9, and 3-10. Consequently, the researcher created a detailed figure 3-6 that reflects previous contributions, clarifies the integration mechanism, and demonstrates its benefits. Reverse supply chain activities, both traditional recycling and contemporary reverse supply chain activities are linked to customer preferences, the rational use of raw materials, and manufacturing ethics, and are integrated with Industry 4.0 technology. This technology can improve recycling by increasing operational efficiency and flexibility. It also helps fulfil customer preferences and desires through comprehensive customisation enabled by advanced Industry 4.0 technologies, thus increasing the value of products tailored to customer needs. Furthermore, through extensive manufacturing customisation, rationalising the use of raw material use reduces waste and protects the environment. Adopting manufacturing ethics by delivering products that add value to customers while maintaining quality reduces waste and prolongs product lifespan, positively impacting customers, manufacturers, and the environment. The diagram 3-7 illustrates how Industry 4.0 technology supports reverse supply chain activities.

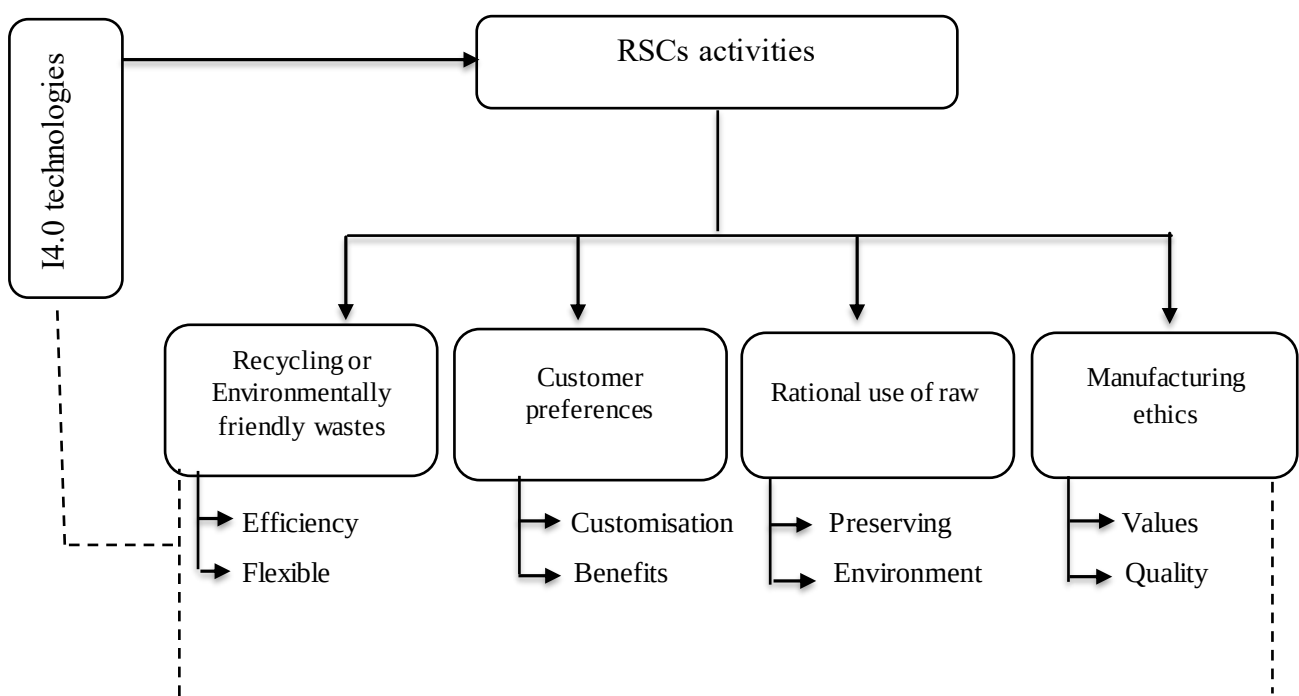


Figure 3- 7 Role of I4.0 technologies in supporting the activities of the RSCs (Source: authors).

The figure 3-7 role Industry 4.0 technologies as key enablers of advanced recycling within reverse supply chain activities. Through digital integration, real-time data analytics, automation, and intelligent monitoring, these technologies facilitate environmentally responsible disposal and resource recovery operations. Simultaneously, they enhance operational efficiency and system flexibility, enabling adaptive production and customised responses to evolving customer preferences. By supporting the rational use and conservation of raw materials, Industry 4.0 contributes to environmentally sustainable practices, ethical manufacturing standards, and value-driven quality enhancement, thereby reinforcing both economic and ecological performance within reverse supply chain activities.

A comprehensive review of the relevant literature establishes the theoretical basis of our study. The research framework is based on the development and expansion of two complementary theories: Sustainability-Oriented Innovation (SOI) and Resource Orchestration Theory (ROT). Drawing on SOI, our research explores the direct relationship between Industry 4.0 technologies and reverse supply chain activities, focusing on how stakeholder-oriented technological integration can promote sustainable operational practices. Furthermore, given previous studies indicating the crucial roles of customer feedback and recycling in reverse supply chains, our research draws on resource coordination theory to examine the indirect relationships between the two variables, with customer feedback and recycling serving as mediating variables.

Through this integration, our research vision develops a comprehensive conceptual framework that not only explores the mechanisms linking Industry 4.0 technology and reverse supply chain activities but also identifies the factors that most effectively enhance this integration. This theoretically coherent context ensures methodological clarity and theoretical consistency, providing a solid foundation for formulating the research questions and hypotheses.

3.7 Concluding remarks:

This chapter provides a focused review of relevant literature, analysing previous studies and highlighting their methodological frameworks and empirical findings. The studies are critiqued, and the strengths and weaknesses of current knowledge are identified. Furthermore, the literature review reveals research gaps and methodological and contextual diversity, necessitating further investigation. By synthesising and comparing available knowledge, this chapter establishes a coherent foundation for our current research and underscores its theoretical and practical contributions. This chapter lays the theoretical groundwork for developing the research's conceptual framework.

Chapter Four

Conceptual Framework and Hypotheses Development

SECTION 1: Conceptual Framework

4.1 Introduction:

The conceptual framework is essential to this research, providing a clear, organised structure for defining research directions and guiding the process. It also helps deepen understanding of the relationships and integration between research variables, supports the hypotheses, and provides a foundation for the research model, allowing the researcher to collect and analyse data efficiently. In Chapter 2 of the thesis, the researcher briefly outlined the main research variables and their sub-dimensions, specifically Industry 4.0 and reverse supply chains. In this chapter, we will focus on establishing the relationships and integration among these concepts, drawing on previous studies. Furthermore, we will clarify the relationships between the variables using a conceptual framework that identifies the main variables, their sub-dimensions, and mediating variables. This framework forms the theoretical basis of the research, providing the necessary foundation for the hypotheses and the model, addressing the research gap, and answering the research questions.

This chapter offers a thorough literature review on the relationship between Industry 4.0 technologies and reverse supply chain activities, examining how these elements can be integrated. The researcher logically presents key points to build a strong theoretical foundation for developing the research's conceptual framework. The research revolves around a central question: "How can Industry 4.0 technologies be effectively integrated into the contemporary vision of RSCs activities?" This question underpins the conceptual framework. The researcher builds on existing knowledge and incorporates current theories to develop this framework. Additionally, the researcher explains the theoretical basis and reasoning behind creating this framework.

The chapter concludes by emphasising the theoretical contributions of the research's conceptual framework, which offers a contemporary vision of RSCs activities. This vision helps address a significant research gap: the rising global waste problem despite ongoing management efforts. To tackle this issue, the researcher adopts a contemporary approach that utilises emerging Industry 4.0 technologies to enhance reverse supply chain activities. Previous studies, both theoretical and empirical, have shown the potential of these technologies to support sustainable manufacturing in reverse supply chains by meeting customer preferences, promoting the efficient use of raw materials, and upholding manufacturing ethics. The study's conceptual framework is grounded in a comprehensive literature review that explores the topic from multiple angles and challenges the mechanisms linking Industry 4.0 technologies to reverse supply chain activities.

Through the development of this conceptual framework, the researcher aims to clarify and expand upon the existing literature and to establish a systematic research plan that enables the empirical testing of theoretical frameworks within a research model.

4.2 Conceptual Framework of relationship and Integration of RSCs activities in I4.0 technology:

In this section, we present a framework of prior scholars' work on the relationship between reverse supply chain activities and Industry 4.0 technologies, as well as their interactions. Building on the modern vision, we also introduce a model of how the researcher perceives the mechanisms that enable industrial technology in reverse supply chain activities. We have thus completed our literature review of the conceptual framework introduced in this chapter.

Implementing Industry 4.0 technologies in reverse supply chains creates a smart, connected, and automated system, thereby boosting efficiency, transparency, and sustainability (Chauhan et al., 2022). This can be combined with IoT to track data, cloud computing to manage data, robotic automation, cyber-physical systems to connect physical components, and big data to support decision-making. These technologies collectively optimise the reverse supply chain, contributing to a more sustainable and circular economy (Lazaroiu et al., 2022).

4.2.1 The connection between reverse supply chain and Industry 4.0:

Companies producing various products are significantly affected by global competition, economic crises, and other factors. This competitive environment compels businesses to identify opportunities within their operations. Hence, Industry 4.0 is one of the means of value addition and waste minimisation. On the other hand, environmental protection and raw material conservation have become urgent in the development of business organisations, prompting academic researchers to study RSCs. Thus, R&D management is driven forward by legal regulation, public pressure, consumer concerns, reputation maintenance, and competitive actions (Li et al., 2021). Additionally, environmental protection, raw material provision, and rational use of natural materials have become urgent in the development of business organisations, encouraging academic researchers to study reverse supply chains (Larsen et al., 2018) & (Li et al., 2021).

In addition, the organisation's culture may support both demanding and flexible processes; therefore, it must adapt to gain a critical understanding of reverse supply chains that support the organisation's operations through evaluation, adaptation, and feedback (Pakdil & Leonard, 2015). In most supply chains, the customer is the last step in the process. On the other hand, returns are part of the reverse supply chain (Covaci, 2019). As a result, reverse supply chains are now a revenue opportunity for

manufacturers (Kovaci, 2019). With this development in the industry, Industry 4.0 technologies will enable independent decision-making and processing algorithms, moving from traditional reverse supply chains to digital reverse supply chains through simulation systems.

Based on the review of previous literature and its analysis by the researcher, the researcher presented a vision of the nature of the relationship between reverse supply chains and Industry 4.0, which reflects the benefits derived from the integration of the relationship between them, as shown in the figure 4-1:

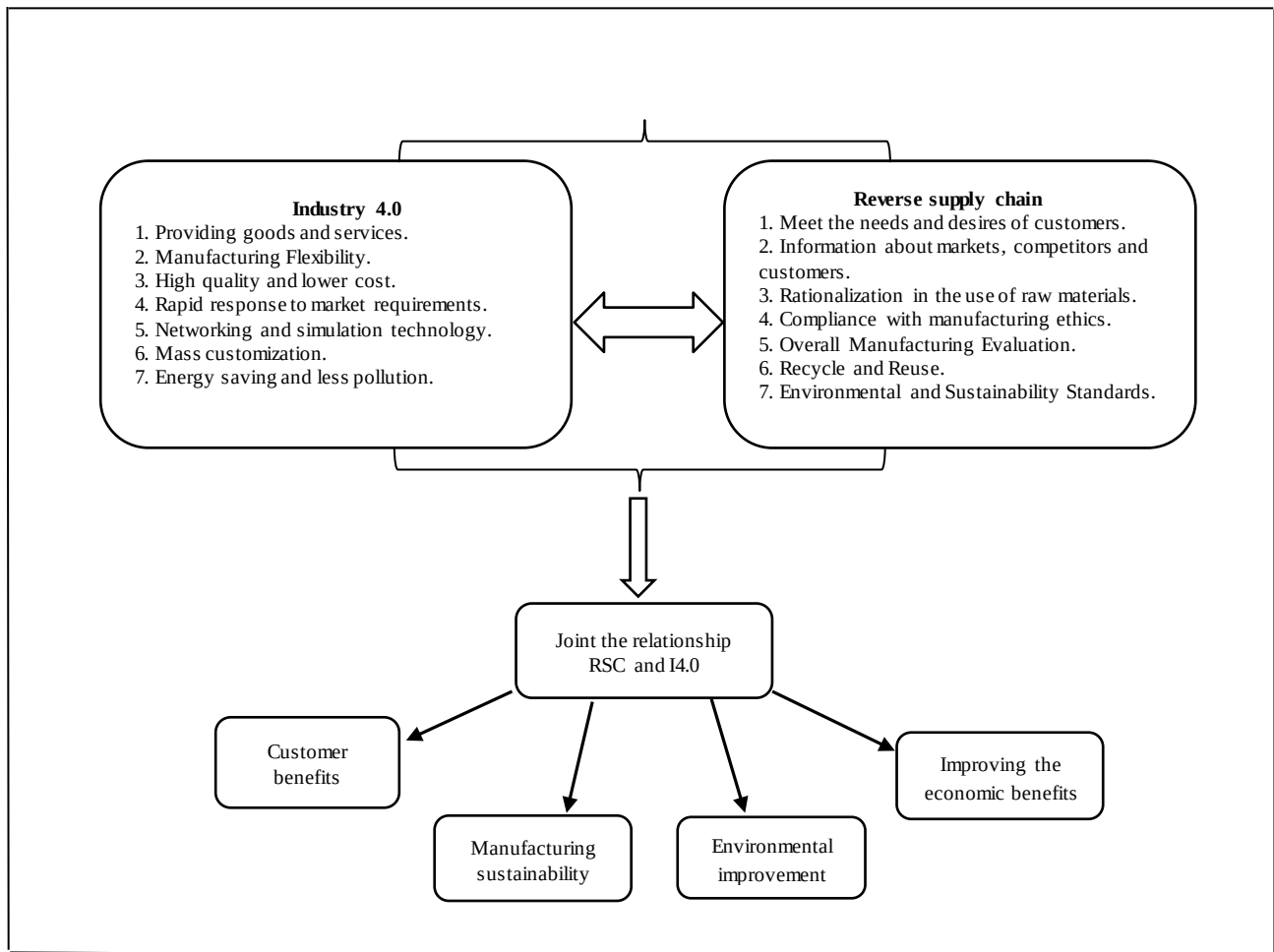


Figure 4 - 1 The relationship between RSC and I4.0 (Source: authors).

The reverse supply chain represents the flow of products and Information from customers to manufacturers. A reverse supply chain is challenging because it must manage every stage at which products are handled and distributed to manufacturers, account for multiple recovery options, and conduct data analysis to benefit customers (Garrido-Hidalgo et al., 2019). From an economic standpoint, the flexible operations enabled by Industry 4.0 technology support long-term development in manufacturing and remanufacturing environments (Dev et al., 2020). Despite the enormous potential of the fourth industrial revolution, it must be continually evaluated and realised. To maximise the benefits of Industry 4.0, we must connect it to reverse supply chains. RSCs and I4.0 simulations help

industrial companies meet customer needs while increasing profits. Unsold and obsolete goods are increasing due to technological advancements in Industry 4.0. Therefore, the need to plan products to optimise the use of raw materials reflects a reduction in manufacturing costs and the preservation of the environment and sustainability. Industrial companies face significant challenges beyond their production processes. They face social and environmental responsibilities, as well as global competition, which requires flexible strategies to respond quickly to market and customer needs. As the industry develops, it must keep pace with reverse supply chains.

In this research, we examine the relationship between reverse supply chains and Industry 4.0 to maximise benefits for customers, companies, the environment, and manufacturing sustainability, thereby achieving social advantage.

4.2.2 Integration of Industry 4.0 with Reverse Supply Chain:

In this section, we review the literature on the integration of Industry 4.0 technologies into reverse supply chain activities. To highlight the theoretical frameworks in previous researchers' contributions, we aim to enhance our research by drawing on the various frameworks they offer. Furthermore, we should utilise them in our current research directions (Fetterman et al., 2018). It is worth noting that manufacturing companies can benefit from I4.0 technologies in several ways, including investing in reducing product processing time, lowering manufacturing costs, improving value chain coordination, increasing process flexibility, enhancing customer service, and boosting product customisation. Additionally, Dev et al. (2020) indicate that integrating forward and back-end logistics into the circular economy is an emerging topic in Industry 4.0, with growing interest among companies and academics in recent years. CE is being promoted in both developed and developing economies. Moreover, closed-loop systems have recently become a focus of research in supply chain (SC) formation. Forward and reverse supply chains are merging into a closed-loop supply chain that recovers value from used products while minimising waste.

On the other hand, a closed-loop supply chain includes returns, making reverse supply chains a revenue opportunity rather than a cost-cutting strategy for manufacturers (Covaci, 2019). The reverse supply chain can integrate Industry 4.0 technologies to reduce waste, as traceability can be enhanced by tracking waste sources via the Internet of Things. The idea begins with monitoring the product's expectations and shelf life. This information can be used to reduce waste. Big data can also be used to identify and track waste. Additionally, a virtualisation system can simulate production processes to identify optimal production practices that minimise waste (Rosin et al., 2020). The holistic evolution of the reverse supply chain and Industry 4.0 integration remains an open field of research that guarantees product returns, resource conservation, raw material recovery, environmental conservation,

and the sustainability of manufacturing operations (Rajput & Singh, 2021). Industry 4.0 manufacturing systems are automated and heterogeneous (containing heterogeneous components) and collect real-time data to improve flexibility and efficiency in production. Consequently, Industry 4.0 advocates sustainable production and consumption, waste reduction, remanufacturing, and efficient use of raw materials. It codes extremely personalisable technologies and describes cyber-physical systems (CPS), cloud computing, and big data (Garrido-Hidalgo et al., 2019).

Reviewing the literature on reverse supply chains, we found that it primarily focuses on traditional activities such as product recovery, remanufacturing, and recycling. Our research will focus on developing an additional advantage in reverse supply chains to better meet customer preferences. Using Industry 4.0 technologies, rapid manufacturing enables the production of more outdated or unused products, offers greater manufacturing flexibility, and better aligns with actual customer preferences. Additionally, the quality, added benefits, and customisation in production help reduce old and unsold products; therefore, mass customisation in production promotes the efficient use of raw materials and reduces waste, benefiting the environment. Manufacturing ethics also impose a duty not to burden customers with products that do not serve their needs. These issues collectively support manufacturing sustainability, product quality, and efficiency, as reflected in extended product life, less waste, increased recycling, and the maintenance of production and environmental sustainability. Our idea for integrating Industry 4.0 with reverse supply chains is beginning to take shape here. Industry 4.0 technology enables activities to adapt to reverse supply chain needs, enabling quick responses to changing customer demands, quality, and efficiency requirements, and delivering added value to customers in line with manufacturing ethics. This is also reflected in the responsible use of raw materials. Reverse supply chains can be integrated with Industry 4.0 technology through customer feedback, which supplies information to optimise operations and achieve the best results for customers, the environment, and manufacturing sustainability. Table 4-1 illustrates the criteria for integrating Industry 4.0 with reverse supply chains.

Table 4 - 1. Integration of Industry 4.0 with reverse supply chains.

Integration	Industry4.0	Reverse supply chain
Remanufacturing	The flexibility of remanufacturing and processing.	Collect and sort returned materials and prepare them for processing.
Technology	High-tech, ultra-high-speed simulation and networking.	Utilise modern technology to connect customers with companies and suppliers, and provide them with relevant information.
Environment	Clean operations, energy saving, and pollution reduction.	Accurate information rationalises material use, cost, and protects the environment.
Evaluate	It requires accurate information to utilise its superior capabilities fully.	Provides accurate information about customers, business environments, and competitors to support Industry 4.0.
Sustainability	When information on customers' needs, desires, and market requirements is available, it helps achieve sustainable production.	Its activities aim to achieve sustainability in manufacturing, production, the environment, and building ordinary relationships.
Socially	The economy has developed significantly, as reflected in the provision of societal services.	Contributes to social welfare.
Manufacturing	Great flexibility in manufacturing (Mass customisation).	Contribute to meeting customers' needs and desires.

Industry 4.0 technology can be integrated with reverse supply chains in various areas, such as remanufacturing. The flexibility and real-time processing features of Industry 4.0 enable immediate responses to returns generated by supply chains, allowing for remanufacturing or reuse based on the material's condition. This technology also facilitates networking among stakeholders, supporting information sharing, transparency, and responsiveness. Environmentally, digital technologies promote clean processes, efficiency, and optimization, while reverse supply chains provide the necessary data to support these efforts, thereby encouraging environmentally friendly practices. Adding value to a product or service depends on accurate information about customers and their changing needs. Supply chains help provide this information, enabling Industry 4.0 to quickly adapt to meet customer demands. Additionally, sustainable Industry 4.0 practices and reverse supply chains can be integrated into manufacturing environments to achieve better results that enhance manufacturing sustainability. From a social perspective, the literature shows that digital technologies promote social well-being. Similarly,

reverse supply chains contribute to improving social conditions by fostering a cleaner environment and better living standards. A key aspect of manufacturing is that Industry 4.0 technology enables the meeting of specific customer requirements through mass customisation, rapid response, and adaptive systems.

This research focuses on the relationship and integration between RSCs and I4.0. It aims to maximise the role of reverse supply chains in Industry 4.0 by leveraging their activities in recycling processes and managing recovered customer information to improve manufacturing processes. This, in turn, benefits the customer, the environment, and manufacturing sustainability.

4.2.3: A Framework of How Industry 4.0 technologies support RSCs activities:

In this section of the chapter, we discuss the integrated structure of Industry 4.0 technologies within reverse supply chain activities, illustrated by the contributions of previous researchers in this field. The researcher presented at the beginning of the chapter in Tables (3-3), (3-5), (3-6), (3-7) and (3-8), which include the classifications of the contributions of previous researchers in the field of reverse supply chain activities (traditional and contemporary vision) and industry and Industry 4.0 technology, which the researcher adopted as a path to develop his research. Based on findings from prior studies, the researcher developed a framework to illustrate the integrative relationship among the research variables, using statistical measures to present and analyse the results. Industry 4.0 technologies contribute to the growth and sustainability of manufacturing by enabling continuous improvement capabilities through cyber systems. This necessitates the use of big data and interoperability to explore most Industry 4.0 technologies. The potential for increased product customisation, rapid responses to consumer and market demands, and benefits for the end user are all essential aspects of Industry 4.0 (Nascimento et al., 2019). I4.0 technology can significantly improve productivity and workflow in recycling plants across the value chain (Baccarelli et al., 2017).

Researchers have contributed to identifying a new path to sustainability in manufacturing, including the development of a logistics business model that uses reverse logistics to recycle and reuse waste, transforming it into higher-value-added products (Leader & Rashid, 2016). In supply chains, consumers are the last stage. On the other hand, returns include reverse logistics activities (Covaci, 2019). Technological developments within Industry 4.0 enable innovation and digitalisation to improve production and enhance flexibility. In this context, energy consumption is a critical factor to optimise to achieve production targets at the lowest cost while meeting customer needs and preferences (Maggiore et al., 2021). Studies by Bag et al. (2023) and Jena et al. (2020) emphasised the role of Industry 4.0 technologies in rationalising raw material consumption and improving process efficiency.

In addition, studies by Kumar et al. (2020) and Anderson & Fort (2024) have indicated that Industry 4.0 technologies enhance manufacturing ethics.

Through a literature review, the researcher developed a framework for integrating Industry 4.0 technology with the contemporary vision of RSCs activities. This framework emphasises meeting customer preferences, the efficient use of raw materials, and ethical manufacturing, and supports these with Industry 4.0 technology to improve manufacturing sustainability. It provides a basis for creating our conceptual framework, allowing us to test the direct relationship between Industry 4.0 technology and the contemporary vision of RSCs activities, grounded in the development and expansion of the SOI theory. In this context, we will explore how Industry 4.0 technologies contribute to autonomous decision-making and processing algorithms, transforming traditional supply chains into digital systems enabled by cyber-physical systems and the Internet of Things. The smart factory's manufacturing flexibility allows adaptation to customer preferences while maintaining quality and efficiency, adding value for customers and optimising resource usage. This also encourages ethical manufacturing practices that directly support manufacturing sustainability. Figure 4-2 illustrates the framework for integrating Industry 4.0 technology to support reverse supply chain activities.

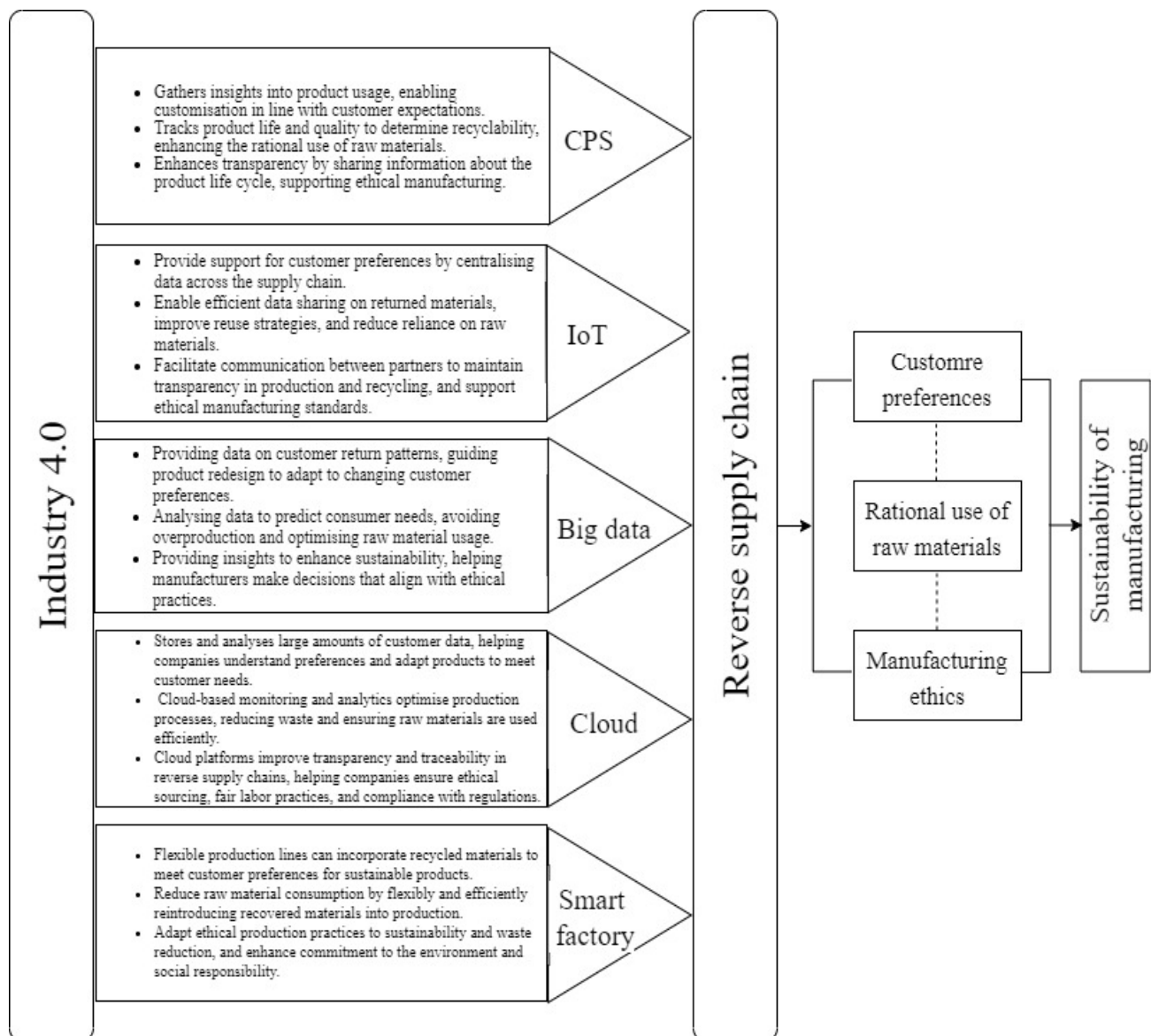


Figure 4 - 2 Integrating I4.0 technology with RSCs activities (Source: authors).

Figure 4-2 highlights how I4.0 technology supports RSCs activities. By responding quickly to Industry 4.0 through (Internet of Things) technology and networking technologies that connect (factory - customer - supplier), customer feedback can be analysed to identify their changing needs and respond quickly to customer preferences. Additionally, utilising CPS technologies can optimise recycling processes, resulting in greater sustainability in manufacturing and better customer satisfaction. In addition, I4.0 technology contributes to saving energy, reducing waste, and producing high-quality and designed products, which would support manufacturing and remanufacturing processes according to the customer's actual needs, which in turn contributes to reducing production costs, enhancing sustainability, and preserving the environment that meets and enhances the requirements of manufacturing ethics. Moreover, the smart factory is a foundational element of Industry 4.0, leveraging

technological applications and flexible manufacturing to significantly enhance process design and optimise recycling. The rationalisation of raw material utilisation also evidences this through recycling opportunities.

The necessity of supplying inputs for Industry 4.0, to be implemented through technological innovations such as sensory technologies, virtualisation, or digital twins. The Internet of Things, big data analytics, customer service, and cloud computing necessitate collaborative evaluation of reverse supply chain activities to support resource requirements and customer feedback (Henrik et al., 2019).

4.3 Conceptual framework development of the research:

Our conceptual framework builds on and broadens the Sustainability-Oriented Innovation (SOI) theory, particularly by expounding on the direct effect of I4.0 technologies on the contemporary vision of RSCs' activities. The first research question is based on this focus. Moreover, the framework simulates the Resource Orchestration Theory (ROT) through the analysis of the indirect interrelationships between I4.0 technology and contemporary visions of RSCs activities, as shown in research questions 2-5. The implementation of these indirect mechanisms is achieved through mediating factors, i.e., customer feedback and recycling as an organisational strategy, which allow companies to use available resources, improve system integration and interoperability, and, therefore, accommodate sustainable and responsible manufacturing processes.

Our framework combines SOI and ROT theories into a comprehensive, interactive model that highlights their synergy. Customer feedback serves not only as a mediating variable in our conceptual framework but also as a strategic driver; it affects and transforms the entire system, aligning with the idea of the sustainability-oriented consumer (SOC). Likewise, recycling is viewed from a different perspective: it is not only its traditional operational aspect; it is also a dynamic organisational capability that integrates enabling technologies and customer feedback, in accordance with the concept of sustainable technologies. The conceptual innovation of our framework is that it extends the Sustainability-Oriented Innovation (SOI) and Resource Orchestration Theory (ROT) theories. To begin with, the framework expands the theory of Sustainability-Oriented Innovation (SOI) by applying I4.0 digital transformation technologies to the context of sustainability and responsible production, thereby offering new insights into the role of technological capabilities in the process of sustainable and responsible practices in a reverse supply chain. Second, the framework builds upon the Resource Orchestration Theory (ROT) by adding sustainability-focused mediating mechanisms, including customer feedback and recycling, through which corporations can coordinate their resources to operate in a dynamic digital context and engage in sustainable and responsible manufacturing. The two theories

are applied in our conceptual framework by adding digital, organisational, and sustainability dimensions. Academically, our conceptual framework adds to the scholarly knowledge by:

1. Connecting the sustainability theory to the digital transformation through adopting I4.0 in the practices of sustainable RSCs.
2. Re-reading mediating processes (customer feedback and recycling) as strategic and interactive processes, which dynamically influence organisational outcomes.
3. Offering both a theoretically based and empirically testable model that illustrates how to coordinate digital and organisational capabilities to use technological capabilities to manufacture sustainably and in a responsible way.

In brief, our conceptual framework not only adds value and further develops existing theories but also provides a new, holistic view of how I4.0 technologies, consumer interactions with products, and organisational strategies interact to facilitate sustainable and responsible production. This renders our conceptual framework a useful addition to the formulation and empirical implementation of theory in digital manufacturing settings, with the aim of encouraging sustainable and responsible practice. Figure 4-3 is a diagram of the research's conceptual framework.

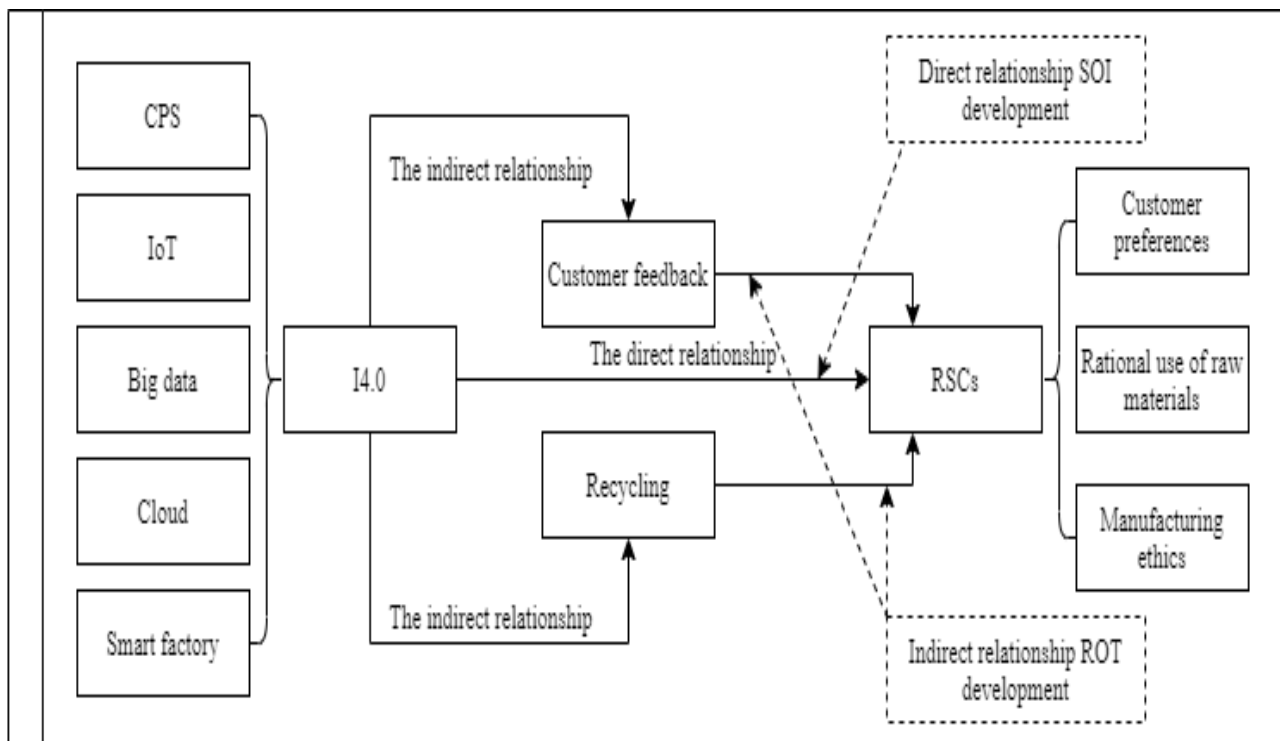


Figure 4 - 3 Develops a conceptual framework for research (Source: authors).

Figure 4-3, which depicts a conceptual framework for the research, illustrates the main research variables, represented by I4.0 and the contemporary vision of RSCs activities, as well as the

intermediate variables, represented by customer feedback and recycling. The core of the research involves linking I4.0 technology with the contemporary vision of RSCs activities outlined in the main research question. It also fills a key research gap related to mechanisms for waste reduction and investment optimisation to improve manufacturing sustainability. Broadly, our research focuses on satisfying customer preferences, enhancing the efficient use of raw materials, and emphasising manufacturing ethics, which has recently become a vital aspect of manufacturing sustainability, as noted in previous literature. The conceptual framework acts as a roadmap, clarifying the research variables reviewed earlier in this chapter and in previous ones. Additionally, it helps define the research model and hypotheses, which must align with the research questions and objectives, thereby supporting the study's experimental component.

4.4 Conceptual Framework: Theoretical Justification

4.4.1 SOI theory and our conceptual framework:

The decision to use the SOI theory as a primary foundation is based on the essence of the research problem. Contemporary RSCs are not measured solely by cost recovery/cost efficiency but are increasingly assessed by economic value, social responsibility, and environmental protection. This transformation is consistent with the fundamental assumption of SOI, which holds that innovation is a multidimensional endeavour aimed at creating overall value across multiple dimensions, rather than focusing on economic returns (Adams et al., 2016).

SOI theory aligns well with our conceptual framework in three main respects: First, it extends beyond the technological perspective on innovation, which focuses on the effective alignment between innovation processes and sustainability. It is an essential consideration in the context of RSCs, and feedback loops are closely linked to the recovery of environmental resources (e.g., recycling and reuse) and to social aspects (e.g., ethical manufacturing and waste management). I4.0 technologies (including CPS, IoT, big data analytics, cloud, and smart factories) are examples of digital enablers that can transform RSCs activities. Nevertheless, SOI maintains that these technologies are only sustainability-oriented innovations when deployed systematically to achieve sustainability outcomes.

Our conceptual framework describes the intentional coordination of digital technologies to support sustainable manufacturing processes, including the efficient use of raw materials, alignment with customer preferences, and adherence to ethical manufacturing practices. Second, SOI theory provides a normative and strategic perspective on how I4.0 technologies contribute to the contemporary vision of RSCs activities. It is through SOI theory that integrating these aspects into a comprehensive analytical framework becomes possible, as the theory views sustainability as a key driver of innovation rather than a secondary effect. In this way, SOI theory supports the idea that sustainability is a

fundamental driver of innovation strategies rather than just an outcome. Therefore, the central research question is grounded in SOI theory, which suggests that adopting I4.0 technology is not only a digital development process but also a strategic change in RSCs aimed at implementing sustainable manufacturing practices. Third, SOI theory helps address an important gap in the literature, since previous research has often examined I4.0 technology in isolation with respect to its effects on RSCs. Through SOI theory, the study recognises I4.0 technology as a powerful tool for achieving sustainability in RSCs, thereby strengthening the research's theoretical foundation and aligning it with current discussions in sustainable manufacturing.

4.4.2 The rationale for using the ROT theory:

Though SOI theory offers a strong strategic and normative basis, it does not align with our research vision for an organisational strategy to allocate available resources to promote sustainable manufacturing practices. To overcome this weakness, we enhanced our conceptual framework by drawing on the ROT theory (Sermon et al., 2007), which provides a more detailed account of how an organisation's resources are coordinated and pooled to align with its strategy and deliver sustainability outcomes.

4.4.3 The ROT theory and our research vision:

First, ROT theory sees resources as evolving through management processes and organisational operations, rather than as fixed assets. I4.0 technology is regarded as a strategic technological resource within our conceptual framework. ROT theory holds that having digital-enabling capabilities alone does not automatically enhance sustainable manufacturing practices or RSCs. Instead, its impact depends on how firms integrate this technology into their operations and combine it with other supportive mechanisms to maximise its benefits. Second, the ROT theory also supports the inclusion of mediating variables, such as customer feedback and recycling, in the conceptual framework.

According to this theory, resources create value only when they are used effectively to support learning, adaptation, and capacity building. Customer feedback serves as an interactive, dynamic information system that enables the company to align reverse logistics with evolving customer preferences and expectations. Recycling, in turn, is an operational process that converts digital potential into tangible sustainability benefits such as material recovery and decreased environmental impact. Therefore, ROT theory explains how these mediating I4.0 technology inputs are transformed into sustainable practices within RSCs. Additionally; ROT theory enhances the research model by explicitly addressing the cause-and-effect relationship between technology and sustainability outcomes. This is important because, using ROT theory, the research responds to the literature's call

for more detailed explanations of digital transformation and highlights that sustainability improvements in RSCs depend on integrating technologies and materials through coordinated feedback and recycling systems.

4.4.4 Combination of SOI and ROT Theories into our Conceptual Framework:

The combination of the SOI and ROT theories in our framework represents a carefully considered, theoretically sound approach to innovation, as it goes beyond merely applying multiple theories in parallel. All the theories address a crucial aspect of our research and are interconnected with the research problem and its objectives.

SOI theory holds because it explains why the I4.0 technology concept must be implemented alongside RSCs to achieve sustainability outcomes, in line with our research vision.

The ROT theory describes how companies can facilitate integration between forward and backward logistics by aligning their available resources with intermediary processes, which in our research can be represented by customer feedback and recycling. This concept can also be extended to the industrial sector, depending on the company's resources and the integration's goal. Combining these two theories enables the development of a conceptual framework that integrates strategic orientation (sustainability-focused technology) with the practical execution (resource orchestration) of RSCs, supported by I4.0 technologies. This dual theoretical foundation strengthens the research model, enhances its explanatory power, and increases its reliability.

The present research integrates Sustainability-Oriented Innovation (SOI) theory and Resource Orchestration Theory (ROT) through a complementary rather than overlapping theoretical linkage. The two theories are not treated as independent, parallel explanations; instead, they are systematically integrated to interpret distinct (but interrelated) levels of analysis from within the same conceptual framework. Thus, the study proposes internal theoretical coherence as its premise, in which each theory is explanatory of a particular functionality aligned with the research questions, the conceptual model, and the hypothesised relations among variables.

SOI theory provides a basic theoretical perspective for this research, justifying the relationship between Industry 4.0 technologies and the contemporary vision of RSCs' activities as directly related to their interaction effect. SOI theory posits that technological innovation becomes strategically important when it advances sustainability-oriented goals by integrating environmental, societal, and operational dimensions into organisational systems. Using this rationale, the research then presents Industry 4.0 conceptually. Industry 4.0 technologies are introduced not only as operational instruments but also as sustainability-oriented innovation capabilities that directly enhance the contemporary vision of RSCs activities through their adoption, thereby improving customer responsiveness, the efficient

use of raw materials, and ethical manufacturing practices. SOI theory justifies the potential of digital technologies to stimulate sustainability-oriented transformation in RSCs systems.

However, SOI theory, on its own, cannot adequately explain how such technological capabilities are embodied in the operational conversion of processes into sustainable outcomes for an organisation. By this, ROT is embedded in the framework to explain how organisations coordinate and use their necessary technological resources indirectly, through mediation, to attain sustainability goals. While SOI focuses on whether technology is available, ROT shifts the analysis to how well an organisation can organise its capabilities through strategic processes and intermediary mechanisms.

Whereas customer feedback and recycling are seen as mechanisms orchestrated by the technology rather than variables that run on their own. The process is a socio-economic, information-based orchestration of customer feedback, to which organisations respond dynamically by adapting RSCs' activities relative to evolving customer sustainability preferences and stakeholder expectations. Recycling is a physical orchestration mechanism that returns recovered resources to manufacturing systems to support sustainability and resource-efficiency goals. Hence, ROT describes how organisations deliberately orchestrate these intermediary processes to translate the capabilities of Industry 4.0 technologies into tangible, sustainable RSC outcomes.

The theoretical interrelation between SOI and ROT theories is grounded in a foundational theory that integrates them, aligning with our research paths to explore direct and indirect relationships within the research's conceptual framework. SOI theory explains the sustainability-oriented purpose and transformative role of Industry 4.0 technology. In contrast, ROT theory provides the organizational strategy through which these technologies are employed and translated into sustainable activities. Therefore, this integration is not theoretical redundancy, but rather a logically sequential and coherent explanation of the direct and indirect relationships within the research model.

This integration is reflected in the research questions and conceptual framework, which together inform the formulation of the research hypotheses. These hypotheses, in turn, underpin the research model, which empirically tests the relationships among the research variables. The first research question addresses the direct integration of Industry 4.0 technology into the contemporary vision of RSCs' activities, drawing on the concept of SOI. Subsequent questions, concerning customer feedback and recycling as mediating variables, are based on ROT. This is because they address the organisational orchestration mechanisms that facilitate the indirect effects of Industry 4.0 technology on the sustainability outcomes of sustainable RSCs. Accordingly; the conceptual framework achieves theoretical consistency by assigning a distinct explanatory role to each theory within an integrated, sustainability-oriented framework.

Therefore, the study's theoretical contribution does not stem merely from combining two theories but from constructing a coherent, multi-level explanatory framework in which SOI provides the logic of sustainability-oriented innovation. At the same time, ROT explains the orchestration processes that operationalise this logic within the contemporary vision of RSCs activities.

4.4.5 Justification for Selecting the Mediating Variables: Customer Feedback and Recycling:

The justification for selecting customer feedback and recycling as mediating variables in the current study is grounded in a model of Industry 4.0 technologies and a contemporary vision of RSCs activities. This section argues that integrating Industry 4.0 technologies into contemporary RSCs activities is not merely a direct relationship but can be achieved through collaboration between organisational and operational mechanisms to generate novel practices that transform existing capabilities into sustainability-driven outcomes. In line with that, customer feedback and recycling were chosen because they represent two underlying mediating processes through which these technologies can facilitate or inhibit customer-oriented responsiveness, as well as rational use of raw materials and ethical practices within RSCs.

The choice of customer feedback as a mediating variable is grounded in the fact that modern conceptualisations of RSCs increasingly model ongoing stakeholder engagement and consumer-based sustainability practices. Industry 4.0 technologies such as IoT, big data analytics, artificial intelligence, and digital platforms improve an organisation's ability to capture, process, and analyse consumer information in real time. The strategic value of these technologies depends on whether customer feedback becomes actionable knowledge that drives adaptive RSCs, informs product recovery decisions, shapes sustainability preferences, and guides ethical manufacturing responses. Thus, customer feedback catalyses information and the internal structure of Industry 4.0 technologies, enabling responsive and Sustainability-Oriented RSCs.

Theoretically, customer feedback acts as a mediator, explained by ROT, which highlights organisational coordination and the use of informational resources to reach strategic goals. In this context, customer feedback serves as a strategic knowledge resource that helps organisations align their technological capabilities with changing customer expectations and sustainability needs. Therefore, the study suggests that I4.0 technologies indirectly boost the contemporary vision of RSCs activities by improving the integration of customer feedback and stakeholder responsiveness.

Recycling was selected as another mediating variable due to its role as an operational mechanism through which Industry 4.0 technologies are hypothesised to lead to sustainability-oriented RSCs outcomes. Recycling is widely recognised in the existing literature as one of three core components of circular economy systems and as an important resource recovery strategy. However, recycling

processes increasingly rely on digital technologies to enhance material tracing, waste monitoring (Integrated Waste Management), and resource recovery. With the advent of Industry 4.0 technologies, recycling industries can develop smart systems that integrate real-time monitoring, automated sorting, and predictive analytics-based resource management.

On a theoretical level, within ROT theory, recycling is understood as the combination of resources. ROT conceptualises how organisations purposefully coordinate the material inputs and recovery processes necessary to achieve enduring operational results. In this study, recycling serves as the means by which digital capabilities convert RSCs into economically rational outcomes and sustainable practices. Hence, the mediating role of recycling denotes an organisation's ability to transform technological resources into tangible sustainability outcomes.

In addition, mediators of customer feedback and recycling reinforce the theoretical integration within the conceptual framework. Customer feedback can be seen as the information- and stakeholder-related aspect of RSCs' sustainability, while recycling is a material-operational domain that contributes to resource recovery and circularity. Together, these mediators explain how Industry 4.0 technologies indirectly contribute to the realisation of a modern conception of RSCs activities by orchestrating processes in coordination, rather than merely adopting technology on its own.

Hence, the choice of these mediating variables is not random but is theoretically driven by the research problem, the literature gaps identified in previous studies, and field reviews conducted for this study, and is grounded in ROT and its application or integration within an overall model/design for testing.

4.4.6 The unique vision of the conceptual framework:

Our conceptual framework will provide a modernised view of the current literature, which has not been taken in depth. Our perspective as researchers differs from established theories of technology, including the Resource-Based View (RBV), in several respects.

Highlighting the theory. The resource-based view (RBV) is widely credited to Jay Barney (1991), who builds on the work of other scholars, including Edith Penrose (1959). It assumes that a sustainable competitive advantage is achieved at the firm level through the presence of valuable, scarce, unique, and unrepeatable assets. Current studies in the RBV field do not abandon the main principles (valuable, scarce, and unique resources) but rather update and expand them by considering new technologies as strategic resources and integrating them with other theories to provide a more comprehensive view of performance and sustainability outcomes.

According to the RBV, a company's resources are primarily fixed assets that confer a competitive advantage when they are valuable, rare, inimitable, and non-substitutable. In contrast, our theorised framework views I4.0 technologies as dynamic, systematic enabling capabilities embedded within

interconnected socio-technological ecosystems. Instead of focusing on resource ownership, our research examines the enabling capabilities and mechanisms that foster a sustainability orientation, coordinating available company resources with organisational strategy to enhance RSCs' sustainable practices in the manufacturing industry. This approach goes beyond the RBV focus on assets to a perspective centred on dynamic interactions and processes. Additionally, although the RBV primarily describes direct performance outcomes based on internal resources, our model presents a clear structure of both direct and indirect relationships, with mediating variables illustrating the role I4.0 technology plays in the contemporary vision of RSCs activities.

The conceptual framework we have developed, incorporating the ROT theory, helps us understand how digital technologies can be used to coordinate a company's resources in line with organisational strategies, particularly through mediating factors. Relational mechanisms cannot fully explain the contexts of multi-party circular supply chains, as RBV theory does not adequately address these contexts. Third, our conceptual framework builds on the theories of SOI and ROT and adds key dimensions aligned with current manufacturing processes. These aspects, including customer tastes, rational utilisation of raw materials, and manufacturing ethics, are not well addressed in existing literature. These aspects are not the focal point of the RBV, which is centred on economic dimensions and outcomes. The advocacy of sustainable and ethical manufacturing practices, however, constitutes the core of our conceptual framework. It not only explains how sustainability-oriented competitive advantages are formed but also indicates why companies and practitioners should embrace modern RSCs practices that promote broader societal and environmental objectives.

Lastly, our research vision addresses the limitations of resource and capacity theory in intensive, circular digital economies by viewing Industry 4.0 as infrastructure to organise, rather than as a resource monopoly. This new model is particularly applicable to RSCs, which are based on inter-organisational cooperation, customer relationships, and ongoing data-driven learning environments, in which the assumptions of enterprise resource and capability theory are less relevant.

4.5 Concluding remarks:

Previous research consistently highlights significant challenges in integrating Industry 4.0 technologies with RSCs, hindering the achievement of sustainability goals. As a result, the evidence remains somewhat unclear, and a fundamental theoretical conflict exists between the widespread belief that technological capabilities should enhance sustainability performance and the empirical evidence that technology adoption alone is insufficient to ensure successful, sustainable RSCs activities.

The cause of this tension can, to a great extent, be attributed to the prevalence of technology-focused theories that conceptualise digital technologies as the primary source of competitive advantage. These

views do not adequately explain the unique nature of RSCs, which are dynamic, coordination-based, and inherently tied to social, ethical, and sustainability imperatives. Therefore, current frameworks offer little insight into how Industry 4.0 technologies should be strategically structured, coordinated, and governed to deliver tangible sustainability outcomes.

To overcome these shortcomings, this study proposes a holistic conceptual framework that builds on Sustainability-Oriented Innovation and Resource Orchestration Theory. This integration transforms Industry 4.0 technologies into conceptualised infrastructures that underpin coordinated, ethically motivated, and sustainability-centred RSCs practices, rather than treating them as standalone technological resources. The framework explains that Industry 4.0 technologies affect sustainable RSCs performance by explicitly modelling mediation mechanisms through customer feedback and recycling orchestration.

By doing so, the proposed framework addresses the identified theoretical inconsistencies by offering a clear, mechanism-based explanation of digitally enabled reverse supply chains. It provides a solid foundation for empirical testing and theory development by systematically and efficiently integrating digital transformation, sustainability-driven innovation, and coordination dynamics into a single conceptual framework that supports impactful scholarly research.

Chapter Four

Section 2: Hypotheses development and research model

Research hypotheses refer to specific statements that can be tested. Hypotheses predict relationships or outcomes among two or more variables, depending on the nature of the research (Lund, T., 2022). Hypotheses are formulated on scientific foundations, such as existing theories and prior research, and are informed by the literature and scientifically documented observations. Hypotheses are considered a scientific basis for verification (Poincaré, 2022). In addition, research hypotheses are central to the scientific method, providing the general framework for testing relationships among research variables (Davidavičienė, 2018). By predicting outcomes, researchers can design experiments, studies, or surveys to collect evidence that supports or refutes the hypothesis, as reflected in the statement of knowledge and its proof in a field (Chigbu, 2019). The following presents the previous literature that informed the formulation of the research hypotheses.

4.2.1 Industry 4.0 and Reverse Supply Chain Contexts:

I4.0 is a modern organisational style that fully manages the value chain throughout the product life cycle. The primary goals of Industry 4.0 were to facilitate demand management, R&D, and the transition of goods from production to use and subsequent recycling. The adoption of network-enabled intelligent factories, intelligent goods, and intelligent services has already significantly advanced the Industry 4.0 revolution. An intelligent waste-recycling machine will greatly enhance recycling practices, stop further environmental pollution, and support manufacturing (Mohajeri et al., 2021).

Reverse supply chains are concerted efforts to manage parts nearing the end of their life, establish a specification model for recycling, and gather customer feedback. Reverse logistics has become a primary specialisation within supply and RSC, as products move from customers to manufacturers (Hidalgo et al., 2019). Internet of Things (IoT) technology, in particular, can considerably improve process-oriented performance, reduce energy use, and enable relevant stakeholders to access information anywhere (Gubbi et al., 2013; Hermann et al., 2016; Zhong et al., 2017). Changes in the business environment and competition between companies have led to the current trend toward product customisation. That prompted many producers to adopt new production strategies and management concepts to meet customer preferences. I4.0 technologies enable companies to communicate quickly and effectively with customers during the co-design process, allowing them to determine what customers want in terms of services and product features. This enables the development and improvement of customised products and service offerings in response to customer preferences (Helms et al., 2008). Big data analytics and deep learning have recently achieved success in various industrial applications, including computer vision and intelligent factories. These technologies are now crucial

components of business intelligence. I4.0 technologies have been widely used in consumer behaviour to enhance personalised marketing and tailor services to customer preferences (Sun et al., 2021).

It is well known that the partial or full recovery of secondary raw materials has become increasingly commercially attractive for use in product manufacturing following recycling. In particular, waste from chemical, metallurgical, and mining enterprises, which are used in large quantities and for long periods in various countries, is utilised in the production of building materials, the manufacture of fertilisers and food additives for agriculture, and other applications (Bogdanov & Grishaev, 2022). The rational use of raw materials, along with their preservation and recycling, would help maintain manufacturing sustainability and protect the environment. Firms and society should improve people's quality of life without further degrading the natural environment (KRŇANOVÁ, 2020). Industry 4.0 is a significant contributor to sustainable development and reverse logistics. Industry 4.0 technologies, particularly the Internet of Things, are recognised as a means of achieving sustainable development and transforming logistics goals, yielding social, economic, and environmental benefits. In this context, Industry 4.0 effectively contributes to the rational use of raw materials in reverse logistics, thereby achieving environmental, economic, and social benefits (Khan et al., 2021).

Refers (Trentesaux & Caillaud, 2020) in the field of ethics in Industry 4.0 to basic and essential dimensions, including that ethics in the I4.0 advanced generation of industry must be in the interest of customers and fulfil their required needs and not harness the modern I4.0 technology in innovations that are harmful to humans and do not benefit them. In line with global production visions, companies have had to reconsider their production methods by implementing reverse logistics activities that uphold ethical standards in manufacturing and performance (Berrah et al., 2021).

Through the previous theoretical framework and the contributions of researchers in this field, the researcher worked on developing the central research hypothesis:

H₁: Industry 4.0 has a significant effect on the contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of industrial company workers.

4.2.2 Industry 4.0 technologies and customers' feedback, recycling:

In this research, the researcher used two intermediate variables (customer feedback and recycling), the main activities of the RSC, to measure their impact on the integration relationship between I4.0 and RSCs.

Three basic conditions must be met to introduce intermediate variables (customer feedback and recycling) to show the relationship between Industry 4.0 and reverse supply chains. The first condition is that there must be a significant influence relationship between the independent and dependent variables, which was met in the first main hypothesis. The second condition is that there must be a

significant influence relationship between the independent variable and the intermediate variables. In addition, the third condition is that the intermediate and dependent variables must be related through influence. Therefore, the researcher formulated hypotheses (2-5) to satisfy the conditions for introducing intermediate variables that link the independent and dependent variables.

Environmental management has garnered the joint attention of producers, customers, and policymakers, leading to a growing need to study reverse supply chains, including recycling processes (Kianpour et al., 2019). I4.0 aims to maximise the closed-loop flow of materials in recycling processes while preserving the core value of materials throughout the reverse supply chain (Rajput & Singh, 2021). I4.0 technology accelerates product development, thereby reducing product life cycles. Therefore, coordination of the reverse supply chain with Industry 4.0 is crucial (Sun et al., 2019). Input on the quality status of products manufactured and remanufactured through reverse supply chains is essential for the production facility undertaking remanufacturing. Generally, it can only assess product quality after disassembly, which is time-consuming and expensive. It is thus worthwhile and necessary to obtain the correct product information from customers or from collection service centres for returned materials. This data is an important resource in the reverse supply chain and would be useful to Industry 4.0, although it may require greater precision (Gu & Tagaras, 2014). The transformation of the seller to a buyer market in the industrial goods market has resulted in saturation where demand is far much less than supply (Blecker et al., 2004).

The present trend towards customisation of products is because of many changes experienced in the business environment. This in turn forces most suppliers to review their production policies and managerial approaches as a way of addressing the changing tastes of the customers. The modern technologies can help the business to talk to customers fast and efficiently in the co-design process, and thus learn what customer's desire in relation to services and product features. The current customer interest is in a quality style and uniqueness over the mass-produced components, and they tend to be supportive of the mass customisation approach to meet the unique and changing needs of the customers. Consequently, the technological aspects of the production and retrieval of information generated by the customer feedback and electronic communications is vital in developing products. Adapting and improving of offering of custom products and services based on the preference of customers requires knowledge management or continuous learning by the customer and stakeholders (Helms et al., 2008). The updated raw materials policy, which aligns with social sustainability and environmental protection, establishes long-term objectives and strategies for the efficient use and preservation of raw materials (Kuzevi et al., 2019). Environmental assessment and environmental quality is a burning issue now. Here, it is necessary to ensure that the use of raw materials is effective and that the basic manufacturing processes are properly trained and sustained in the end. Businesses

and society must raise the standard of living of the populace without endangering the environment or the natural world (KRANOV, 2020). Understanding consumers' feedback requirements will enable producers to meet consumer demand (McIntyre-Bhatty & Parker, 2011). Moreover, the benefit of products offered to customers to meet their actual needs and desires at a high level of quality is a matter of manufacturing ethics (Chang, 2011). Manufacturing ethics in the I40 field is everyone's responsibility throughout the production process, ensuring we deliver the best to improve people's lives. Defining precisely what the "good life" is complex. In the context of the I40, customers can translate the word "good" at least with respect to technical, social (quality, value, and actual utility), societal, environmental, and economic expectations. It proposes to define manufacturing ethics in the I40 as follows: "Ethical design and use of ethical standards in Industry 4.0 for production and logistics that benefit the customer without additional burdens." (Trentesaux & Caillaud, 2020).

A study by Zheng et al. (2021) examines the relationship between manufacturing and recycling processes and proposes Internet-facilitated reverse supply chains to achieve optimal outcomes for manufacturers and customers by electronically linking material retrieval and follow-up operations. This approach offers several advantages for both manufacturers and customers. One of the major issues facing contemporary economies and societies is the decline in aggregate consumption, alongside new trends in sustainable consumption and production. This may be achieved through the analysis of customer preferences for products that suit their actual needs and wants, the implementation of Industry 4.0, and sustainable consumption and production (SCP). The study has revealed that the more products the company can customise them to the individual preferences of customers, the less people will consume them, and the more sustainable the production will become (Saniuk et al., 2020). Past studies have revealed that recycling activities have been an object of interest to most industrial firms because it has ceased to be an activity that incurs extra expenditure but a lucrative venture. Recycling is also a way of ensuring sustainability in production and rationalisation of raw materials consumption and, as a result, conserving the environment (Alzly, 2023). In the study (Margherita & Braccini, 2021), the concept of business ethics was linked to the idea of business development in the field of Industry 4.0 technology, as the term business development refers to the organisational practices of the economic system and represents the executive position to create value in the production and distribution of goods and services. In manufacturing-oriented organisations, these practices aim to drive economic growth and increase profits to support business capital, while also promoting business ethics in the context of Industry 4.0. It is the pursuit of a decent life with oneself. Additionally, in fair institutions, others meet the customer's needs in both quantity and quality. Moreover, it preserves producers' interests. Reviewing and studying the literature (Margherita & Braccini, 2021).

Through reviewing the previous literature on the role of Industry 4.0 in reverse supply chains through recycling activities and customer feedback, the second and third hypotheses of the research were formulated:

H₂: There is a significant effect relationship between Industry 4.0 and customer feedback at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

H₃: There is a significant effect relationship between Industry 4.0 and recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

4.2.3 Customer feedback, recycling, and RSCs activities:

To satisfy the third condition for introducing the intermediate variables (customer feedback and recycling), it is necessary to test their relationship with the dependent variable. Accordingly, the researcher developed the fourth and fifth hypotheses to address the requirements outlined in the introduction for the intermediate variables.

Customer feedback plays an important role in improving reverse supply chain initiatives by informing responses to customer preferences, optimising raw material use, and promoting ethical manufacturing (Taghikhah et al., 2019). Product reviews would give companies a clear understanding of consumer needs for product volume and quality, thereby encouraging sustainable production processes such as recycling and eco-friendly practices. This enables manufacturers to design products according to customer preferences (Moldavska & Welo, 2017). The rational utilisation of raw materials is also aided by the use of customer feedback as a means of product customisation to meet actual customer needs, hence having a longer life for the product. This is indicated by a decrease in old products and waste, as recycled materials can be used in manufacturing (Papazoglou et al., 2020). Moreover, business organisations will be able to optimise their material recovery system, enhance resource use, and minimise their dependence on raw materials (Di Maio et al., 2017). Moreover, feedback facilitates the production of ethics as it gives information about the environmental and social effects of production and disposal (Sutherland et al., 2016). Companies to demonstrate ethical behaviour through increased recycling reduced ecological footprint, and more responsible production (Gupta et al., 2021). Can use this information. In most cases, reverse supply chain feedback plays an essential role in developing more sustainable and ethical supply chain processes that meet market needs and environmental goals (Hsu et al., 2016).

Reverse supply chain recycling operations are effective in promoting manufacturing ethics, improving raw material utilisation, and meeting customer demand (Hsu et al., 2016). Companies should incorporate recycling into their supply chains to meet the growing demands of consumers who are increasingly sustainability conscious (Taghikhah et al., 2019). A company can promote the use of

circular economies by producing products that are readily recyclable or reusable to meet consumer demand for environmentally friendly products (Awan & Sroufe, 2022). From a resource-efficiency perspective, recycling will make the use of raw materials more reasonable. Another way to reduce waste is to use and reuse materials in returned products, thereby conserving natural resources rather than relying excessively on raw materials (De Sa & Korinek, 2021). This will reduce production costs and the environmental footprint of the production process, thereby helping to achieve long-term sustainability objectives (Oláh et al., 2020). Ethically, recycling in the reverse supply chain supports responsible manufacturing by mitigating concerns about waste, pollution, and resource depletion (Manavalan et al., 2021). A company that focuses on recycling is more likely to pursue ethical business practices, including a smaller carbon footprint and responsible waste disposal, as part of its broader environmental and social responsibility (Eyo-Udo et al., 2024). In brief, recycling through reverse supply chains is expected to meet customer expectations, enhance resource efficiency, and strengthen the ethical foundation of business activities (Sehnem et al., 2019).

Based on the prior literature, the fourth and fifth hypotheses, which concern the relationship between the mediating variables and the dependent variable, were formulated.

The following hypotheses represent the productive relationship of the mediating variables with the presence of dependent variables, as follows:

H₄: There is a significant effect relationship between customer feedback and contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of workers in industrial companies.

H₅: There is a significant effect relationship between recycling and contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of workers in industrial companies.

4.2.4 I4.0 Technologies and RSC activities with intermediate variables, customer feedback, and recycling:

Industry 4.0 technologies and reverse supply chain operations are integrated through customer feedback and recycling (Dev et al., 2021). They can successfully maintain the entire value chain through advanced Industry 4.0 technologies. Customer comments, gathered using Industry 4.0 tools such as IoT and Big Data, allow receiving useful feedback about product performance and end-of-life problems (Nagy et al., 2018). Reverse logistics is facilitated by real-time data that help companies identify products that need to be recycled, repaired, or returned (Wilson & Goffnett, 2022). In addition, manufacturers can escalate their forward and reverse logistical systems through customer feedback to

design a better product and maximize efficiency, which leads to less energy use, high flexibility in manufacturing of products, and easier recycling (Lee & Lam, 2012).

Through smart factory technologies that effectively contribute to manufacturing flexibility, enabling the meeting of customer preferences and improved resource utilisation, as well as smart sensing technologies that streamline sorting and material recovery processes, Industry 4.0 technologies also enhance recycling processes. This, in turn, reflects environmental standards that align with current trends in manufacturing ethics (Javaid et al., 2022). Based on the previous literature review, the relationship between Industry 4.0 technologies and reverse supply chains is explained through customer feedback and recycling processes. The previous literature helped the researcher to formulate the sixth, seventh, and eighth research hypotheses as follows:

H₆: There is a significant effect relationship for Industry 4.0 in the contemporary vision of RSCs activities mediated by customer feedback as an intervening variable at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a sample of research.

H₇: There is a significant effect relationship for Industry 4.0 contemporary vision of RSCs activities mediated by recycling as an intervening variable at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a sample of research.

H₈: There is a significant effect relationship for Industry 4.0 on contemporary vision of RSCs activities mediated by both customer feedback and recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

Summary of research hypotheses:

The first main hypothesis:

H₁: Industry 4.0 has a significant effect on the contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of industrial company workers.

The second hypothesis:

H₂: There is a significant effect relationship between Industry 4.0 and customer feedback at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

The third hypothesis:

H₃: There is a significant effect relationship between Industry 4.0 and recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

The fourth hypothesis:

H₄: There is a significant effect relationship between customer feedback and the contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of workers in industrial companies.

The fifth hypothesis:

H₅: There is a significant effect relationship between recycling and contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of workers in industrial companies.

The sixth hypothesis:

H₆: There is a significant effect relationship for Industry 4.0 in reverse supply chains (RSC) mediated by customer feedback as an intervening variable at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a sample of research.

The seventh hypothesis:

H₇: There is a significant effect relationship for Industry 4.0 contemporary vision of RSCs activities mediated by recycling as an intervening variable at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a sample of research.

The eighth hypothesis:

H₈: There is a significant effect relationship for Industry 4.0 on contemporary vision of RSCs activities mediated by both customer feedback and recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

4.2.5 Research Model:

Designing a research model requires a thoughtful understanding of how to integrate theoretical frameworks and practical methodologies. This is achieved through a comprehensive understanding of the research topic, which begins with a thorough review of the existing literature. From here, the researcher's knowledge base expands with an in-depth exploration of the research aspects. By exploring in-depth knowledge, the researcher can determine their research paths and identify the research gap. The research model represents a conceptual framework that clarifies the relationships among research variables according to the research hypotheses, which the researcher must formulate to enable them to answer the research questions.

To develop a research model, and by reviewing the literature, I found that there is previous literature that highlights the relationship between the main research variables I4.0 and RSCs, which includes

researchers' contributions to I4.0 technologies, sub-dimensions of the independent research variable in our study, which confirms the scientific research path of the researcher according to the contexts. In addition, researchers' contributions on RSCs consider the second research variable (the dependent variable). In addition, the researcher relied on sub-dimensions of the variable and on relationships between theoretical frameworks regarding the variable. Moreover, the researcher employed intermediate variables, including customer feedback and recycling processes, which are activities consistent with the research variable, RSCs, to examine their impact on the relationship between I4.0 and RSCs. Accordingly, the researcher has developed a research model to show the effect of the research variables and their sub-dimensions and intermediate variables, as shown below:

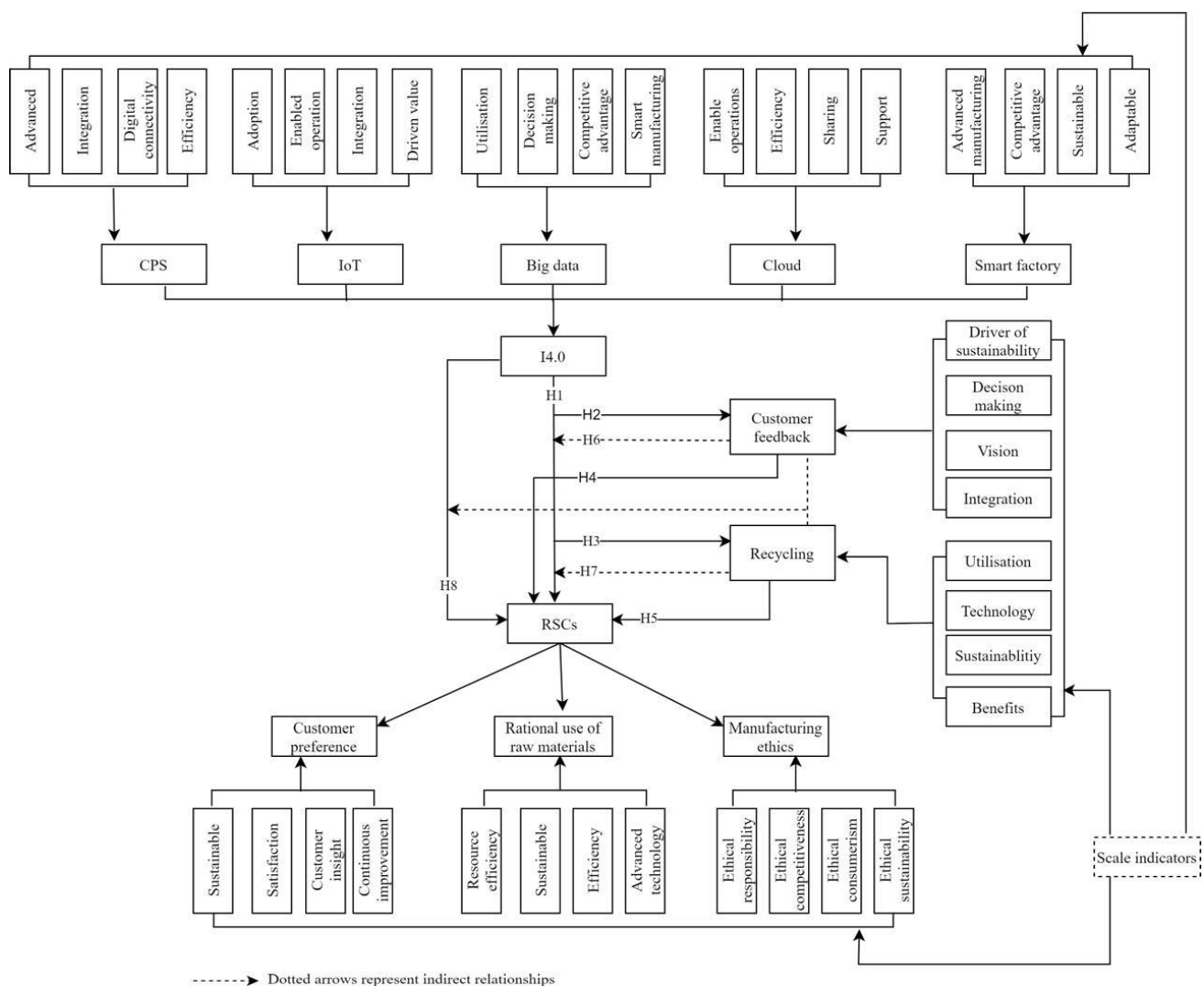


Figure 4 -2- 1 Research model

The research model was depicted visually to illustrate the relationships among the main and sub-research variables and the intermediate variables. The model clarifies the primary and secondary

questions and hypotheses. Additionally, it will involve testing statistical relationships among the research variables, as outlined in the research questions and hypotheses, using suitable statistical tools. Additionally, we relied on the Resource Orchestration Theory (ROT) proposed by Sirmon et al. (2007) to design the research model, consistent with its use in formulating research questions (2-4). We aimed at leveraging administrative and technical processes to utilise available resources to achieve strategic outcomes. This theory partly aligns with our research vision, as it employs available resources (such as customer feedback and recycling) as mediating variables to test how they can enhance and connect the relationship between Industry 4.0 technology and the contemporary vision of RSC activities.

In our research context, despite the enabling capabilities of Industry 4.0 technology identified, its impact on the contemporary vision of RSCs activities depends on how companies organise and manage their operational processes and link them to mechanisms that boost performance. Therefore, ROT provides a solid theoretical foundation for our research model. It helps translate Industry 4.0 technology inputs into sustainable RSCs practices that support customer preferences, efficient use of raw materials, and manufacturing ethics, through intervening variables (customer feedback and recycling) that serve as organisational and operational mechanisms. Essentially, companies' ownership of digital technology not only advances sustainability but also requires optimal utilisation through integrated mechanisms rooted in organisational and operational principles. These tools can facilitate connections that improve the integration of forward and reverse logistics operations, aligning with the aims of our current study.

The SOI approach emphasises making innovation processes more sustainable, whereas the ROT approach emphasises the importance of resource coordination. Nevertheless, neither provides a full explanation of how stakeholder interactions and resource coordination can affect sustainability-oriented innovation. Our research fills this gap by constructing and empirically evaluating an integrated framework that explicitly accounts for these dynamics in real-life situations across industries. Customer feedback is regarded as both a product of technology and a driver of change in this model, with implications for operational reconfigurations and structural transformations. On the same note, recycling is redefined to mean the next level of RSCs practices to respond to the demands of the high-tech manufacturing process, which enhances the outcomes of circularity and sustainability. The model, which incorporates customer-centric and sustainability-oriented digital technologies and the principles of the circular economy, including recycling, highlights the synergistic alignment of I4.0 technologies with the changing needs of customers and sustainability objectives. This is integrated into the organisation of forward and reverse logistics services, providing a more holistic view of sustainable value creation. In addition to advancing theoretical progress, our study contributes to the development of sustainability and innovation theories by empirically demonstrating the interaction between

customer engagement and technological adaptation within circular practices. At the same time, it provides a practical overview, showing how the orchestration of resources and stakeholder engagement can be utilised to achieve meaningful sustainability outcomes.

4.2.6 Mediating variables:

Through the research model, we observe that the researcher relies on introducing intermediary variables to facilitate the integration of the independent variable (Industry 4.0) and the dependent variable (reverse supply chains). The intermediary variable (or the mediator) helps explain the association between the independent and dependent variables (Nitzl et al., 2016). This means that it is a process in which the independent variable affects the dependent variable.

The adoption of the intermediary variable in the research model must meet conditions (Abualoush et al., 2018).

In adopting the introduction of the intermediary variable into the research model, three critical issues have to be confirmed, which are:

1. The independent and dependent variables have to have a significant relationship of influence.
2. A substantial relationship of influence exists between the independent variable and the intermediary variable.
3. The influence relationships between the intermediary variable and the dependent variable must be significant.

As for the mechanism of action of the intermediary variable, the independent variable influences it, which, in turn, influences the dependent variable (Nitzl et al., 2016). The significance of the mediating variable lies in explaining the relationship between the independent and dependent variables by providing insight into how the relationship is logically grounded in processes or mechanisms (Elia et al., 2022). It also contributed to the development of more elaborate and integrated theoretical frameworks. In brief, the mediating variable explains the strong relationships between the independent and dependent variables in the study (Tabouli et al., 2016).

In formulating research questions 2-4 that were housed on the Resource Orchestration Theory (ROT), we highlighted the fact that this theory provides that companies build their capabilities by exploiting the available resources based on a strategic organisational structure. Based on this theoretical framework, the research model incorporates the customer feedback and recycling as mediating variables, as we acknowledge it as organisational resources present in the companies under study that may be exploited to enhance the performance on the organisational level as well as at the strategic level. In particular, the research model provides a case of how business firms can turn intangible (customer feedback) and tangible (recyclable materials) inputs into sustainability-promoting

mechanisms by incorporating I4.0 technology and sustainable reverse logistics into their operations. By doing so, our research model accounts for the fact that resources do not operate independently of one another but rather because of their combination and dynamic interplay within the larger system. Consequently, the inclusion of these mediating variables enhances the explanatory power of the Resource Orchestration Theory (ROT) by demonstrating that companies advantage available resources to enhance the integration of digital technology into their sustainable and responsible reverse logistics programs. Our study contributes to the theoretical development of ROT and empirically demonstrates its application in industry practice.

4.3 Concluding remarks:

The second section of the chapter discusses the development of research hypotheses based on theoretical foundations. Each hypothesis was formulated in line with our conceptual framework, which later provides the theoretical basis for translating the hypotheses into a form that can be empirically tested through the integrated structure of the research model. This will subsequently enable the appropriate statistical analyses.

Chapter 5

Research Methodology

5. Research Methodology:

5.1 Introduction:

This chapter outlines the research methodology. At the beginning of the study, the researcher describes the methodological model that guides the research through the data collection, analysis, and discussion stages. The chapter reviews the research design and framework, and explains how the research questions are addressed within these structures. Research questions serve as the first step in choosing the research approach; in this case, the selected strategy is mixed methods. Previous research has shown limited understanding of the reverse supply chain and its potential benefits, with a focus mainly on recycling processes. The role of reverse supply chains in Industry 4.0 requires a comprehensive understanding of different perspectives to define it effectively. Researchers need to establish the research framework and scope, as highlighted by Farouk et al. (2021) in their discussion of the importance of tracing research pathways. This is a common practice in management and related fields (Kirouz et al., 2020).

As such, the chapter first presents the research design, the course philosophy, and the methods, data collection, and analysis. Moreover, the research methodology has been elaborated in the chapter, along with the methods commonly used by researchers in this discipline. Next, according to the selected research method, the scale for gathering quantitative data and the stages of its development were proposed, as well as the scale for gathering qualitative data, and statistical tools employed to analyse the quantitative data were mentioned. In addition, the research sample, its details, and characteristics were highlighted, as were those of the companies under study. Afterwards, the research methods were presented in detail, and how each technique addresses the research questions was explained. The part of the fifth chapter concludes with a presentation of the researcher's experimental survey to ensure the reliability and accuracy of the research scale.

5.2 The rationale for the research approach:

This section refers to the rationale for adopting the research methodology. The research strategy should be compatible with the nature of the research. The research questions should be considered to identify the research's direction (philosophical issue) (Baškarada & Koronios, 2018). The selection of a research method will rely on the data collected and analysed by the researcher to present the results, and on the nature of the research itself, be it quantitative, qualitative, or both, based on the research and data available to the researcher (Abutabenjeh & Jaradat, 2018).

The justification for a research method explains why a specific approach was chosen to address the research question (Snyder, 2019). The validity of the research depends on various underlying factors aimed at improving the reliability and validity of the findings (Sürücü & Maslakci, 2020). The choice of research method is based on several considerations, including the nature of the phenomenon being studied and whether the method aligns with the research objectives and questions. Certain methods are better suited for particular types of phenomena (Turner et al., 2017). For instance, qualitative methods often rely on interviews, making them more suitable for exploring complex social behaviours. Quantitative methods are typically appropriate when objective data or statistical analysis is needed. Additionally, cognitive factors (e.g., the theory of knowledge) may influence the researcher's methodological choice (Tomaszewski et al., 2020). Furthermore, other factors, such as the type of data, its availability, and the research design, can affect the choice of methodology, sometimes requiring a specific approach for the researcher (Abutabenjeh & Jaradat, 2018).

5.3 Concepts and definitions of search terms:

5.3.1 What are the customer preferences?

Meeting customer requirements quickly and effectively involves understanding what they want in terms of the product and its advantages, including quality, efficiency, mass customisation, and costs, to cater to consumers' unique and evolving preferences. Consequently, the role of technology in gathering information from customer feedback and interactions is vital to product development.

5.3.2 What are the raw materials?

Environmental issues and the evaluation of ecological indicators are currently hot topics. As a result, the revised raw material policy establishes long-term objectives and tools for the rational use and protection of raw material resources while maintaining manufacturing sustainability and environmental protection (Kuzevič et al., 2019).

In our research, raw materials are essential components of the production process. In reverse supply chain operations, materials returned by consumers or used as raw materials can be recovered, which requires governments and manufacturers to prioritise the rational use and preservation of these materials.

5.3.3 What are manufacturing ethics?

In this study, manufacturing ethics refers to companies' introduction of their products to customers in a manner that communicates their advantages and benefits. It provides customers with the value and benefits of the required quality. Additionally, it does not impose additional costs on the customer that do not benefit them.

5.3.4 Contemporary vision of RSCs activities:

Refer to the research perspective on customer preferences, the rational use of raw materials, and manufacturing ethics.

5.4 Systematic approach to current knowledge:

To provide a strong theoretical justification for our current research methodology, the researcher created a synthesis matrix of the most prominent prior contributions in the field of I4.0 technology in the context of RSCs activities, focusing on the variables' dimensions and the methodologies used in their studies. This matrix can be used to define the research methodological frameworks. To update the current knowledge, we tested methodological frameworks that require further investigation.

Table 5- 1 A synthesis matrix of the most prominent previous contributions to I4.0 technology to support RSCs activities.

Study	Methodology	I4.0 Technology Focus	RSCs Dimension Addressed	Measurement Mechanisms
Bag et al. (2020)	Quantitative (Survey; PLS-SEM)	IoT, Big Data Analytics	RSCs performance, Environmental Sustainability	Likert-scale survey items, SEM
Frederico et al. (2021)	Case Study (Multi-case, qualitative)	CPS, IoT, AI	Decision-making in RSCs; Traceability	Interviews, Thematic Coding
Tseng et al. (2018)	Mixed Methods (Quantitative + Fuzzy DEMATEL)	CPS, RFID	Reverse logistics barriers & enablers	fuzzy logic-based causal analysis
Subramanian & Gunasekaran (2020)	Simulation & Optimisation Modeling	Blockchain, IoT	Product returns management, Remanufacturing	Simulation metrex (cost, time, accuracy)
Dalenogare et al. (2018)	Survey (Quantitative)	AI, IoT, Cloud Computing	Supply Chain Innovation (including RSCs)	Regression models, Innovation indices
Jayaraman et al. (2019)	Analytical Modeling	Big Data, Digital Twins	Optimal product recovery, Reuse/Recycle	Mathematical modeling, scenario analysis
Kamble et al. (2021)	SEM	Blockchain	Transparency in RSCs, Anti-counterfeit	SEM indicators, constructs from the literature
Queiroz et al. (2020)	Survey + Bibliometric Analysis	AI, Blockchain, IoT	Circular Economy integration with RSCs	Keyword co-occurrence, Bibliometric indices

Highlighting previous contributions by I4.0 researchers to supporting RSCs activities, we aim to strengthen our research approach. Studies such as (Bagh et al.,2020; Kamble et al., 2021), and

Subramanian & Gunasekaran (2020) have focused on quantitative approaches, often using SEM techniques in data analysis or simulation models, to assess the impact of technologies such as IoT, CPS, big data analytics, and blockchain on various aspects of reverse logistics. Other studies, such as those by Frederico et al. (2021) and Tseng et al. (2018), have employed qualitative or mixed-methods research approaches to identify the challenges and enablers of integrating I4.0 technologies into RSCs. Bagh et al. (2020) also used mediating variables from supply chain practices to link the research variables.

The majority of past research has focused more on RSCs operations, with an emphasis on operational outcomes such as cost reductions, process efficiencies, traceability, and recycling. Such research has made significant contributions to the development of enabling technologies that underpin RSCs activities. Although our study is based on existing knowledge, it will contribute to the field's development by providing a multidimensional perspective on RSCs' activities. It is grounded in theoretical pillars that support the research questions, and it offers a vision that extends beyond technological drivers to encompass environmental practices and consumer-centric manufacturing ethics in the modern industrial environment. Building on the earlier works, which were devoted to efficiency and cost-related metrics, our study investigates the connection between the I4.0 technologies (cyber-physical systems, the Internet of Things, big data, cloud computing and smart factories) and RSCs activities in the context of the modern vision that is not explored in the literature. These practices reflect emerging consumer expectations, environmental determinants, and ethical manufacturing in RSCs and consequently affect manufacturing sustainability. Our research has a major strength: its methodological depth. Although SEM has been extensively applied in this area, we extend the use of quantitative analysis through semi-structured interviews to provide rich, meaningful contextual information from industry practitioners. This type of mixed-methods approach not only justifies the research model but also provides a realistic picture of the nature of the relationship between the research variables in business contexts.

Moreover, our study is based on a prospective theoretical framework that contextualises RSCs activities within the further development of sustainable, digitally enabled manufacturing systems. It examines how these practices by the same RSCs mediate the enhancement of the complementarity between forward and backward logistics. This approach provides a global view that connects technological competencies with the strategic and ethical orientation of manufacturing, an area that remains largely underexplored in current research.

Altogether, our study aligns with the current body of knowledge on the facilitating role of I4.0 technology in improving RSCs activities. It also reflects recent developments in manufacturing. These include ethical production, consumer tastes, and rationalised use of materials. This adds to a more

balanced, holistic, and futuristic approach to the role of I4.0 technology in transforming RSCs' operations.

5.5 Research design:

Turner et al. (2017) note that a research design outlines the process the researcher will follow to obtain the desired results. This aids the researcher in identifying the appropriate research channels and access points required for the type of research (Carcary, 2020). It also defines the techniques that could be employed to understand the phenomenon under study, ensuring consistency with the research's broad aim. Equally, Ragab & Arisha (2018) present a set of methods and procedures for gathering and analysing measurements of the variables identified in the research design.

When choosing the appropriate design, a researcher must first identify the purpose of the research. This enables the selection of the most suitable design and methodology to address the research questions (Adeoye, 2024). As a result, the important design issues should be determined in advance (Abutabenjeh & Jaradat, 2018).

The study's systematic design is based on the research model. Here, the framework is transformed into quantifiable indicators, and the variables pertinent to the research are mapped onto the research model to demonstrate how these relationships are structured in the proposed hypotheses. The approaches used to collect, measure, and analyse data are presented in the following subsections to elucidate the presumed relationship among the study variables.

To illustrate how these aspects are structured within the quantitative paradigm, Figure 5-1 presents the quantitative research design for the current study, showing the flow of variables, procedures, and analytical steps.

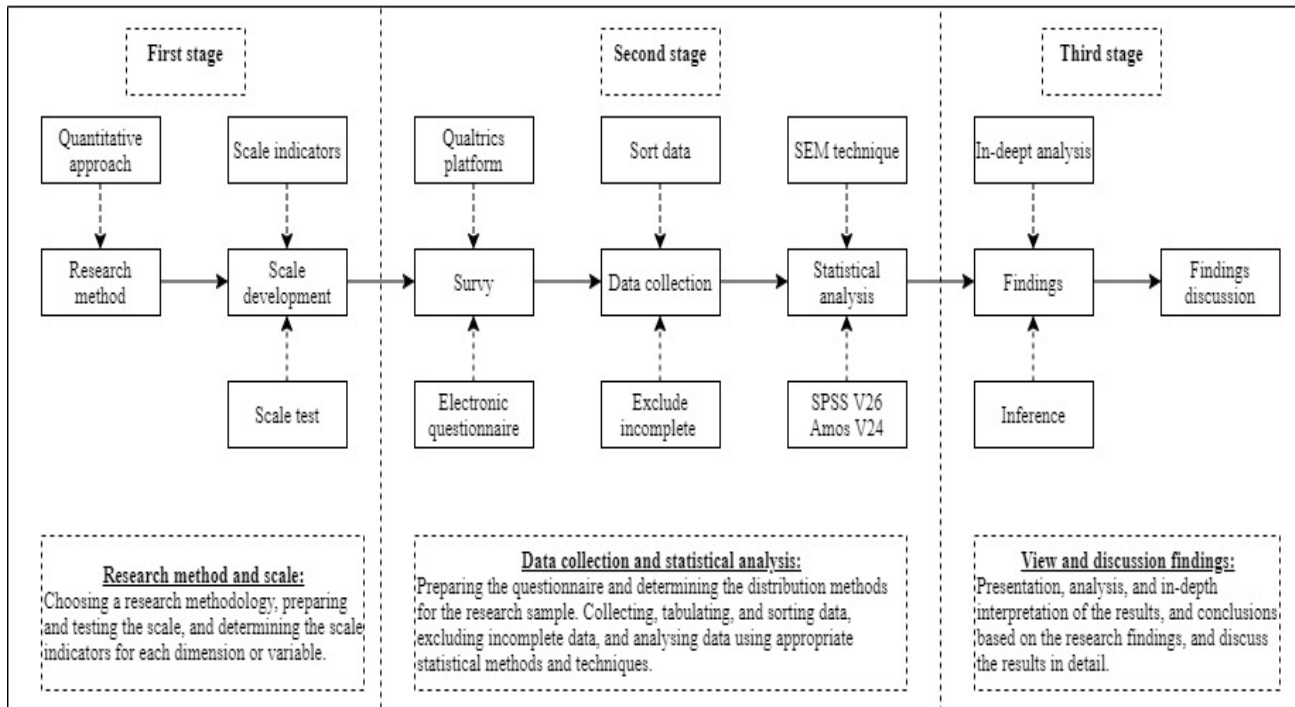


Figure 5- 1 quantitative research design (Source: authors).

Similarly, the study's quantitative design incorporates elements of the qualitative design to enhance the findings. Thus, Figure 5-2 presents the mixed-methods research design and underscores the integration of qualitative and quantitative stages to enhance triangulation and strengthen empirical validity.

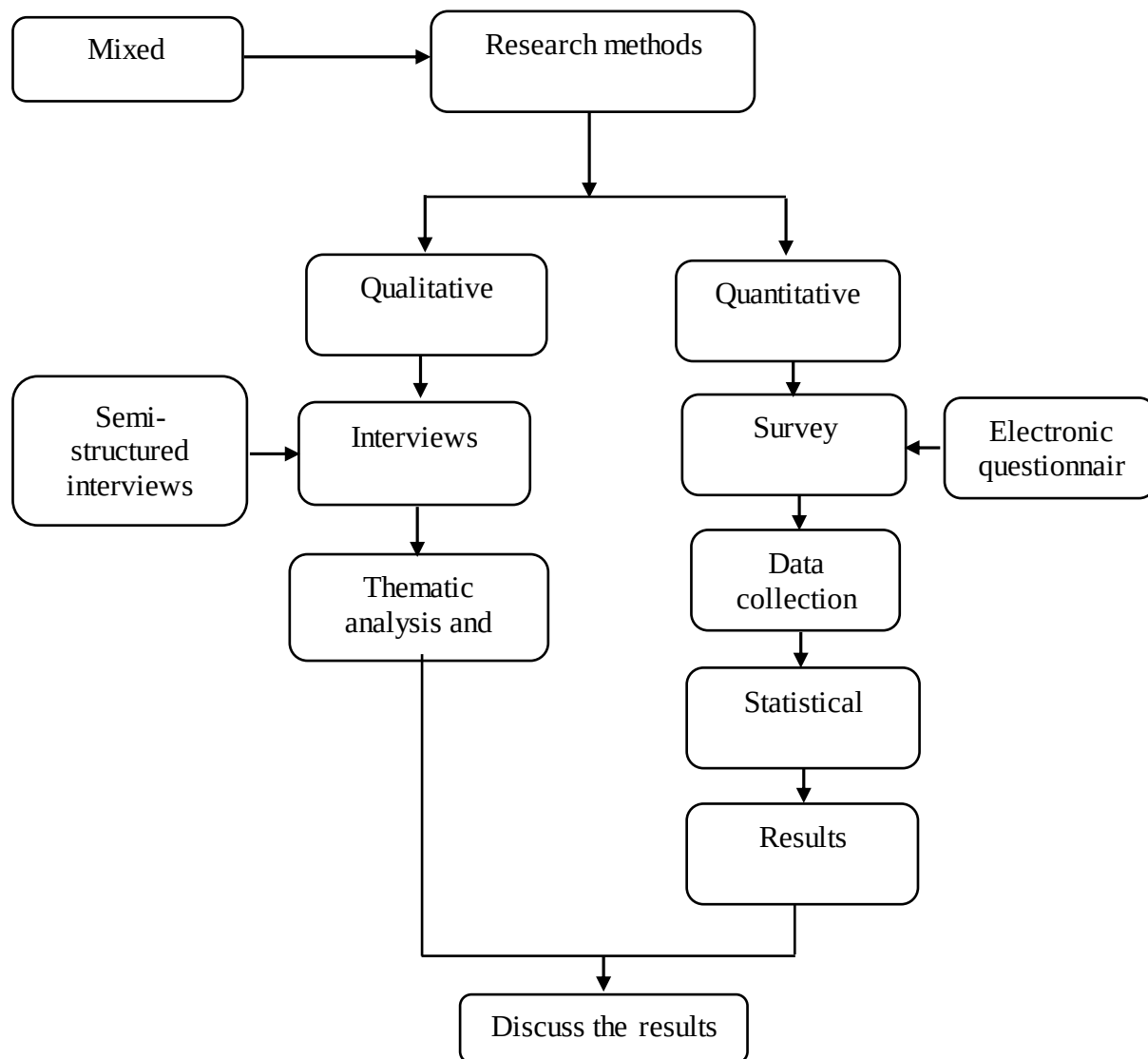


Figure 5- 2 Mixed research design (Source: authors).

The research methodology structure presents a logical map through which the study should be carried out since every methodology would play an effective and systematic role in responding to the research questions, delivering the results they want and supporting them with empirical and practical research in the industry reality.

This section describes the process of implementing mixed-method approach. Sequential explanatory design (SED) is a design that entails sequential phases of mixed-methods research as a necessary explanatory route of the method employed in the selected research. To illustrate, in this research, a quantitative methodology will be used, and then a qualitative approach will be applied, and lastly, a synthesis of the two methodologies will be done.

A sequential explanatory design (SED) is a research design that combines qualitative and quantitative methods in a single study or in a sequence of stages (Teddle & Tashakkori, 2009; Creswell, 2008). A

sequential explanatory design is a sequence of steps addressed in order, with the first step potentially qualitative or quantitative. A sequential explanatory design (SED) outlines research directions that integrate quantitative and qualitative methods across one or more phases, yielding mixed-methods research (Creswell, 2008; Clark et al., 2008). The application of the SED method aligns with our current research directions in data collection. It should fulfil the research objectives by analysing two data sources (questionnaires and interviews) to provide a comprehensive picture of the two research variables (reverse supply chains and Industry 4.0). It also enhances the overall thoroughness of the findings by showing how qualitative interview data yield interpretations that validate and supplement the quantitative research strategy is statistical analysis. It also enhances the accuracy and diversity of the results, as the outcomes of both the quantitative and qualitative stages can be accessed and verified for consistency and logical interpretation. Therefore, mixed methods research can significantly enhance the demonstration of the impact of the relationship and integration between Industry 4.0 technology and reverse supply chain activities.

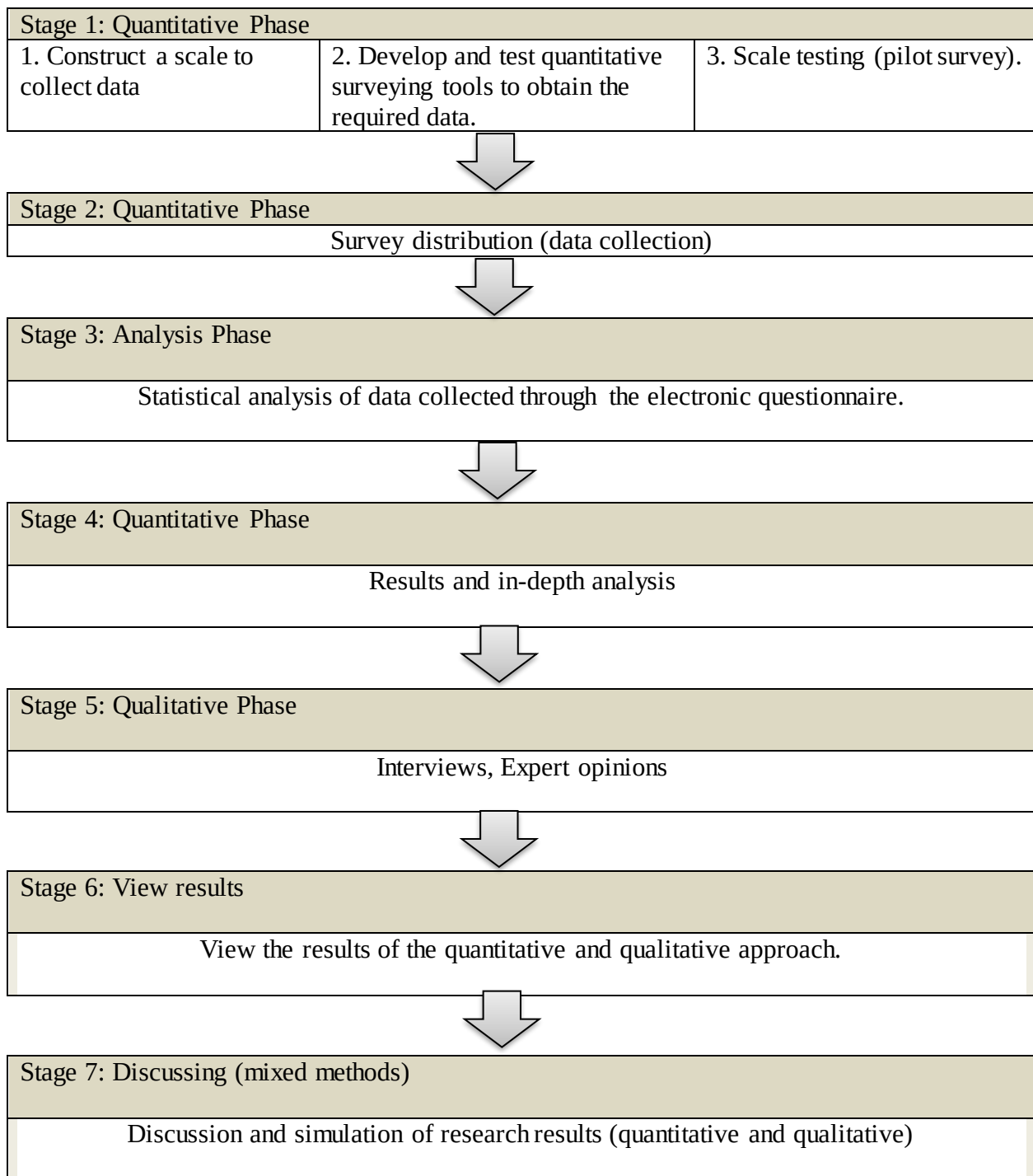


Figure 5- 3 Design research method based on SED

5.6 Research philosophies:

Existential and epistemological assumptions are the philosophical foundations of any research (Neesham, 2017). It provides insight into recognising the limitations imposed on our thinking, which helps us choose the approach to follow for data collection and the research methods, allowing us to shape the methodological research approach (Abutabenjeh & Jaradat, 2018). The methodological

assumptions of the research reflect the scientific philosophy underpinning its strategies. The following categories apply to research philosophies (Al-Haracha & Pius, 2020):

Ontology - represents the study of the nature of reality and existence.

Epistemology pertains to the study of the nature of knowledge.

Methodology: the overall research strategy.

Methods are the means used to collect and analyse data to develop knowledge.

According to positivist principles, reality can be seen and described objectively, and various phenomena can be selected and replicated (Antwi & Hamza, 2015). In positivist approaches, ontology is usually viewed objectively, while epistemology concerns phenomena that can be directly observed and measured. Positivism often favours quantitative research and methods that manipulate variables to identify relationships among observations (Ugwu et al., 2021; Babones, 2016). In contrast, the qualitative method, often combined with the interpretive philosophy of reality, is the only way to fully understand the phenomenon (Fuster Guillen, 2019).

5.6.1 Philosophical framing:

The ontological and epistemological presuppositions are philosophical in nature and serve to justify any research (Baškarada & Koronios, 2018). It creates philosophical consciousness in the researcher and clarifies the direction taken, allowing them to envision the data collection and research methods required to achieve results aligned with the research method (Dzwigol, 2022). A research philosophy is a set of basic beliefs and assumptions that inform the researcher's information collection, knowledge generation, and interpretation of results (Alem, 2020). It forms the basis for decisions about the research methodology, approaches, and techniques to be used in a study (Abutabenjeh & Jaradat, 2018). Various research philosophies exist, each grounded in distinct perspectives on the nature of knowledge and reality, and on the relationship between the researcher and the subject of study (Al-Ababneh, 2020).

5.6.2 Philosophical issues and the choice of research method:

Researchers systematically work to discover new knowledge, thereby enhancing their understanding of various phenomena (Yilmaz, 2013). Researchers employ scientific methodologies consistent with previously defined hypotheses and objectives, depending on the nature of their research. According to the methodologies that correspond to the nature of the study, researchers must choose research methods that align with the nature of each research, whether quantitative, qualitative, or a combination, to obtain the best and most accurate results.

In this section of the research, we will clarify the philosophical dimension on which this research is based. A review of the management sciences literature reveals that researchers have adopted different philosophical perspectives (Dzwigoł, 2022). Therefore, researchers specialising in various management sciences adopted a philosophical perspective that is typically experimental and traditional (Dzwigoł & Dzwigoł-Barosz, 2018). The previous theory holds that reality can be perceived only through sensation. This approach employs mathematical modelling to infer causal relationships from data gathered (Rodgers et al., 2016).

On the other hand, numerous investigators have observed that many studies primarily rely on statistical analysis. The authors found that most publications adopted a positivist viewpoint. Thus, positivism has prevailed, while acknowledging the validity of other philosophical frameworks, such as interpretivism. In addition, positivist philosophy effectively conveys reality through observation and experimentation. Interpretivists' orientations are the opposite: they hold that reality exists independently and that everything is relative to subjective perceptions of it (Kakuru, 2019). A recent review of management science publications has confirmed the prevalence of positivism as the accepted research philosophy. In addition, the interpretive perspective has gained significance in management science due to the recognition that businesses are social entities. As a result, interpretive philosophy has been the subject of numerous research papers (Turyahikayo, 2021; Crane & Glozer, 2016).

In the late 1980s, the mixed-methods research model was officially introduced and reached its peak in the evolution of research models (McKim, 2017). As a result, this model rapidly developed into a combination of quantitative and qualitative approaches to overcome their individual limitations. However, adopting this research method required significant effort. The quantitative approach is often linked to a post-positivist stance, while the qualitative approach is usually associated with a constructive (interpretive) stance (Gamlen & McIntyre, 2018). Therefore, mixing these methods seems incompatible due to their differing philosophical foundations. Consequently, proponents of mixed methods research must provide strong motivation and justification for combining these approaches and develop a solid philosophical basis for their integration (Shan, 2022).

Based on the existing debate between positivists and interpretivists regarding the appropriate philosophical approach compatible with mixed research methods (Baškarada & Koronios, 2018). Joseph Maxwell & Kavita Mittapally (2010) have developed a critical realist stance appropriate for mixed methods research. This critical realist position assumes that there is a mind-independent physical world and that “there can be more than one scientifically valid way of understanding reality in terms of conceptual schemes with different objects and classes of objects (Zachariadis et al., 2013)”. Maxwell and Metapally argue that these critical realist assumptions entail a mechanistic account of causality, a mechanistic account of mental phenomena, a realist conception of validity, and a realist

account of variation. Accordingly, they argue that these “realistic assumptions” justify a process-based qualitative approach to causality, a critical approach to qualitative research, and a mixed-methods approach to validation, thereby overcoming the neglect of methodological diversity in practice. In this way, Maxwell and Mitapalli argue that mixed-methods research can be justified from a critical-realist perspective (Shan, 2022).

Furthermore, critical realism is a recent philosophical perspective that has emerged in management science (Frederiksen & Kringelum, 2021). It highlights the importance of critical realism to management studies. In critical realism, the realistic and empirical are distinguished (Armstrong, 2019). Critical realism aligns well with modern research directions. The research perspective aligns with the philosophical framework that asserts reality exists independently of the observer (Bogna et al., 2020). A critical, realistic outlook can guide the researcher's analysis of the relationship between Industry 4.0 technology and reverse supply chain activities. Critical realist approaches can explore the fundamental concepts underlying the connections among key and subsidiary research variables, thereby providing a deeper understanding of the research philosophy.

The critical realist approach can accommodate multiple variables and integrate multiple methods, thereby enabling a comprehensive picture of the physical and moral world (Mingers, 2006). The reason why the researcher chose this research philosophy is that it aligns with the researcher's approach to employ mixed research methods by administering surveys and questionnaires to industrial companies, and conducting semi-structured personal interviews with professionals in the field of Industry 4.0 and reverse supply chains in order to provide more detailed interpretations of the data that was gathered. Analyse it, expand the scope of knowledge, and compare any differences in the answers of the research sample or any bias in the answers of the respondents from the research sample.

This research will use both quantitative and qualitative methods to achieve the most accurate and comprehensive results. The quantitative part of the study will support the qualitative element, improve the accuracy of the results, and provide data and insights that cannot be captured through descriptive measurement within the organisation.

This research employs pre-structured questionnaires to collect responses from the research sample, personal interviews, structured literature reviews, industry surveys, expert interviews, modelling and simulation, and analysis of company documents to generate results.

5.7 A theoretical framework in research methods:

5.7.1 Research Methods:

Research methods refer to the plans and procedures for gathering and evaluating data to address research questions (Abutabanja & Jaradat, 2018). Furthermore, several research approaches include

quantitative, qualitative, and mixed-methods designs (Baškarada & Koronios, 2018). Variables are measured through quantitative techniques and quantified. Data in this research method are usually analysed using statistical procedures and numerical data (Mohajan et al., 2020). On the contrary, qualitative methods depend on grasping the meaning and complexity of phenomena; the purpose of qualitative research is to address human phenomena through meanings, experiences, and interpretations. It is commonly used in social science and humanities studies, as well as in teaching, to facilitate understanding of diverse perspectives (Fuster Guillen, 2019). Mixed-methods research integrates quantitative and qualitative approaches. Furthermore, the researcher selects the research method based on factors such as the research aim, research questions, and research design (Plano-Clark, 2017).

5.7.2 Qualitative Research Methods:

The purpose of qualitative research is to unravel and comprehend the social or human problems that certain individuals experience (Creswell, 2013). Qualitative research gathers and analyses non-numeric data to gain insight into concepts, views, experiences, or phenomena. It may be used to collect data on a given issue or to generate new research directions. Qualitative research is common in the humanities, social sciences, and other sciences (Mason, 2010). Eriksson & Kovalainen (2008) identify five categories of quantitative research: social surveys, experiments, official statistics, structured observation, and content analysis, each with its own peculiarities and advantages. Qualitative research is preferable when the phenomenon being studied is not known in advance, making it exploratory and flexible (Donmoyer, 2012). Advantages: Qualitative research yields detailed descriptions of participants' feelings, opinions, and experiences. Its findings reveal the precise, in-depth relationship between information processing and performance, as well as an understanding of human experience in specific settings and of various personal meanings and events. Qualitative research enables researchers to gain insight into participants' inner experiences and perspectives. There are numerous data collection methods. Qualitative research design is flexible because it can be built and reconstructed (Rahman, 2020). The disadvantages of this method include that research approaches sometimes condone contextual sensitivities in support of focusing on meanings and experiences; policymakers may be sceptical of qualitative results; the sample size may not accurately reflect the entire population of the study; and case analyses can take a long time (Harry & Lipsky, 2014).

In this study, we will use a qualitative method to analyse part of the data by conducting interviews, gathering experts' opinions, and performing content analysis to generate the researcher's ideas inductively and interpretively, consistent with the research philosophy, as reflected in the research sample's responses.

5.7.3 Quantitative Research Methods:

The availability of economic, financial, and business data, and their use in empirical research on entrepreneurship, have increased substantially in recent decades. Therefore, any quantitative work of this nature should be approached with careful statistical analysis and a thorough understanding of the strengths and weaknesses of the methods and data used to assess the contribution and challenges posed for future research. (Saridakis et al., 2020). The advantage of this method is that information analysis requires minimal input, provided that the numerical data are available. Quantitative research focuses on aspects of social behaviour that can be quantified and modelled, rather than just discovering and interpreting meanings (Carroll & Bailey, 2016). The disadvantage of this method is that the quantitative research approach overlooks the interconnections among social phenomena. When it comes to determining deeper implicit meanings and explanations, it also needs to catch up. Quantitative research goals are measurable and cannot be separated into variables and hypotheses; variables are concepts that vary and can take multiple values, whereas hypotheses are untested assumptions or propositions about relationships between variables. The survey, case study, and experimental research strategies are the most frequently used in quantitative research (Håkansson, 2013). In this study, we will employ a quantitative approach, utilising surveys and questionnaires to analyse and present results using appropriate statistical methods.

5.7.4 Mixed Methods:

Mixed methods research is a research design that employs multiple methods (Venkatesh et al., 2013). Mixed-methods research identifies three basic types of mixes. Includes the mere use together, linking, or actual integration of one or more Quantitative and qualitative elements at one or more time points in one study or a research program encompassing multiple studies (Flick, 2017; Timans et al., 2019). Mixed-methods research combines qualitative and quantitative research components to broaden and strengthen a study's conclusions, thereby contributing to the body of knowledge. Mixed-methods research should be employed in studies that aim to answer research questions. A researcher may wish to strengthen the research study and its conclusions for various reasons or purposes, despite the validity of answering the research question(s). Every accurate mixed-methods study has at least one "point of integration," known as a "point of interface" (Schoonenboom & Johnson, 2017).

Although a few similar studies have employed both approaches, prior literature has been limited in examining industry-reverse supply chains, often adopting quantitative, qualitative, or mixed-methods approaches (Castro et al., 2014). Mixed methods research is the third methodological movement (paradigm), with quantitative and qualitative methods representing the first and second movements (paradigms). However, proponents of mixed-methods research have suggested that a mixed-methods

approach may be superior to a single-method design in certain situations. There has been considerable discussion about whether combining multiple methods from radically different paradigms is appropriate (Venkatesh et al., 2013).

This research will focus on several activities and recycling operations within the reverse supply chain. Our study must adopt a mixed approach to data collection, analysis, result extraction, and customer information management. As a result, combining positivist and interpretive viewpoints requires a user-friendly approach, such as a mixed-methods design (Castro and colleagues, 2014). This study supports a mixed-methods approach to address research questions, as it can be used both quantitatively and qualitatively, providing objective explanations when necessary. Moreover, qualitatively, it is essential to understand others' meanings and nuances (Mertens & Hesse-Biber, 2013).

5.8 Research scale:

In this study, because no scale was found compatible with the research variables identified in our previous literature review, the researcher developed a new scale encompassing the primary and secondary research variables and their sub-dimensions, while meeting all scientific requirements for scale development. The 5-point component is appropriate for collecting and analysing research data and has been confirmed to fit the scale's context. Moreover, several academic experts with analytical experience will assess the survey's accuracy and compatibility with the study's requirements. A preliminary survey will be conducted to determine the type and strength of the relationship between the research variables and to exclude non-influential variables.

5.8.1 Scale development concepts:

Measures aim to clarify core concepts that cannot be directly explored by relying on concrete statements. It can be defined as a combination of multiple components that aims to reveal relationships between theoretical variables that cannot be directly observed. Absolutely, scientists cannot directly keep the relationship between the elements, but using measures can determine whether the elements are sufficiently related (Carpenter, S., 2018). The survey questions were carefully formulated and reviewed by experts. The questions were designed to capture key indicators that accurately and comprehensively represent each variable or dimension. Furthermore, the indicators clearly and precisely conveyed the purpose of developing the scale, which was to measure the relationships between variables and demonstrate their role in promoting sustainable and responsible practices in RSCs activities. Appendix 4 provides detailed information on the measurement indicators.

5.8.2 Scale development steps:

To ensure the reliability and validity of the five-point Likert scale and its suitability in accurately measuring the research variables and their sub-dimensions, several procedures are necessary to develop and refine it for the desired purpose. As in the following steps:

1. Careful review of the research variables and highlighting in depth the theoretical framework (identifying the appropriate nomenclature, concepts, definitions, dimensions, or sub-elements) and designing the questionnaire (creating the questionnaire framework, adopting a suitable scale, preparing the questionnaire questions, presenting the questionnaire to a group of experts, and benefiting from the nutrition review).
2. Select the target sample based on the size of the research community and assess the data quality for the sample.
3. Verify the susceptibility of the data to the following factors:
 - a. Kaiser-Meyer test for adequacy of sampling (≥ 0.60).
 - b. Bartlett's Sphericity Test is used to ensure the quality of the measurement in terms of (Chi-Square). To ensure the quality of this test, the results must be significantly less than (0.50%).
4. Correlation matrix check (≥ 0.30).
5. Test (Analysis Factor Confirmatory) to determine the degree of saturation of each questionnaire paragraph with the sample's answers. This test determines whether some questionnaire paragraphs need to be excluded or reduced.
6. The following statistical tests were performed to ensure the scale's validity: the composite reliability coefficient (CR) for internal consistency, the interpreted mean variance (AVE), and the ratio of variable to univariate features (HTMT) for discrimination validity.
7. Reliability tests: Reliability is one of the crucial tests that must be conducted on the research scale. Moreover, a test is accurate if it consistently yields the same results and can be replicated on the same sample under the same conditions. Cronbach's Alpha is used to assess the internal consistency of scale items and the reliability of results across periods. Its value must exceed 0.70 to be statistically significant in management and behavioural research. The Cronbach's alpha reliability coefficient is also calculated for the odd and even vertebrae, in addition to conducting the forms using the Correlation coefficient test, the Brown-Spearman coefficient, and the Coefficient Split Guttman coefficient.

5.8.2.1 Planned Diagnostic Tests for Assessing EFA Assumptions:

Exploratory factor analysis aims to reduce a large number of questions to the smallest possible number of variables (dimensions). Each dimension is saturated with many questions that represent it. These dimensions are somewhat heterogeneous among themselves but homogeneous within themselves. These dimensions also account for the maximum possible total variance, so adding a new dimension does not increase the variance already explained. Exploratory factor analysis is characterised by using statistical tools to achieve all of the above. In addition, the application of exploratory factor analysis requires a set of conditions, namely:

1. The questions have a normal distribution, which is unnecessary if the sample size is large.
2. The sample size must be suitable for conducting exploratory factor analysis. This is tested using the Kaiser-Meyer-Olkin (KMO) index, which must be at least 0.5.
3. There is no problem with autocorrelation between the questions. The determinant of the correlation coefficient matrix demonstrates this. If the value of the determinant is less than 0.0001, this indicates an autocorrelation problem. Therefore, questions with correlation coefficients greater than 0.80 should be excluded.
4. The values of the correlation coefficients between the questions must be significant. This is tested using Bartlett's Sphericity index, which is based on the chi-square distribution. If the probability value of this index is less than 0.5, it indicates the significance of the correlation coefficients between the questions.
5. The dimensions resulting from exploratory factor analysis must be realistic and can be interpreted by the researcher within the framework of the research's theoretical context.

This research conducted an exploratory factor analysis (EFA) of the research variables: I4.0, RSCs, customer feedback, and recycling. Before conducting EFA, diagnostic tests were planned to assess sampling adequacy and factorability across all four variables. Table 5-1- 1 Summarises the dimensionality of each construct and the specific assumption tests to be applied.

Table 5- 2 Diagnostic Tests Planned for Assessing EFA Assumptions.

Variable	Number of Dimensions	Diagnostic Tests to be Applied
Industry 4.0	5	KMO Measure of Sampling Adequacy; Determinant; Bartlett's Test of Sphericity
Reverse Supply Chain	3	KMO Measure of Sampling Adequacy; Determinant; Bartlett's Test of Sphericity
Customer feedback	1	KMO Measure of Sampling Adequacy; Determinant; Bartlett's Test of Sphericity
Recycling	1	KMO Measure of Sampling Adequacy; Determinant; Bartlett's Test of Sphericity

As shown in Table 5-1, all variables will be evaluated for factorability using the KMO measure, determinant values, and Bartlett's Test of Sphericity. These criteria reflect established thresholds in the EFA literature ($KMO \geq 0.60$, determinant > 0.00001 , Bartlett's $p \leq 0.05$), ensuring that the data meet statistical adequacy requirements before proceeding with factor extraction.

5.9 Statistical tools (mathematics):

Statistical analysis is the cornerstone of research, enabling researchers to derive meaningful insights from data and test hypotheses. Different tools are employed in data analysis depending on the research questions, hypotheses, data type, and desired results. The researcher will rely on a set of statistical measures in addition to verifying the validity of the hypotheses, which we explain through their uses as follows:

1. **Frequencies:** Used to display the answers of the individuals being studied.
2. **Percentages:** To clarify the percentage of responses to a specific variable compared to the total responses.
3. **Arithmetic mean:** Displays the average responses to a specific variable through the sum of the values divided by the number of values.
4. **Standard deviation:** To show the degree of dispersion of the research sample's responses from their arithmetic mean.

5. **Relative importance:** To display the positions of the individuals in the research sample towards their variables, and is calculated using the following equation: Relative importance = arithmetic mean of the individual's responses to the area of the scale/Likert scale used * .100
6. **Cronbach's alpha coefficient:** To measure the stability of the questionnaire tool.
7. **Internal consistency:** This measure measures the degree of interdependence of paragraphs within the variable and is calculated by dividing the sum of the correlations (for paragraphs) within the variable by the number of those correlations.
8. **Test of (Kolmogorov-Smirnov):** Examining the probability distribution of the dimensions and variables of the study and matching it with the normal probability distribution.
9. **Test of (Harman single factor):** Examining the presence or absence of bias in the common method (CMB).
10. **Confirmatory factor analysis:** To diagnose the validity of the construction of the study scales through structural equation modelling (SEM).
11. **Simple correlation coefficient:** Measuring the nature and strength of the relationship between any two variables.
12. **Simple linear regression coefficient:** Estimating the mathematical picture of the relationship between one independent variable and a dependent variable.
13. **Multiple linear regression coefficient:** Estimating the mathematical picture of the relationship between more than one independent variable and a dependent variable.
14. **Path analysis:** To show the direct and indirect influential relationships between the study variables.
15. **Statistical software and tools:** Use the SPSS V26 and Amos V24 programs.

Using one of these tools, or combining some of them, and following the research design in Figure 3-1, the researcher can systematically conduct data analysis and answer the research questions in line with the research hypotheses and objectives.

5.9.1 Mediation tests:

To investigate the direct and indirect effects of Industry 4.0 on contemporary visions of RSCs activities, a mediation analysis was conducted in IBM SPSS Amos, with customer feedback and recycling specified as the mediating construct. The model was estimated using the Maximum Likelihood (ML) method. Given that indirect-effect distributions are typically non-normal in mediation models, statistical inference for these indirect effects was based on a bootstrap resampling procedure rather than normal-theory approaches (e.g., Sobel's test).

Five thousand bootstrap resamples with replacement were generated from the original sample of 250 valid questionnaires. Path coefficients were estimated for each resample, and the indirect effect was computed. This procedure produced 95% BC confidence intervals (BC 95%), based on an empirical distribution of these M estimates, which was calculated directly in AMOS. The bias-corrected method was selected because it corrects for both bias and skewness in the bootstrap distribution, yielding more accurate interval estimates than percentile methods in mediation contexts (Tibbe & Montoya, 2022). When the confidence interval for an indirect effect excluded zero, the effect was considered statistically significant.

5.10 Interviews:

In continuation of the research, the sample data collection process (qualitative method) will parallel the quantitative data collection process. As shown in Figure 5-1-1, Research design. In this section, we will discuss the types of interviews used in scientific research to collect qualitative data, which are categorised as unstructured, semi-structured, and structured (Naz et al., 2022; Harrell & Bradley, 2009). Data collection methods. Semi-structured interviews and focus groups. Unstructured interviews are characterised by informality. There is no need to create a questionnaire or a pre-determined structure for the interview. Specific topics in this type of interview are emergent and exploratory (Opie, 2019; Wongsuphasawat et al., 2019).

The interviewer asks questions as the conversation unfolds (Kallio et al., 2016). For the second type, semi-structured interviews, a predetermined structure must be established, as the interview guide outlines the main points and the content focuses on relevant topics through specific questions (Naz et al., 2022). Based on the interview guide, the topics are systematically investigated with each interview participant. Accordingly, some questions are discussed in more detail (Alam, 2021). The third type of structured interview uses complete questionnaires prepared for this purpose. The questionnaire contains standardised questions, and the interviewer asks identical questions simultaneously (Sturgis et al., 2021). This type of interview is usually conducted to collect measurable data (Saunders et al., 2019).

Accordingly, the researcher employed a semi-structured interview to collect qualitative data. This method is beneficial in mixed-methods research, as it demonstrates and validates the results that will emerge from the quantitative aspect of the research. Specifically, it enables an in-depth investigation of certain topics by comparing quantitative results with respondents' qualitative responses. In addition, the semi-structured interview method allows for comparisons of responses across interview participants. It is also possible to analyse respondents' views on the nature of the relationship between Industry 4.0 and reverse supply chains, as well as the mechanisms of their integration, to enhance the research findings or inform research recommendations.

5.11 Interview design:

One of the most popular techniques for collecting data in qualitative research is interviewing (Crouch & McKenzie, 2016). Interviews vary in nature and are classified into two types: structured and unstructured. Structured interviews are closely related to surveys, as they are face-to-face and primarily focus on ensuring the accuracy of the data structure, which will be subjected to statistical analysis (Harris & Brown, 2019). Unstructured interviews are open-ended discussions intended to uncover a specific aspect whose truth is to be revealed, with brief questions used to initiate the conversation (Klenke, K., 2016). If the people interviewed were more interactive and experienced in their field of specialisation, the results would be more accurate, as the level of interest depends mainly on the nature of the questions, their focus, the respondent's answers, and the results obtained from the interview after analysing it using appropriate statistical tools (Alam, 2021).

Researchers often combine the two methods, adopting a semi-structured approach that balances structured questions with unstructured discussions, thereby facilitating in-depth analysis by respondents and enabling comparisons across multiple data-collection methods (Brannen, 2017). It is possible to find appropriate comparisons and achieve accuracy. Information is obtained by comparing the answers of the selected sample of respondents in the interviews with the answers of the research sample. This allows the researcher to use an alternative measure to collect data on the same research questions, thereby enabling more accurate and reliable exploration of the facts. Additionally, it enables comparisons and simulations between any differences in answers. The two samples conform to the two standards used by the researcher (Snyder, 2019).

5.12 Selection of participants for the qualitative method:

After the researcher has determined the semi-structured interview method, the sampling method for semi-structured interviews must be determined. Typically, two types of sampling methods are distinguished: probability and non-probability sampling techniques. Probability sampling methods are

mechanisms for selecting a sample randomly from a population. Non-probability sampling refers to techniques in which the sample is not selected randomly.

In this research, the researcher employed a non-probability sampling method to ensure that interviews were conducted with individuals possessing high expertise and skills within the scope of the research. There are different non-probability sampling techniques. Quota sampling is a technique in which the sample is selected based on pre-specified variables. The rationale for this method is that the final sample should have the same variance in specific characteristics as the population under study. Purposive sampling is another method for selecting the sample based on the researcher's judgment. Some participants may be considered more beneficial to the study than others may. Another method of non-probability sampling is voluntary sampling. Through this approach, participants volunteer for the research rather than being selected. According to these sampling techniques, the researcher employed intentional sampling, a non-probability sampling method, as it is more suitable for the requirements of our current research.

5.13 Conducting interviews:

The interview method influences the credibility, reliability, and validity of the data obtained (Saunders et al., 2019).

The beginning of the interview is significant for building mutual trust with the interviewees. The interviewer should first express gratitude for the participant's time, introduce themselves, and state the purpose of the interview and the research topic. Participants were also assured that their identities would not be disclosed without their consent. After that, participants were asked to refrain from answering any questions they did not wish to answer, or that required further information. The researcher selected participants based on their experience in Industry 4.0 and reverse supply chains.

5.14 Interview data quality:

Data quality issues should be considered when conducting semi-structured interviews. Data reliability, freedom from bias, cultural differences, generalisability, and validity should be regarded (Belina, A., 2023). Data are considered reliable if they are supported by other scholars' opinions on the same data and method. The exact replication of findings in qualitative research is seen as unrealistic (Toma, J. D., 2011). Various biases can also reduce the value of the collected interview data. There are several reasons for the unreliability and inaccuracy of data. One is that data quality may be compromised by interviewer bias. This type of bias can arise from the way the interviewer asks questions, which may influence participants' answers (Mohorko & Hlebec, 2015).

Conversely, bias may also stem from the interviewer's tone of voice or non-verbal behaviour. Additionally, interviewer bias can result from misinterpreting interviewees' responses or from the interviewer's inability to build trust with them (Irvine et al., 2013). On the other hand, bias might originate from the interviewees' responses, such as when they fail to express their true opinions. This leads to poor and unreliable data (Small & Cook, 2023). Furthermore, bias may arise from the selection of interviewees; for instance, choosing only managers can yield biased data because their responses may portray the organisation unrealistically, thereby distorting the results (Saunders et al., 2019).

Therefore, these issues must be taken into account when conducting interviews to obtain reliable, credible data. Thus, the researcher conducted interviews in a manner that minimised the risk of the aforementioned biases. The interviews were conducted neutrally, and participants' responses were carefully transcribed. Some participants were asked to elaborate on specific answers and to write a clear summary of their opinions. In the interview, without any personal judgment. Sometimes, probing questions were used to elicit further clarification of specific answers. Similarly, the interviewer partially summarised the answers to ensure a correct understanding of the information provided. Participants were informed about the research in a participant information sheet prior to the interviews. Participants were informed of the research's purpose and assured that their information and data would be kept confidential at the beginning of each interview. As a result, the interviews were characterised by participants' credibility.

This was reflected in the data quality, increasing the likelihood of obtaining more accurate and reliable data and reducing the possibility of response bias. The researcher also worked to minimise bias by purposively selecting interview participants. All interview participants were considered to have expertise relevant to our current research, and their diverse perspectives could enrich the research findings. The interview data were not adversely affected by cultural differences. All participants confirmed that the questions and the written language were clear and understandable, facilitating more accurate responses. Before the interviews, participants in this study were informed about the research's main themes and objectives. In this way, the interviewees could prepare for the interview and provide more insightful information. To better understand the information provided, the interviewer also learned about the organisations of the experts interviewed beforehand. Similarly, during the interviews, queries were posed to clarify specific answers.

5.15 Qualitative data analysis:

After completing the interviews with the participants and preparing the data, the data are ready for analysis and interpretation. Several methods exist for analysing qualitative data (Creswell, 2013; Yin, 2016; Saunders et al., 2019). Qualitative data analysis methods are not specific to the research

purposes; instead, their analysis is tailored to the nature of the data and its goals, as some techniques depend on analysing qualitative data in line with their analytical focus. Other methods focus on specific topics, while some aim to analyse particular procedures (Saunders et al., 2019). The purpose of the researcher's interviews was to enhance the quantitative findings by comparing them with qualitative responses and to discuss any differences between the results. Therefore, the researcher relied on thematic analysis to analyse the interview data (a qualitative method). Thematic analysis was chosen because it facilitates the examination of multiple aspects of the research, clarifying the relationships among Industry 4.0, reverse supply chains, their sub-dimensions, and intermediate variables. This method can be used flexibly in both deductive and inductive research (Braun & Clarke, 2016). Thematic analysis of qualitative data involves several steps. This technique is not a linear process where steps are repeated (Creswell, 2013; Saunders et al., 2019).

5.16 The quantitative part of the methodology of research:

Methodology of the quantitative part of the research. It outlines the procedures for selecting the research sample and its characteristics, developing the tool, and collecting data using the questionnaire prepared for this purpose. The questionnaire employs a quantitative scale, as used in I4.0 and RSCs research in previous studies, in addition to surveys, since the researcher has built upon the contributions of earlier researchers in this context. Therefore, no pre-prepared questionnaires were found that were well-suited to this research, so the researcher developed a new scale to collect the data. All approved steps were followed when establishing a new scale, in accordance with the relevant literature. A five-point Likert scale ranging from strongly agree to strongly disagree is adopted. This scale yields valid results in this type of research.

5.16.1 Measurement and Structural Modelling Assessment:

Structural Equation Modelling (SEM) was employed as the primary analytical technique to assess both the measurement and structural components of the proposed research model.

Several prominent researchers are credited with developing SEM. Sewall Wright's early work in the 1920s laid the foundations for path analysis, introducing path coefficients and using graphs to represent causal relationships (Westland, 2019). Carl Joreskog was instrumental in integrating metrics and structural models into what is now known as SEM, and his development of the LISREL (Linear Structural Relationship) model in the 1970s marked a turning point, bringing mathematical rigor and computational power to the field (Kline, 2023). Peter Bentler's contributions to model fit indices and the development also expanded access to SEM among applied researchers. Although Judea Pearl's work was grounded in artificial intelligence and computer science, his emphasis on causal inference

and graphical models had a far-reaching impact on SEM by making the causal assertions underlying structural models more precise. Structural equation modelling (SEM) is understood in research as a combination of two interlocking models: the measurement model and the structural model (Karimi & Meyer, 2014). The measurement model specifies how latent variables are operationalised in observed indicators (questions). This component of the model resembles confirmatory factor analysis (CFA), in which the researcher pre-identifies the indicators expected to measure the latent variables. The explicit modelling of measurement error is a major benefit of this model over other regression-based methods, which do not allow differentiation between the actual and error variances of a latent variable and its observed measures.

Conversely, the structural model explains the postulated causal relationships among the latent variables (as specified in the research model). These relationships are often described as directional and constitute a system of equations that may be estimated simultaneously. SEM can evaluate relationships among intermediates, feedback, and reciprocal causation, thereby enabling researchers to more easily identify specific theoretical assumptions (Zyphur et al., 2023).

Finally, SEM is a versatile and powerful method grounded in scientific principles for testing complex models in management, economics, and the social and behavioural sciences. It allows experimental testing of hypotheses involving latent variables, rigorous evaluation of measurement properties, and the study of causal relationships between variables. It thus constitutes part of quantitative research, a complex phenomenon across most fields of study.

5.16.2 The theoretical justification for using the SEM technique is carried out through a methodological framework as follows:

Structural equation modelling (SEM) is a broad statistical method for testing hypotheses about the associations between observed and latent variables. Scientific research should take great care in the steps of statistical preparation and validation to ensure that the results are reliable, valid, and interpretable. Each stage of SEM preparation and testing is grounded in statistical theory and psychometric principles (Owolabi et al., 2020).

SEM relies on exploratory factor analysis (EFA) and confirmatory factor analysis (CFA), which are designed to uncover the underlying structure of a set of measured variables (Marsh et al., 2020). This approach is supported by classical factor analysis and the understanding that observed variables are imperfect predictors of latent variables. Exploratory factor analysis enables researchers to identify the latent dimensions of variables, while confirmatory factor analysis evaluates how well the observed data fit the proposed measurement model (Byrne, 2013; Tarka, 2018). The exploratory factor analysis reveals the latent structure of research variables and sub-dimensions, and identifies trends in

relationships among observed items (Kamble et al., 2020). It helps establish the presence of distinct underlying constructs, assesses the consistency of sub-dimensions within larger variables, and supports structural validity by uncovering latent dimensions in the data. This analysis is grounded in psychometric theory and provides a basis for refining measurement tools prior to conducting confirmatory analyses (Baharum et al., 2023). Confirmatory factor analysis is also crucial for testing construct validity, such as convergent and discriminant validity, before proceeding to a full structural model (Byrne, 2013; Tarka, 2018).

Moreover, sample size is a major consideration in standardised factor analyses. The statistical theory underlying sample size determination relies on standardised factor analysis within maximum likelihood estimation, which presupposes large-sample properties to ensure the accuracy, stability, and convergence of the parameter estimates (Kyriazos, 2018). According to McCallum et al. (1996), the model's complexity, the number of coefficients, and the interdependence among indicators all affect the choice of sample size (Qureshi & Kang, 2015). Such a model can include general rules that set the minimum at 200 observations. It also involves defining research variables using measures of central tendency, such as the arithmetic mean, and of dispersion, such as variance. These statistics are not limited to descriptive purposes; they also aid in detecting potential violations of assumptions (homogeneity or asymmetry). The tests can also be used to conduct additional reliability and validity assessments and to estimate a latent variable.

In addition, the SEM method requires evaluating personal and group reliabilities across dimensions and variables, particularly using Cronbach's alpha (Sideridis et al., 2018). This involves composite reliability and mean variance, which measure internal consistency and the extent to which a construct accounts for variance relative to measurement error. It is through the internal consistency evaluation of research variables and dimensions that measurement models precisely reflect their consistency, thereby making the research measure more valid and accurate (Hajjar, 2018).

Most of the estimates used in SEM are also based on normality tests, where normality influences standard errors and the chi-square test of model fit (Ainuret al., 2017).

The common-methods bias test also reflects the possibility of measurement bias arising from the data-collection method rather than from the constructs. Other techniques, such as Harman's one-factor test, are used to determine whether bias is present (Aguirre-Urreta & Hu, 2019). SEM models the method using latent variables to statistically control for this bias.

In a word, the use of SEM in scientific studies should be grounded in solid theoretical and methodological premises. All the preparatory statistical tests, starting with descriptive statistics and ending with confirmatory factor analysis, are effective in justifying assumptions and enhancing the

strength of the structural model. The synthesis of these processes aims to ensure that the findings from the SEM analyses are valid, statistically sound, and meaningful.

5.17 The qualitative element of the research methodology:

The qualitative research approach will be used to supplement and validate the conclusions of the quantitative research. Grounded in scientific evaluation, the researcher adopted semi-structured interviews as the qualitative method. Participants' opinions were solicited through practical insights using a pre-prepared list of statements. The list addresses the critical dimensions of the research variables and is designed to be relevant to the quantitative approach, thereby enhancing research outcomes and increasing the knowledge base. Furthermore, to highlight frameworks not evident in the quantitative results, the researcher presented them through practical insights. Therefore, the quantitative approach will help highlight the most critical challenges in integrating research variables, based on practical insights from practitioners in the same field. In addition, semi-structured interviews enable comparison of the research sample's questionnaire responses with participants' semi-structured interview responses to demonstrate the extent to which their viewpoints converge. The responses from the semi-structured interviews will also help identify pressing issues in the manufacturing sector to enhance the integration of Industry 4.0 technologies and reverse supply chain activities, aligning with the contemporary vision.

5.18 How does the mixed methodology answer the research questions?

This research employs a mixed-methods approach, combining quantitative and qualitative methods to address the research questions and hypotheses. This approach is most appropriate for the nature of this research. Furthermore, the opinions of participants in semi-structured interviews, used as a qualitative approach, can complement the quantitative approach, thereby enhancing the accuracy and reliability of the research findings. A mixed method was used to obtain the research results. Using structural equation modelling (SEM), the study tests the research hypotheses, demonstrates relationships among the research variables, and addresses the research questions. On the other hand, respondents' opinions in the semi-structured interviews support the research findings or highlight differences between the quantitative and qualitative results, thereby explaining and discussing the reasons behind these differences.

5.19 Rationale and Interpretive Integration of the Mixed-Methods Research Design:

This study used a mixed-methods approach to identify measurable links between Industry 4.0 technologies and the contemporary vision of RSCs activities, and to gain a deeper contextual understanding of these links. The quantitative, questionnaire-based method enabled testing of

statistical relationships within the research model. Although this approach was successful in testing hypotheses and detecting relationships among variables, it was limited in its ability to interpret and examine these relationships in real-world work settings.

To overcome this limitation, semi-structured interviews were performed as a qualitative research methodology. Data collection involves semi-structured interviews in which people tell their stories; descriptions of experiences and interpretations, or decision-making moments, not defined by predetermined metrics. This methodological approach emphasises understanding the dynamics of complex problems in a work context; for instance, manufacturing ethics, consumer preferences, organisational sustainability strategies, or digital technologies are integrated into RSCs systems. This, in turn, allows for clarification and exploration of unexpected themes that are not a priori identifiable within research questionnaires and provides interpretive context beyond mere statistical associations. Because the research context required specific information and deeper insights, a purposive sampling strategy was used to select experts from each field. This qualitative sampling method (or purposive sampling) is common. We interviewed people with both strategic and operational backgrounds to gain a deeper understanding of RSCs activities. Qualitative sampling was conducted not with the intention of statistical generalisation, but rather to provide analytical depth and theoretical elaboration of the quantitative model.

Integration of quantitative and qualitative methodologies extended beyond the parallel presentation of data. The quantitative results confirmed the structural model and established statistically significant relationships, while the qualitative results explained or elucidated these mechanisms. The interview insights explained how Industry 4.0 technology improves supply chain management through practices such as continuously processing customer feedback, making ethical manufacturing decisions, and implementing effective recycling systems. In some instances, the qualitative findings supported the quantitative results by empirically confirming statistical associations; in others, they expanded the relevance by describing additional contextual factors beyond those considered in the model, such as organisational and management issues or implementation challenges.

The methodologically complementary integration guarantees not only richness and generalisation through quantitative outcomes but also depth and contextual interpretation through qualitative data. Consequently, the overall result of mixed methods is not a juxtaposition of two different sets of data and exhibits, in our case. Convergent interpretive synthesis, where qualitative insights appropriate the quantitative structural model to provide stronger validity and generalisability to key constructs, leading to a better understanding with greater theoretical depth of how Industry 4.0 technology embraces the contemporary vision of RSCs activities, which then provides synergies for manufacturing sustainability.

5.20 Research sample:

The research sample was drawn from workers across several industrial companies that implement Industry 4.0 technologies and maintain effective reverse supply chains. Specifically, the sample was selected based on criteria outlined in the questionnaire, including the question, (Do you work in the field of Industry 4.0 or reverse supply chain?). Additionally, the questionnaire asked, (Do you have experience with Industry 4.0 technologies such as cyber-physical systems, Internet of Things, big data, cloud, smart factories, and reverse supply chains?). These questions were conditional, with yes-or-no answers. If a respondent answered 'no', the questionnaire program prevented further responses. The study targeted workers in departments related to Industry 4.0 technology, supply chains, and reverse supply, considering factors such as gender, age, educational background, and scope of work, to examine their specialisation in forward or reverse supply chains. The research sample was selected from companies that operate mainly in technology-oriented fields, particularly smart manufacturing, Industry 4.0-related issues, energy systems & renewable energy technologies, digital & Industry value chain solutions, and Smart Medical Device Manufacturing. They were chosen because they represent an industrial environment in which Industry 4.0 technologies are more mature than those of other sectors, and their operational relevance for the sustainability practices we study, recycling systems, or digitally integrated manufacturing processes is higher. Thus, participants were deemed competent enough to evaluate the relationship between Industry 4.0 technologies and the current RSCs activities vision. The data were gathered from industrial organisations in technologically and industrially advanced contexts (France, Germany, the United Kingdom, China, and Turkey). We include multiple geographical regions to capture varied industrial perspectives and the extent of digital transformation, manufacturing practices, and sustainability integration in Industry 4.0 environments. The selected countries have been chosen for their active engagement in advanced manufacturing systems, digital transformation projects, renewable energy technologies, and smart industrial production.

The purposive sampling method was adopted for the study, as it targeted respondents with specific expertise and firsthand experience with Industry 4.0 technology in the domain of sustainability-oriented manufacturing systems. Consequently, purposive sampling enabled the selection of participants with technical know-how and practical experience, as well as an organisational common structure, who would provide accurate, reliable responses relevant to the research goals and closely aligned with its conceptual framework. The purposive sampling method was adopted for the study because it targeted respondents with specific expertise and firsthand experience with Industry 4.0 technology in the domain of sustainability-oriented manufacturing systems. Consequently, purposive sampling enabled the selection of participants with technical know-how and practical experience, as well as an organisational common structure, who would provide accurate, reliable responses relevant

to the research goals and closely aligned with its conceptual framework. The purposive sampling method we adopt aligns with the exploratory and theoretical nature of our research, which aims to explore inter- and intra-firm organisational relationships among Industry 4.0 technologies, customer feedback, and recycling activities within sustainability-oriented RSCs, using a qualitative approach (i.e., semi-structured interviews). Thus, the researcher purposively selected the research sample rather than a statistical representation.

While purposive sampling may limit the generalisability of findings. The research sample comprised experts and specialists from specific, highly technical production environments, which raises questions about the potential generalisation of the results to other manufacturing environments and geographic locations, as well as to organisations that do not fully embrace elements of Industry 4.0 technology. In addition, countries differ in their national industrial policies and practices, technological maturity, and organisational culture. However, participants from multiple industrial nations increase the diversity of research samples and enhance the analytical relevance, robustness, and transparency of research findings.

The electronic questionnaire was distributed to employees of a multi-industrial company to gather responses. The sample size was set at 261, as this type of study typically requires between (200 to 300) participants, which is appropriate for such research. The sample was based on prior research for similar specialties; responses were collected and organised, resulting in the exclusion of 11 invalid questionnaires. As a result, 250 participants remained for statistical analysis.

All data were collected via an online survey administered via the Qualtrics platform. The survey was administered to the research sample from February to July 2024. The involvement was voluntary, and respondents were assured that their information would remain confidential. The participants reviewed the survey information and the ethics form, and consent was obtained via email. The software settings were incorporated to avoid duplicate submissions. Qualtrics exported the data as an Excel spreadsheet, which was then analysed. The mean time of completion was about ten minutes.

5.21 Characteristics of the research sample:

The research sample was chosen from workers in the manufacturing industry (Industry 4.0) and reverse supply chains because they have direct connections to the research variables and their sub-dimensions, as well as to the mediating and control variables. The sample also included workers with scientific and academic qualifications, since the research variables focus on modern manufacturing technologies. The focus was on participants with specialisations such as engineers, technicians, work supervisors, controllers, department managers, and operations managers. The questionnaire stipulated that the sample should consist only of workers involved in Industry 4.0, reverse processing chains, or both. To

better define the sample, a question was added to identify participants with experience in Industry 4.0 technologies and reverse supply chain activities. The answer options were yes or no. If respondents answered 'no', they could not proceed. Their responses to the research questions need revision. The goal is to select individuals with relevant experience and skills in Industry 4.0 technologies and reverse supply chain activities to provide more accurate and credible responses.

5.22 Characteristics of the researched companies:

The researcher carefully selected companies that met specific conditions, ensuring that the research sample's answers accurately reflect the industry's objective reality. Among the conditions that the companies must meet under study is the adoption of Industry 4.0 technologies in their factories. In addition, they must have effective reverse supply chains. In doing so, the research companies align with the primary and subsidiary research variables and provide suitable industrial environments for conducting the questionnaire.

All the surveyed companies are among the leading global companies that use Industry 4.0 technology, keep pace with manufacturing developments, and maintain effective, efficient reverse supply chains. Therefore, the researcher chose them because they are compatible with the research requirements and represent a suitable survey environment.

5.23 A pilot survey:

A pilot survey is a method that enables researchers to experimentally test a questionnaire with a smaller sample than the target research sample before conducting the main research survey (Aithal & Aithal, 2020). Conducting any test or examination is preferable to not conducting it; therefore, if you conduct a survey, it is better to test it using your available capabilities (Eyisi, 2016). After conducting the pilot survey, obtaining and analysing the results, you can address any errors or obstacles encountered during the pilot survey process, especially if you are surveying the Internet (Griffin et al., 2021).

Conducting a pilot survey before the final survey greatly helps the researcher. It achieves several benefits for the researcher, such as exploring elements that could harm the research, for example, the inappropriate design of the questionnaire, which may cause some questions to be left out by the respondents, or questions that are asked in an unclear manner that confuses the participants in answering, causing them to answer incorrectly (Robinson, 2018). Experimental surveys can help save time and effort by detecting errors early, making it easier for the researcher to address any issues and obtain reliable results (Curran, 2016).

Chapter Six

Findings from the survey

6.1 Introduction:

The following section depicts the quantitative part of the mixed-methods research approach. The quantitative approach employed an online survey. The questionnaire contained questions on the key research variables and their sub-dimensions. In addition, the survey's primary purpose was to test the research hypotheses, which were aligned with the research questions.

The researcher used descriptive and inferential statistics to interpret and confirm the results of the data analysis. Based on the research model and the relationships among the research variables as they relate to the research questions and hypotheses, we can obtain meaningful results and draw logical conclusions about our research topic: the relationship between Industry 4.0 technologies and reverse supply chain activities. We previously indicated that we used a quantitative approach to collect and analyse survey data and apply appropriate statistical methods to obtain the results.

The aim of our research, as revealed by the statistical analysis, is to clarify the relationships between the research variables and their sub-dimensions. Moreover, the extent to which mediating variables enhance the relationship between the independent variable (Industry 4.0) and the dependent variable (reverse supply chains) significantly clarifies the research in both theoretical and practical terms.

6.2 Description of the statistical work:

This topic encompasses various applications, including the characterisation of research variables and their diagnosis through the analysis of respondents' responses from a selected sample of employees in industrial firms. The analysis utilises the statistical software (SPSS V26) to compute percentages, means, standard deviations, significance levels, stability metrics, common method bias, and internal consistency. The program (AMOS V24) was utilised to conduct confirmatory factor analysis and investigate the influence relationships as outlined.

6.3 Determining the sample size:

Before starting any study, it is necessary to determine the appropriate sample size to analyse the data accurately. Since our research employs structural equation modelling (SEM) to analyse the questionnaire, it requires a specific sample size for use in AMOS. Several programs are available on the Internet to determine the minimum appropriate size for applying structural equation modelling, the most important of which is the site at the link below:

(<https://www.danielsoper.com/statcalc/calculator.aspx?id=89>). On this site, we are required to enter some information, including information related to the questionnaire form under study, as listed in the following Table (6-1):

Table 6- 1 Determining the minimum sample size for applying structural equation modelling:

Inputs	Acceptable values	Selected values
Anticipated effect size	0.10 small 0.30 Medium 0.50 large	0.3
Desired statistical power level	Must not be less than 0.80	0.80
Number of latent variables	-	10
Number of observed variables (Questions)	-	40
Probability level	0.01 0.05 0.10	0.05
Output		
Minimum sample size to detect an effect		190
Minimum sample size for the structural model		100
Recommended minimum sample size		190

Source:

1. Teo, T., Tsai, L. T., & Yang, C. C. (2013). Applying structural equation modelling (SEM) in educational research: An introduction. In *Application of structural equation modelling in academic research and practice* (pp. 1-21). Brill.
2. RVSPK, R., Priyanath, H. M. S., & Megama, R. G. N. (2020). Methods and rules-of-thumb in determining minimum sample size when applying structural equation modelling: A review. *J Soc Sci Res*, 15(2), 102-109.

The results of the above table indicate that the minimum sample size appropriate for this study is (190). This means that the researcher must distribute at least 190 questionnaire forms to achieve the required accuracy in the structural equation modelling results conducted using the AMOS program.

6.4 Description of the research sample:

The following is a detailed description of the sample based on data provided by participants in the first part of the questionnaire, which included demographic (general) data for each respondent. The participants had to complete this information as a condition for being allowed to complete the rest of the questionnaire questions, as follows:

Table 6- 2 Demographic data (general data) of participants.

	Class	No	%
Gender	Male	149	60
	Female	101	40
Age	Less than 25 years	21	8
	25-35 years	98	39
	36-45 years	96	38
	46 years and over	35	14
Qualification	Primary	2	0.8
	Preparatory	30	12
	Bachelor's	120	48
	Master's / Ph.D.	98	39
Scope of works	Reverse supply chains	107	43
	Forward supply chains	143	57

Source: Researcher according to the statistical analysis results using SPSS V26 software. n=250.

In addition, this part of the data included conditional questions; i.e., if the participant fails to meet these conditions, they are not allowed to complete the questionnaire, and only participants who answer these questions with 'yes' are allowed to continue. These questions are as follows:

Do you work in the field of Industry 4.0 or reverse supply chain?

Do you have expertise in Industry 4.0 technology (cyber-physical systems, Internet of Things, big data, cloud, smart factories) and reverse supply chains?

The following are the details for each:

1. Gender:

Table 6-2 and diagram 6-1 show the percentage of male and female respondents (workers in industrial companies), where the percentage of males was higher than the percentage of females, as their percentage reached 60%. In comparison, the percentage of females reached (40%).

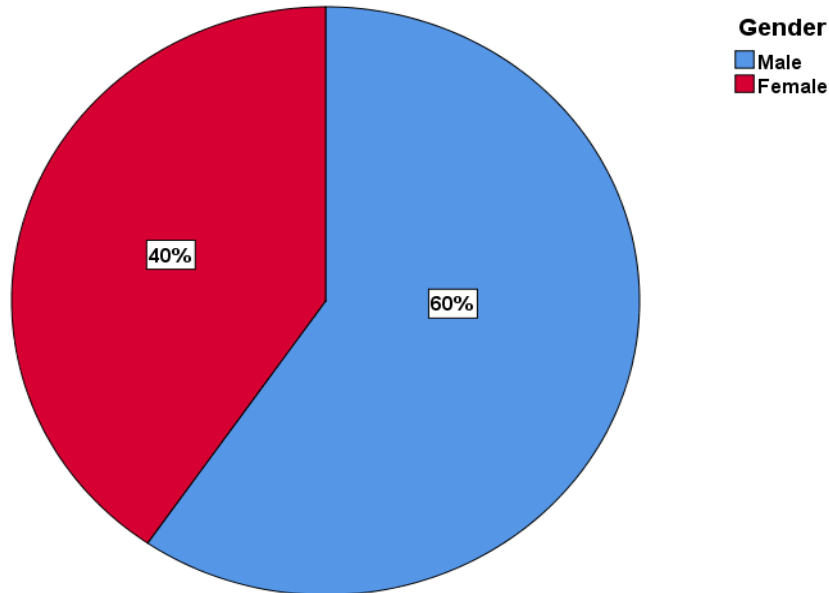


Figure 6- 1 shows the Distribution of researched individuals by gender

2. Age:

Figure 6-2 shows that the highest percentage of the research sample is individuals aged 25-35 years, with a percentage of (39%). The age group (36-45) years came in second place with a percentage of (38%), while the age group (46 years and over) came in third place with a percentage of (14%), and finally the age group (Less than 25 years) came in fourth place with a percentage of (8%).

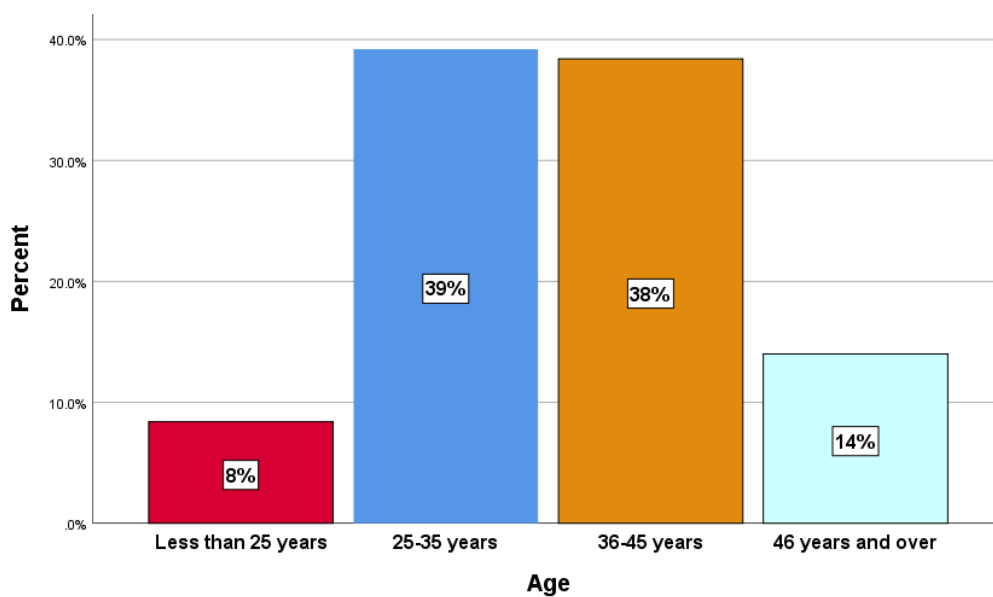


Figure 6- 2 shows the distribution of sample members by age.

3. Qualification:

Table 6-2 and Figure 6-3 show that the highest percentage of the research sample holds a Bachelor's degree, at a rate of (48%). In second place came those holding a Master's / Ph.D. Degree, at a rate of (39%). Third place went to those holding a Preparatory degree, at a rate of (12%). In fourth and last place came those holding a Primary degree, at a rate of (1%).

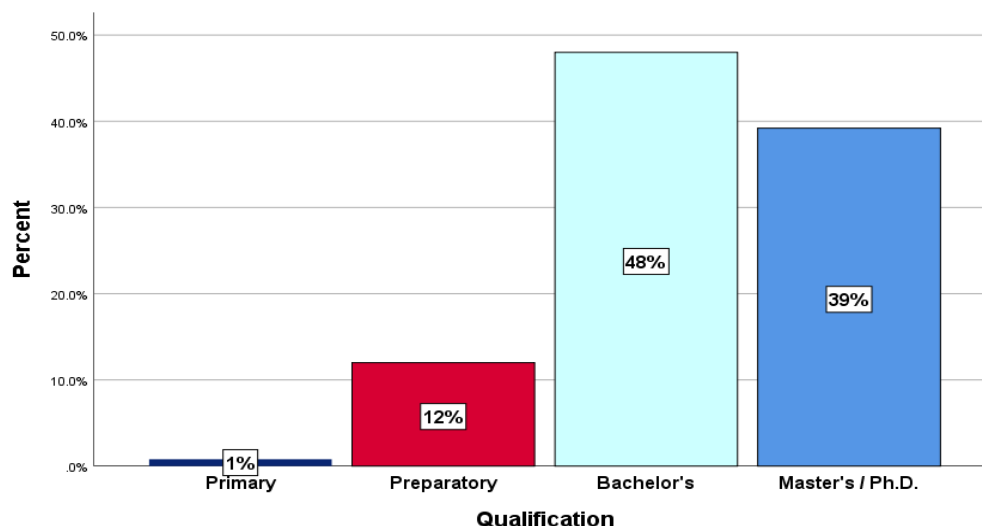


Figure 6 - 3 shows the Distribution of researched individuals by Qualification

4. Scope of works:

Table 6-2 and Figure 6-4 show that the largest proportion of the research sample comprises workers in forward supply chains (i.e., in the field of Industry 4.0), at 57%. The percentage of the research sample of workers in Reverse supply chains is lower, at a percentage of (43%).

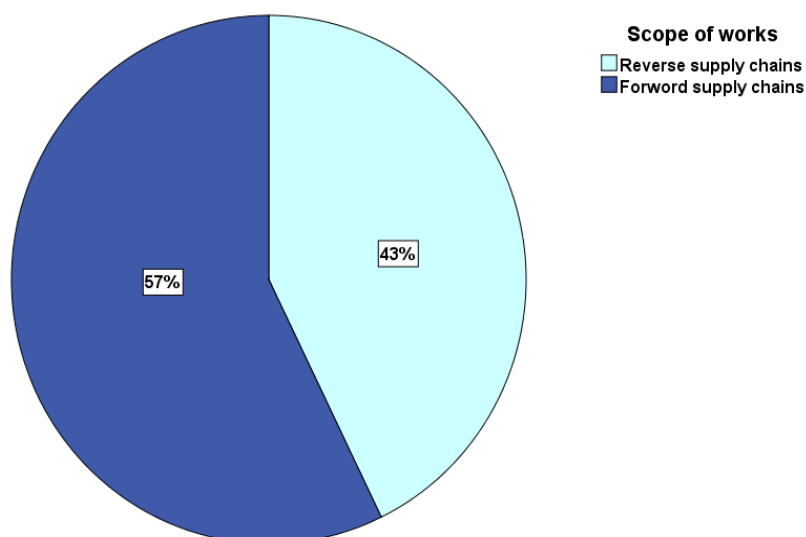


Figure 6 - 4 shows the distribution of individuals researched by the scope of work.

6.5 Description and diagnosis of the research variables:

6.5.1 Description and diagnosis of the respondents' answers to the Industry 4.0 variable:

The content of this paragraph refers to the description of the research variable Industry 4.0, which represents the independent variable of the research, and its diagnosis in terms of its sub-dimensions expressed within the scope of the respondents' answers to the paragraphs embodying each of them, as follows:

6.5.1.1 Cyber-physical systems (CPS):

The data in Table (6-3) indicate consensus among the surveyed individuals regarding the Cyber-physical systems (CPS) dimension for statements (X11-X14), with a general agreement rate of 90.30% among respondents who responded affirmatively (strongly agree and somewhat agree). This indicates consensus among respondents on the Cyber-Physical Systems (CPS) dimension, with a tendency towards favourable evaluations on the five-point Likert scale. Conversely, the extent of widespread dissent (Strongly Disagree and Somewhat Disagree) among the surveyed persons regarding the Cyber-physical systems (CPS) dimension was 3.80%. The proportion of replies indicating, "Neither agree nor disagree" is 5.90%, the arithmetic mean is 4.31, and the standard deviation is 0.78. The relative relevance rate for the Cyber-physical systems (CPS) dimension was 86.28%, indicating significant consensus among participants regarding these statements. In paragraph (X11), which pertains to the company's use of (CPS) technology in production, the highest relative importance was recorded at (89.92%), with an arithmetic mean of (4.50) and a standard deviation of (0.67). Paragraph (X14) attained the lowest relative importance at (82.96%), indicating that cyber-physical systems offer advantages in process enhancement, with the study sample concurring at a rate of (83.6%), an arithmetic mean of (4.15), and a standard deviation of (0.89).

As shown in Table 6-3, respondents expressed a clear level of agreement with statements related to the CPS dimension under study. The high percentages of agreement and elevated relative importance values indicate that respondents consistently hold positive perceptions of the concepts represented by the measurement items. This consistency in responses lends support to the relevance and clarity of the questionnaire items and indicates that respondents are sufficiently aware of or familiar with the topic under study. Collectively, the results provide some empirical support for the appropriateness of this measurement dimension within our research model.

Table 6- 3 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (CPS) dimension.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
1	89.92	0.67	4.50	0.80	2	0.80	2	2.80	7	39.20	98	56.40	141	X11
2	87.28	0.73	4.36	0.80	2	2.00	5	4.40	11	45.60	114	47.20	118	X12
3	84.96	0.83	4.25	1.60	4	3.20	8	6.00	15	47.20	118	42.00	105	X13
4	82.96	0.89	4.15	1.60	4	4.40	11	10.40	26	44.80	112	38.80	97	X14
	86.28	0.78	4.31	1.20		2.60		5.90		44.20		46.10		Average
					3.80			5.90			90.30			Total

Source: Researcher based on the (SPSS V.26) program outputs. n=250.

6.5.1.2 Internet of Things (IoT):

Table (6-4) indicates a consensus among the surveyed individuals concerning the Internet of Things (IoT) dimension for questions (X21-X24), with a total agreement rate of (83.70%) for responses categorised as strongly agree and somewhat agree. This signifies consensus among respondents' responses to Internet of Things (IoT) dimension questions, indicating a tendency toward favourable opinions, as assessed on a five-point Likert scale. Conversely, the extent of widespread dissent (Strongly Disagree and Somewhat Disagree) among the surveyed persons regarding the Internet of Things (IoT) dimension was 4.80%. The proportion of neutral responses was 11.50%, the arithmetic mean was 4.20, and the standard deviation was 0.94. The relative relevance rate for the Internet of Things (IoT) dimension attained 84%, indicating exceptional significance. The respondents concur, to some extent, on these questions from their respective perspectives. At the partial level, inquiry (X21), which concerns the company, indicates that it has implemented Internet of Things technology in its operations, with a relative importance of 85.52%, an arithmetic mean of 4.28, and a standard deviation of 0.87. In contrast, question (X22) attained the lowest relative significance at (82.72%), indicating that the Internet of Things contributes to manufacturing operations, with the research sample concurring at a rate of (82.40%), an arithmetic mean of (4.14), and a standard deviation of (0.94).

The results in Table 6-4 indicate strong agreement among respondents with the statements associated with the measured IoT dimension. The high level of agreement and the relative importance values indicate positive, consistent perceptions among respondents regarding the concepts represented by the questionnaire items. In addition, the convergence of responses and the limited variation in standard deviation values support the consistency and stability of respondents' evaluations. Overall, these

findings provide empirical support for the measured dimension's relevance and adequacy within the research framework.

Table 6- 4 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (IoT) dimension.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
1	85.52	0.87	4.28	2.40	6	0.80	2	10.80	27	38.80	97	47.20	118	X11
2	82.72	0.94	4.14	3.20	8	2.40	6	12.00	30	42.40	106	40.00	100	X12
3	83.28	0.95	4.16	3.60	9	1.20	3	13.20	33	39.20	98	42.80	107	X13
4	84.48	0.99	4.22	4.40	11	1.20	3	10.00	25	36.40	91	48.00	120	X14
	84.00	0.94	4.20	3.40		1.40		11.50		39.20		44.50		Average
				4.80				11.50		83.70				Total

Source: Researcher, according to the Statistical analysis results using SPSS V26 software. n=250

6.5.1.3 Cloud:

The findings in Table (6-5) demonstrate consensus among respondents for the Cloud dimension enquiries (X31-X34), with an overall agreement rate of 86.60% for responses categorised as either strongly agree or slightly agree. This indicates consensus among respondents regarding their answers to the Cloud dimension enquiries, with responses predominantly favourable on the five-point Likert scale. Conversely, the extent of overall dissent (Strongly Disagree and Somewhat Disagree) among respondents regarding the Cloud dimension questions was 3.80%. The percentage of responses indicating "Neither agree nor disagree" is 9.60%, the arithmetic mean is 4.25, and the standard deviation is 0.82. The relative relevance rate for the Cloud dimension was 84.96%, indicating significant importance. This indicates that the respondents reached a certain consensus on these questions, as reflected in their responses. At the partial level, question (X31), indicating the company's adoption of cloud technology in its operations, achieved the maximum relative value of (87.12%), with an arithmetic mean of (4.36) and a standard deviation of (0.69). In contrast, question (X33) attained the lowest relative significance at (83.28%), indicating that the cloud facilitates time and cost efficiency in information exchange, with the study sample concurring at (88.0%), an arithmetic mean of (4.25), and a standard deviation of (0.89).

The results in Table 6-5 show a high degree of agreement among respondents with the statements related to the measured dimension Cloud. Elevated levels of agreement and relative importance

indicate that respondents hold consistent, positive perceptions of the concepts represented by the questionnaire items. Furthermore, the response patterns demonstrate reasonable consistency and stability, supporting the clarity and appropriateness of the measurement items within the research framework. Overall, these results provide empirical evidence supporting the adequacy of the measured dimension and respondents' awareness of the subject under investigation.

Table 6- 5 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (Cloud) dimension.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
1	87.12	0.69	4.36	0.00	0	0.80	2	10.00	25	42.00	105	47.20	118	X11
2	84.48	0.92	4.22	2.80	7	2.80	7	8.40	21	41.20	103	44.80	112	X12
3	84.96	0.89	4.25	2.80	7	2.00	5	7.20	18	43.60	109	44.40	111	X13
4	83.28	0.80	4.16	0.00	0	4.00	10	12.80	32	46.00	115	37.20	93	X14
	84.96	0.82	4.25	1.40		2.40		9.60		43.20		43.40		Average
				3.80		9.60		86.60						Total

Source: Researcher, according to the Statistical analysis results using SPSS V26 software. n=250

6.5.1.4 Big data:

The findings in Table (6-6) demonstrate consensus among the surveyed individuals concerning the Big Data dimension questions (X41-X44), with an overall agreement rate of 84.20% for responses categorised as strongly agree and somewhat agree. This signifies a degree of concordance between the responses of the surveyed individuals and the enquiries within the Big Data dimension, indicating that the respondents' opinions are predominantly favourable on the five-point Likert scale. Conversely, the proportion of general dissent (Strongly Disagree and Somewhat Disagree) among the surveyed individuals regarding the Big Data dimension was (3.20%), while the percentage of neutral responses (Neither Agree nor Disagree) was (12.60%). The arithmetic mean was (4.13), and the standard deviation was (0.78). The relative relevance rate for the Big Data dimension was 82.60%, indicating significant importance. The polled persons concurred, to varying degrees, with these paragraphs from their perspective. At the partial level, Question (X42), which pertains to big data's role in helping organisations understand market demands and requirements, achieved the highest relative relevance of 83.76%, with a mean of 4.19 and a standard deviation of 0.85. In contrast, Question (X43) attained

the lowest relative significance (81.12%) in the inquiry, "Is big data a competitive advantage for companies?" The study sample concurred at a rate of (80.80%), with a mean of (4.06) and a standard deviation of (0.82).

Table 6-6 shows the respondents' level of agreement with each Big Data statement. High relative importance values and a predominance of agreement responses indicate stable perceptions of the concepts represented by questionnaire items among respondents. Secondly, the range of scores in responses indicates they are relatively consolidated stable. Despite these methodological considerations, the results overall provide support for the validity and appropriateness of the measurement items; they also supply empirical grounding regarding how participants consider this dimension.

Table 6- 6 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (Big data) dimension.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
1	82.72	0.73	4.14	0.40	1	2.00	5	12.00	30	54.80	137	30.80	77	X11
2	83.76	0.74	4.19	0.00	0	2.40	6	12.40	31	49.20	123	36.00	90	X12
3	81.12	0.82	4.06	1.20	3	2.80	7	15.20	38	50.80	127	30.00	75	X13
4	82.80	0.84	4.14	2.00	5	2.00	5	10.80	27	50.40	126	34.80	87	X14
	82.60	0.78	4.13	0.90		2.30		12.60		51.30		32.90		Average
						3.20		12.60				84.20		Total

Source: Researcher based on statistical analysis results using SPSS V26 software. n=250

6.5.1.5 Smart factory:

The results of Table (6-7) indicate the existence of an agreement between the answers of the research sample regarding the questions of the Smart Factory dimension for questions (X51-X54), as the general agreement rate for the answers of the researched individuals in agreement (strongly agree and somewhat agree) reached (56.30%). This indicates a degree of agreement among the participants regarding the paragraphs of the Smart Factory dimension, suggesting that their opinions tend toward the positive, as measured by the five-point Likert scale. In contrast, the degree of general disagreement (Strongly Disagree and Somewhat Disagree) among the researched individuals regarding the Smart Factory dimension questions was 12.40%. The percentage of (Neither agree nor disagree) answers was (31.30%), the arithmetic mean was (3.54), and the standard deviation was (0.94). The relative importance rate for the Smart Factory dimension was 70.74%, which is a good value. This means that

the individuals under study agreed to a precise degree on these paragraphs, given their respective points of view. At the partial level, paragraph (X52), which represents the smart factory, provides a competitive advantage for companies, obtained the highest relative importance of (71.92%) with an arithmetic mean of (3.60) and a standard deviation of (0.95). In comparison, question (X51) achieved the lowest relative importance of (68.64%), which represents the factory in its manufacturing processes, with the study sample agreeing at a rate of (78.0%) with an arithmetic mean of (3.43) and a standard deviation of (0.89).

The smart factory dimension, as represented in Table 6-7, indicated a moderate-to-high level of support among respondents. Although agreement responses were still more frequent than disagreement responses, the particularly high ratio of neutral responses indicated some variability in respondents' attitudes toward the concepts represented by the questionnaire items. However, the overall relative importance and arithmetic mean show a moderate level of support for the measured dimension in terms of research philosophy. Furthermore, the distribution of responses demonstrates a reasonable level of consistency among respondents in their evaluations, supporting the conclusion that the measurement items are sufficient to capture their intended purpose.

Table 6- 7 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (smart factory) dimension:

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
4	68.64	0.89	3.43	2.40	6	10.00	25	39.20	98	38.80	97	9.60	24	X11
1	71.92	0.95	3.60	2.80	7	8.40	21	31.60	79	40.80	102	16.40	41	X12
2	71.28	0.90	3.56	3.20	8	7.60	19	29.20	73	49.60	124	10.40	26	X13
3	71.12	1.01	3.56	4.00	10	11.20	28	25.20	63	44.40	111	15.20	38	X14
	70.74	0.94	3.54	3.10		9.30		31.30		43.40		12.90		Average
						12.40		31.30		56.30				Total

Source: Researcher, based on statistical analysis results using SPSS V26 software. n=250

Summary of the description of the variable Industry 4.0:

With respect to the dimensions of the independent research variable (Industry 4.0), as described. Table (6-8) illustrates the relative importance of the dimensions of Industry 4.0 in relation to the research sample's responses, as indicated by the arithmetic mean, standard deviation, and relative importance

values. It is possible to conclude that all of the answers and all of the dimensions of the Industry 4.0 variable exceeded the hypothetical arithmetic mean of (3). Additionally, we concluded that the CPS dimension is the most critical aspect of the Industry 4.0 variable. The arithmetic mean value of (4.31) and the standard deviation of (0.78), together with a relative importance of (86.28%), revealed that the Smart factory dimension was the least significant. This was further supported by the arithmetic mean value of (3.54) and the standard deviation of (0.94), as well as a relative importance of (70.74%).

Table 6- 8 Relative importance of Industry 4.0 dimensions.

NO.	Dimensions	Arithmetic mean	Standard deviation	relative importance %	Arrangements
1	Cyber-physical systems (CPS)	4.31	0.78	86.28	First
2	Internet of Things (IoT)	4.20	0.94	84.00	Third
3	Cloud	4.25	0.82	84.96	Second
4	Big data	4.13	0.78	82.60	Fourth
5	Smart factory	3.54	0.94	70.74	Fifth

Source: Researcher According to the statistical analysis results using SPSS V26 software. n=250.

6.5.2 Description and diagnosis of the respondents' answers to the variable reverse supply chains (RSCs):

The content of these questions refers to the description of the adopted research variable, reverse Supply chains (RSCs), and its diagnosis in terms of its sub-dimensions in the context of the respondent's answers to the questions for each dimension, as follows:

6.5.2.1 Customer Preferences:

Refer to the results from Table (6-9), which shows an agreement between the opinions of the respondents regarding the questions of the customer preferences dimension for Questions from (Y11-Y14), as the general agreement rate for the answers of the respondents in agreement (Strongly agree and Somewhat agree) reached (84.10%). This indicates a degree of agreement with the respondents' answers regarding the customer preferences dimension. This suggests that the respondents' answers are positive, as indicated by their responses on a five-point Likert scale. While the degree of general disagreement (Strongly Disagree and somewhat disagree) for the answers of the respondents to the questions of the customer preferences dimension reached (4.50%), for the percentage of (Neither agree nor disagree answers), it is (11.40%), the arithmetic mean was (4.11). The standard deviation was (0.82). The relative importance rate of the customer preferences dimension was (82.28%), which is

good relative importance. This means that the individuals being researched agreed to a certain degree with these paragraphs from their point of view.

At the partial level, question (Y14), which represents (The company's developing reverse supply chain activities), obtained the highest relative importance of (83.60%) with an arithmetic mean of (4.18) and a standard deviation of (0.78). In comparison, question (Y12) achieved the lowest relative importance of (80.72%), which represents (The company cares about meeting the preferences of the customer), with the research sample agreeing at a rate of (78.40%) with an arithmetic mean of (4.0) and a standard deviation of (0.88).

Table 6-9 shows that respondents agree with the statements related to the measured dimension of customer preferences. Since the responses to most of these items fell within the agreement scale, it can be said that relatively positive perceptions and partially consistent opinions are evident among respondents regarding what the items represent, which reflects positively on the relative importance values. Moreover, the pattern of responses shows a reasonable degree of consistency and stability, affirming their clarity and appropriateness for inclusion as measurement items in this research framework. Overall, these findings provide empirical support for the goodness of fit and validity of the measurement dimension.

Table 6- 9 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (customer preferences) dimension.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
2	82.80	0.86	4.14	1.60	4	4.40	11	8.00	20	50.40	126	35.60	89	Y11
4	80.00	0.88	4.00	1.60	4	4.40	11	15.60	39	49.20	123	29.20	73	Y12
3	82.72	0.77	4.14	1.20	3	1.60	4	12.00	30	30.00	132	32.40	81	Y13
1	83.60	0.78	4.18	1.20	3	2.00	5	10.00	25	51.20	128	35.60	89	Y14
	82.28	0.82	4.11	1.40		3.10		11.40		50.90		33.20		Average
						4.50		11.40				84.10		Total

Source: Researcher. According to the statistical analysis results using SPSS V26 software. n=250

6.5.2.2 Rational use of raw materials:

The data in Table (6-10) show that there is an agreement between the opinions of the researched individuals regarding the questions of the Rational use of raw material dimension for questions from (Y21-Y24), as the general agreement rate for the answers of the researched individuals in agreement

(Strongly agree and Somewhat agree) reached (73.20%). This indicates a degree of agreement among the researched individuals' answers to the questions on the Rational use of raw materials dimension, meaning that their opinions tend towards the positive on the five-point (Likert) scale. In contrast, the degree of disagreement (Strongly Disagree and Somewhat Disagree) for the answers of the research sample to the questions of the rational use of raw materials dimension reached (9.10%), and the percentage of answers (Neither agree nor disagree) was (17.70%). The results of the arithmetic mean (3.94) and the standard deviation (0.95) appeared, and the relative importance rate of the dimension rational use of raw materials reached (78.70%), which is a good relative importance, which means that the respondents agreed to some degree on these questions according to their answers. At the partial level, question (Y21), which represents (The company is interested in the rational use of raw materials), obtained the highest relative importance of (79.28%) with an arithmetic mean (3.96) and a standard deviation of (0.95). In contrast, question (Y24) achieved the lowest relative importance of (78.08%), which represents that modern technology has contributed to the rational use of raw materials, with the research sample agreement at a rate of (71.20%) with an arithmetic mean (3.90) and a standard deviation of (0.96).

In Table 6-10, the results show that participants generally agree with statements related to the measured rational use of raw materials dimension. Despite a relatively high number of neutral responses, the large number of agreement responses indicates that respondents perceive most of the concepts represented by the questionnaire items positively. The response distribution is also acceptable, indicating consistency and stability across the measurement items, which are considered clear and relevant to this study. In general, these results provide reasonable empirical evidence that the measured dimension is sufficient.

Table 6- 10 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (Rational use of raw materials) dimension.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
1	79.28	0.95	3.96	1.60	4	7.20	18	16.00	40	43.60	109	31.60	79	Y11
3	78.48	0.96	3.92	2.00	5	7.20	18	16.40	41	45.20	113	29.20	73	Y12
2	78.96	0.94	3.95	1.20	3	6.40	16	20.40	51	30.00	101	31.60	79	Y13
4	78.08	0.96	3.90	0.40	1	10.40	26	18.00	45	40.80	102	30.40	76	Y14
	78.70	0.95	3.94	1.30		7.80		17.70		42.50		30.70		Average
						9.10		17.70				73.20		Total

Source: Researcher According to the statistical analysis results using SPSS V26 software. n=250

6.5.2.3 Manufacturing Ethics:

The data in Table (6-11) indicate agreement among the research sample's responses to the Manufacturing ethics dimension questions (Y31-Y34). The general agreement rate for the answers of the researched individuals in agreement (Strongly agree and somewhat agree) reached (84.40%). This indicates a score below the average, consistent with the individuals' responses to questions in the Manufacturing Ethics dimension. While the degree of disagreement (Strongly Disagree and somewhat disagree) for the answers of the researched individuals on the questions of the Manufacturing ethics dimension reached (3.50%), for the percentage of answers (Neither agree nor disagree), it is (12.10%). The arithmetic mean was (4.17), and the standard deviation was (0.79). The relative importance rate for the Manufacturing ethics dimension reached (83.46%), which is good relative importance. This means that the individuals studied agreed to a moderate degree on the questions in this dimension, as indicated by their responses. In addition, at the partial level, question (Y32), which represents (Manufacturing ethics adds a competitive advantage to the company), had the highest relative importance (86.40%), with an arithmetic mean of (4.32) and a standard deviation of (0.68). In comparison, question (Y31) achieved the lowest relative importance of (81.36%), which represents (The company is committed to the standards of manufacturing ethics), with the research sample agreeing at a rate of (81.20%) with an arithmetic mean of (4.07) and a standard deviation of (0.94). The findings summarised in Tables 6-11 show that respondents are largely supportive of the statements on this aspect of manufacturing ethics. The agreement-level values and relative importance indicate consistently strong perceptions among respondents towards the concepts represented by the questionnaire item. In addition, the response distribution exhibits adequate consistency and stability, confirming clarity in the test items and that most items are relevant to performance. The results provide strong evidence of this measure's reliability and the stability of respondents' responses.

Table 6- 11 Frequency distributions, arithmetic means, standard deviations, and relative importance of the (Manufacturing ethics) dimension.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
4	81.36	0.94	4.07	2.00	5	6.00	15	15	15	45.60	114	35.60	89	Y11
1	86.40	0.68	4.32	0.40	1	0.40	1	1	1	47.60	119	42.80	107	Y12
2	83.12	0.75	4.16	0.40	1	1.60	4	4	4	30.00	123	34.40	86	Y13
3	82.96	0.80	4.15	0.40	1	2.80	7	7	7	46.40	116	36.00	90	Y14

83.46	0.79	4.17	0.80	2.70	47.20	37.20	Average
				3.50	12.10	84.40	Total

Source: Researcher, based on statistical analysis results using SPSS V26. n=250

Summary of the description of the variable reverse supply chains (RSCs):

The tables present the dimensions of the dependent variable (reverse supply chains). Indicate that all answers and all dimensions of the variable were higher than the hypothetical arithmetic mean of (3) and that Table (6-12). Shows the relative importance of the dimensions of reverse supply chains (RSC) according to the answers of the research sample (a specific sample of workers in industrial companies), through the values of the arithmetic mean, standard deviation, and relative importance. It became clear to us that the most important dimension of the variable reverse supply chains (RSC) is the dimension of Manufacturing ethics, as indicated by the value of the arithmetic mean of (4.17) and the standard deviation of (0.79), and with a relative importance of (83.46%). In contrast, the dimension of Rational use of raw materials was shown to be the least important dimension, as indicated by the value of the arithmetic mean of (3.94) and the standard deviation of (0.95), and with a relative importance of (78.70%).

Table 6- 12 Relative importance of reverse supply chain dimensions.

NO.	Dimensions	Arithmetic me	Standard deviation	Relative importance %	Arrangement
1	Customer preferences	4.11	0.82	82.28	Second
2	Rational use of raw materials	3.94	0.95	78.70	Third
3	Manufacturing ethics	4.17	0.79	83.46	First

Source: Researcher According to the statistical analysis results using SPSS V26 software. n=250

6.5.3 Description and diagnosis of the respondent's answers to the customer feedback variable:

These questions refer to the description of the intermediate variable of customer feedback. The results of Table (6-13) show that there is an agreement between the opinions of the surveyed individuals regarding the customer feedback variable for the statements (Z1- Z4), as the general agreement rate for the surveyed individuals' answers in agreement (Strongly agree and Somewhat agree) reached (87.00%). This indicates that there is a degree of agreement for the surveyed individuals' answers on the customer feedback variable, i.e., the surveyed individuals' opinions tend towards the positive based on the five-point Likert scale, while the degree of disagreement (Strongly Disagree and somewhat disagree) for the surveyed individuals' answers on the customer feedback variable reached (2.10%). As for the percentage of answers (Neither agree nor disagree), it is (10.90%), the arithmetic mean was

(4.19), and the standard deviation was (0.71). The relative importance rate for the customer feedback variable reached (83.78%), which is good relative importance. This indicates that the surveyed individuals largely agree on these questions from their perspective. At the partial level, question (Z1), which represents (Customer feedback helps in manufacturing decisions), obtained the highest relative importance of (84.48%) with an arithmetic mean of (4.22) and a standard deviation of (0.74). In comparison, question (Z4) achieved the lowest relative importance of (80.24%), which represents (Customer feedback is of interest to the company), with the study sample agreeing at a rate of (82.80%) with an arithmetic mean of (4.19) and a standard deviation of (0.76).

The results in Table 6-13 show a high level of agreement between customer feedback statements and respondents' means, based on the average scores for each factor category (indicator) within that dimension. The primary influence of agreement responses and the relatively high values assigned to relative importance suggest that survey respondents view the domains represented by those items positively. The low dispersion in responses also indicates a satisfactory level of consistency and stability across respondents' prior evaluations, suggesting that the measurement items are clear and well-suited to the research framework. Overall, these findings provide considerable empirical evidence that the adequately measured dimension is relevant.

Table 6- 13 Frequency distributions, arithmetic means, standard deviations, and relative importance of the mediating variable, customer feedback.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
1	84.48	0.74	4.22	0.40	1	2.00	5	10.00	25	50.00	125	37.60	94	Z1
3	83.60	0.71	4.18	0.00	0	2.40	6	10.40	26	54.00	135	33.20	83	Z2
2	84.24	0.65	4.21	0.00	0	0.80	2	10.00	25	30.00	141	32.80	82	Z3
4	82.80	0.76	4.14	0.40	1	2.40	6	13.20	33	50.80	127	33.20	83	Z4
	83.78	0.71	4.19	0.20		1.90		10.90		52.80		34.20		Average
						2.10		10.90		87.00				Total

Source: Researcher. According to the statistical analysis results using SPSS V26 software. n=250

6.5.4 Description and diagnosis of the respondents' answers to the mediating variable (Recycling):

The content of these questions refers to the description and diagnosis of the Recycling variable according to the research sample's answers. The data in Table (6-14) indicate that there is an agreement

between the opinions of the surveyed individuals regarding the Recycling variable for questions (W1-W4), as the general agreement rate for the surveyed individuals' answers (Strongly agree and somewhat agree) reached (87.00%). This indicates that there is a degree of agreement for the surveyed individuals' answers on the Recycling variable, i.e. the surveyed individuals' opinions tend towards the positive based on the five-point Likert scale, while the degree of general disagreement (Strongly Disagree and somewhat disagree) for the surveyed individuals' answers to the Recycling variable paragraphs reached (2.10%). As for the percentage of answers (Neither agree nor disagree), it is (10.19%), the arithmetic mean was (4.37), and the standard deviation was (0.83). Additionally, the relative importance rate for the Recycling variable reached (87.32%), which is good relative importance, which means that the surveyed individuals agree to a clear degree on these questions according to their answers. On the other side, the partial level question (W3), which represents (Recycling is a core activity of reverse supply chains), obtained the highest relative importance of (88.96%) with an arithmetic mean of (4.45) and a standard deviation of (0.74). In comparison, question (W4) achieved the lowest relative importance of (76.56%), which represents (Recycling brings economic, social, and environmental benefits), with the research sample agreeing at a rate of (84.10%) with an arithmetic mean of (4.30) and a standard deviation of (0.89).

The results in Table 6-14 show very strong agreement among respondents regarding all of the responses associated with each dimension measured in recycling. The elevated levels of agreement responses and high relative importance values indicate the universal, strong belief that respondents hold in regard to concepts directly represented by each item on our questionnaire. In addition, the response distribution exhibits a good level of stability and consistency to further support that measurement items within research framework are clear, relevant and adequate. In total, these results provide evidence consistent with the measured dimension and reinforce the consistency of respondents' evaluations.

Table 6- 14 Frequency distributions, arithmetic means, standard deviations and relative importance of the mediating variable Recycling.

Question order	Relative importance %	Standard deviation	Arithmetic mean	Response scale										Questions
				Strongly Disagree (1)		Somewhat disagree (2)		Neither agree nor disagree (3)		Somewhat agree (4)		Strongly agree (5)		
				%	No.	%	No.	%	No.	%	No.	%	No.	
3	86.64	0.83	4.33	2.00	5	0.40	1	10.00	25	37.60	94	50.00	125	Z1
2	87.76	0.85	4.39	0.00	0	2.40	6	10.40	26	33.20	83	54.00	135	Z2
1	88.96	0.74	4.45	0.00	0	0.80	2	10.00	25	30.00	82	56.40	141	Z3
4	85.92	0.89	4.30	2.40	6	0.40	1	13.20	33	33.20	83	50.80	127	Z4
	87.32	0.83	4.37	1.10		1.00		10.90		34.20		52.80		Average

	2.10	10.90	87.00	Total

Source: Researcher, according to the statistical analysis results using SPSS V26 software. n=250.

6.6 Exploratory factor analysis:

Sample Adequacy and Factor Analysis:

Table 6-15 presents the results of the Kaiser-Meyer-Olkin (KMO) Sample Adequacy Scale, the correlation matrix determinant, and the Bartlett test for sphericity for the four research variables: I4.0, RSCs, customer feedback, and recycling. These tests are used together to assess the suitability of the data for multivariate analysis, particularly exploratory or confirmatory factor analysis.

Kaiser-Meyer-Olkin (KMO) Scale:

The values of all variables in the KMO test exceed the acceptable minimum of 0.60, indicating sufficient common variance among the research variables. Nonetheless, both I4.0 (KMO = 0.867) and RSCs (KMO = 0.885) have acceptable sample adequacy based on Kaiser's (1974) classification. These findings indicate strong correlations, suggesting that the simple model framework is sound and clear. The customer feedback dimension (KMO = 0.820) demonstrates an adequate level of the sample, which proves that there are statistically significant underlying dimensions even though the indicators are few. Similarly, the recycling dimension showed a KMO value of 0.767, which is within a good range, indicating that although the covariance is relatively low, it remains sufficient to justify factorisation.

Overall, the consistently high KMO values in the model structure provide strong empirical evidence that the data are suitable for factor analysis and that multicollinearity is not a problem at the dimensional level.

Consistency of the Correlation Matrix:

Consistency of the correlation matrix supports the feasibility of factorizing the data. For the I4.0 variable (determinant = 8.837×10^{-5}) and RSCs (determinant ≈ 0.000), very low determinant values indicate a high degree of intervariate correlation, which is desirable for factor analysis. It is significant that these values do not go to zero, implying that issues of multicollinearity or extreme singularity are unlikely.

However, by comparison, the customer feedback variables (determinant = 0.155) and recycling variables (determinant = 0.395) have significantly higher determinant values indicating a more moderate intervariate relationship. This trend is not surprising since, they are single variables that do not have any connections with the sub-dimensions and, thus, are only depicted in the model with four questions that convey them. This does not undermine factor analysis but instead shows a balanced

correlation structure that avoids redundancy and, at the same time, facilitates the determination of underlying factors.

Bartlett's Spherical Test:

The spherical test by Bartlett shows that all the variables are statistically significant ($p < 0.001$), thus rejecting the null hypothesis that the correlation matrices are unit matrices. These high chi-square values, particularly for I4.0 ($\chi^2 = 2254.154$, $df = 190$) and RSCs ($\chi^2 = 2082.259$, $df = 66$), indicate that the correlations are high and systematic, thereby justifying factor analysis.

In the case of the lower-index variables, namely, customer feedback ($\chi^2 = 460.252$, $df = 6$) and recycling ($\chi^2 = 228.769$, $df = 3$), the Bartlett test is also highly significant, indicating that the correlations are not merely random but substantial.

Overall Assessment:

The Kaiser-Meyer-Olkin (KMO) metric, the determinant value, and the Bartlett test results are strong indicators of the acceptability and strength of the data for factor analysis of all four variables. The results show that the constructs have sufficient sample sizes, exhibit valid correlation patterns, and show significant interrelations among the indices.

Therefore, the results justify proceeding with exploratory factor analysis and lend methodological credibility to subsequent validation of the measurement model and structural modelling.

Table 6- 15 Results of EFA Assumption Testing

Variable	KMO	Determinant	Bartlett Approx. χ^2	df	p-value	Decision
Industry 4.0	.867	8.837E-5	2254.154	190	<.001	Acceptable
Reverse Supply Chain	.885	.000	2082.259	66	<.001	Acceptable
Customer feedback	.820	.155	460.252	6	<.001	Acceptable
Recycling	.767	.395	228.769	3	<.001	Acceptable

As shown in Table 6-15, all four variables met acceptable sampling adequacy, significant Bartlett's test statistics, and non-problematic factor loadings; therefore, the dataset meets the statistical assumptions for conducting EFA.

6.7 Reliability and Validity Assessment:

6.7.1 Reliability Test:

To measure the reliability of the research scale for the combined dimensions of the research and intermediate variables, we used the stratified alpha coefficient as defined by Ursachi et al. (2015). This classified the reliability coefficient values into three levels: values greater than (70%) are considered

high, and values between (40%-70%) are considered medium. At the same time, it is low if the reliability coefficient value is less than (40%) (Greco et al., 2018). Table (6-15) shows the Cronbach's alpha coefficient test results. Each dimension and its stratified alpha coefficient are combined, as shown in the table. Indicates that the value of the stratified alpha coefficient reached (0.96), which is greater than (0.70), and this shows the strength of the reliability of the questionnaire in general, meaning that the research scale is very suitable for measuring the relationships between the research variables and their sub-dimensions. The following mathematical equation was used to calculate the alpha coefficient for the combined dimensions and variables:

$$\alpha_{st.} = 1 - \left[\frac{\sum_{i=1}^m \sigma_i^2 (1 - \alpha_i)}{\sigma_c^2} \right]$$

Where:

σ_i^2 : Variance of each dimension (component variance of the sum of questions for each dimension).

σ_c^2 : Component variance of the sum of dimensions.

α_i : Cronbach's alpha coefficient for each dimension.

m : Number of dimensions.

Table 6- 16 Measurement of reliability of the research dimensions and variables individually and collectively.

Variables	Dimensions	Questions	Cronbach's alpha coefficient for each dimension	The alpha coefficient for combined dimensions $\alpha_{st.}$
Industry 4.0	Cyber-physical systems (CPS)	X11-X14	.81	.93
	Internet of Things (IoT)	X21-X24	.64	
	Cloud	X31-X34	.80	
	Big data	X41-X44	.86	
	Smart factory	X51-X54	.79	
reverse supply chains (RSC)	customer preferences	Y11-Y14	.87	
	Rational use of raw materials	Y21-Y24	.92	
	Manufacturing ethics	Y31-Y34	.80	
	customer feedback	Z1-Z4	.86	
Recycling		W1-W4	.75	

Source:

1. According to the statistical analysis results, the researcher used SPSS V26 software. n=250.
2. Cho, E. (2016). Making reliability reliable: A systematic approach to reliability coefficients. Organisational research methods, 19(4), 651-682.

6.7.2 Convergent Validity:

Following the reliability assessment, convergent and discriminant validity were evaluated using AVE and HTMT, respectively.

The reliability and convergent validity of the measurement model were evaluated using composite reliability (CR), average variance extracted (AVE), maximum shared variance (MSV), and maximal reliability (MaxR(H)). CR and MaxR(H) assess the internal consistency of the constructs, while AVE evaluates convergent validity by indicating the proportion of variance captured by a construct relative to measurement error. MSV was examined to provide an initial assessment of discriminant validity by

comparing shared variance between constructs. Table 6-16 reports the CR, AVE, MSV, and MaxR(H) values for all constructs.

Table 6- 17 The reliability and convergent validity of the measurement model were evaluated using composite reliability (CR), average variance extracted (AVE), maximum shared variance (MSV), and maximal reliability (MaxR(H)).

	CR	AVE	MSV	MaxR(H)	XX1	XX2	XX3	XX4	XX5	YY1	YY2	YY3	ZZ1	WW1
XX1	0.815	0.529	0.676	0.846	0.727									
XX2	0.661	0.336	0.303	0.691	0.441***	0.580								
XX3	0.821	0.536	0.676	0.840	0.822***	0.399***	0.732							
XX4	0.866	0.619	0.718	0.872	0.695***	0.503***	0.744***	0.787						
XX5	0.800	0.500	0.016	0.801	0.000	-0.126	0.093	-0.035	0.707					-0.038
YY1	0.876	0.639	0.718	0.878	0.575***	0.464***	0.628***	0.847***	0.012	0.799				
YY2	0.923	0.751	0.526	0.928	0.500***	0.441***	0.537***	0.628***	0.066	0.725***	0.866			
YY3	0.833	0.561	0.378	0.877	0.485***	0.436***	0.525***	0.615***	-0.096	0.569***	0.542***	0.749		
ZZ1	0.866	0.618	0.357	0.870	0.527***	0.461***	0.453***	0.543***	0.004	0.597***	0.494***	0.578***	0.786	
WW1	0.759	0.443	0.303	0.767	0.192	0.551	0.136	0.201	**	0.331	0.349	0.280	0.305	0.665

Table 6-17 shows the values of composite reliability (CR), extracted mean variance (AVE), maximum common variance (MSV) and MaxR(H), and correlation coefficients between constructs and square roots of AVE (diagonally). In general, the internal consistency of most constructs is reasonable, and the CR and MaxR(H) scores are equal or above the suggested values. The values of AVE of the variables XX2 and WW1 are less than the traditional value of 0.50, but they have CR values that are near or greater than acceptable criteria, which imply that there is adequate convergent validity as suggested by Furnell & Larker (1981). Moreover, some constructs have an MSV greater than their AVE, suggesting potential overlap. Nevertheless, an additional criterion for testing discriminant validity was the use of the HTMT, which is regarded as more precise and reliable. Because all the HTMT values were below the recommended value, the presence of discriminant validity is supported. The relatively high correlations observed between some concepts reflect theoretical and conceptual convergence of notions within the I4.0 and RSCs frameworks, rather than redundancy in measures.

6.7.3 Test HTMT (Discriminant Validity):

The variable-to-univariate feature ratio (HTMT) was used to assess discriminant validity and to quantify the extent of empirical variance between concepts. It is believed that HTMT is a better and more valid measure than conventional measures of discriminant validity. An HTMT value below the recommended minimum indicates established discriminant validity. Table 6-18 presents the ratios of all the concept pairs in HTMT.

Table 6- 18 Test HTMT (Discriminant Validity).

	XX1	XX2	XX3	XX4	XX5	YY1	YY2	YY3	ZZ1	WW1
XX1										
XX2	0.425									
XX3	0.835	0.485								
XX4	0.714	0.525	0.817							
XX5	0.003	0.100	0.083	0.038						
YY1	0.581	0.504	0.654	0.839	0.012					
YY2	0.491	0.512	0.603	0.639	0.050	0.734				
YY3	0.487	0.472	0.599	0.658	0.104	0.635	0.637			
ZZ1	0.533	0.481	0.491	0.545	0.000	0.611	0.506	0.619		
WW1	0.165	0.565	0.140	0.197	0.022	0.334	0.355	0.287	0.291	

Table 6-18 shows the heterotrait monotrait (HTMT) ratios that were used to test discriminant validity between the study constructs. All HTMT values are below the recommended threshold (0.90), indicating that the constructs are empirically distinct and that discriminant validity is supported.

Although a small number of construct pairs exhibit relatively high HTMT values, these remain within acceptable limits and are theoretically justifiable given the conceptual proximity of the constructs within the I4.0 and RSCs context. Overall, the results confirm the validity and accuracy of the measurement model.

6.8 Internal consistency of research variables and dimensions:

Internal consistency refers to the correlation between questions within a single dimension. To measure internal consistency at the dimension level, we need to consider the correlation between questions within that dimension. Additionally, it reveals the extent of correlation between the dimensions within a single variable. Internal consistency is measured by the mean (Mean) of the (absolute) correlation coefficients between pairs of questions within a single dimension or variable. Sources indicate that if this mean is greater than or equal to (0.3), this suggests the presence of internal consistency. The results of Table (6-19) indicate the presence of internal consistency at the level of each variable with its dimensions, as indicated by the absolute value of the arithmetic mean of the correlations (Mean), which all appeared greater than (0.3).

Table 6- 19 internal consistency values at the level of variables and their sub-dimensions.

Variables	Dimensions	Inter-Item Correlations				No of Items
		Mean	Minimum	Maximum	Variance	
Industry 4.0	Cyber-physical systems (CPS)	0.526	0.447	0.708	0.009	4
	Internet of Things (IoT)	0.312	0.194	0.489	0.010	4
	Cloud	0.511	0.287	0.658	0.018	4
	Big data	0.616	0.561	0.686	0.002	4
	Smart factory	0.500	0.456	0.537	0.001	4
Reverse supply chains (RSCs)	customer preferences	0.639	0.592	0.687	0.001	4
	Rational use of raw materials	0.750	0.677	0.852	0.04	4
	Manufacturing ethics	0.524	0.297	0.726	0.020	4
	customer feedback	0.614	0.567	0.680	0.002	4
	Recycling	0.440	0.373	0.519	0.002	4
	Industry 4.0	0.323	0.145	0.708	0.048	20
	Reverse supply chains (RSCs)	0.483	0.223	0.852	0.022	12

Source:

1. According to the statistical analysis results, the researcher used SPSS V26 software. n=250.

2. Wu, M., Tam, H. P., & Jen, T. H. (2016). Educational measurement for applied researchers. Theory into practice, 136.

6.9 Normal Distribution Test:

This section of the chapter presents a probability distribution analysis of the research variables. This test is a fundamental requirement in any statistical study. Most estimation and hypothesis-testing methodologies require a fundamental condition: the variables under investigation have a known probability distribution. The distribution is typically normal; if this condition is not satisfied, alternative methods to least squares must be employed to estimate the parameters of the regression model, such as generalised least squares, free distribution, or unweighted least squares. We must also utilise nonparametric tests, which do not require the normality of the variables, when conducting statistical hypothesis testing. The Kolmogorov-Smirnov test is among the most widely used statistical tests for assessing normality. This test is distinguished by its appropriateness for extensive sample sizes. The test results presented in Table (6-20) demonstrate that all probability values (P-values) are less than (0.05), indicating that the four variables and their dimensions do not adhere to a normal probability distribution. The null hypothesis posits that the variable adheres to a normal distribution, whereas the alternative hypothesis asserts that it does not.

Table 6- 20 Values of the (Kolmogorov-Smirnov) criterion for examining the normal distribution of research variables and dimensions.

Tests of Normality				
Kolmogorov-Smirnov				
Classification	Description	Statistic	N	P-value
Dimensions	Cyber-physical systems (CPS)	.153	250	.000
	Internet of Things (IoT)	.144	250	.000
	Cloud	.157	250	.000
	Big data	.178	250	.000
	Smart factory	.171	250	.000
	customer preferences	.176	250	.000
	Rational use of raw materials	.182	250	.000
	Manufacturing ethics	.148	250	.000
Variables	customer feedback	.210	250	.000
	Recycling	.242	250	.000
	Industry 4.0	.165	250	.000
	Reverse Supply Chains (RSCs)	.169	250	.000

Source: Researcher According to the statistical analysis results using SPSS V26 software. n=250

6.10 Common Method Bias Test (CMB):

This test is one of the basic requirements for obtaining accurate and correct estimates and relationships. Researchers indicate that this bias is due to several factors, including the use of non-diverse data sources, the simultaneous application of the scale, a lack of diversity in the Likert scale used in the questionnaire, the similarity of statements, the ambiguity of some statements, and the length of the questionnaire. The presence of this bias distorts the relationships among variables, leading to inaccurate results. The presence or absence of bias in the standard method is revealed by the Harman single-factor test (Aguirre-Urreta & Hu, 2019). Indicated that if the value of this test is greater than (50%), this is evidence of the presence of bias in the standard method, as the value of this test can be obtained through the value of the explained variance of the factor after applying the exploratory factor analysis method according to the SPSS program. For the current research data, the value of this test was (CMB=31.752%), which is less than (50%), so we can conclude that there is no bias problem in the Common method.

The total variance explained by a single factor was 41.96%, which falls below the usually recommended threshold of 50% in bias assessment using Harman's One-factor test; thus, this should be considered only an initial screen for common Method bias and not used alone to provide a sufficient diagnosis. This is attributed to the metric's relatively low sensitivity and its tendency to miss complex or multidimensional sources of measurement bias. As a result, additional procedural and statistical precautions were taken to mitigate the risk of systematic response bias. While the one-factor Harman test indicated that a single factor explains less than 50% of the total variance (a commonly recommended cutoff for common method bias), it is only an initial diagnostic test and not sufficient in isolation to make an overall diagnosis. This likely reflects the relatively low sensitivity and the inability to identify markers of more nuanced or multidimensional origins of measurement bias using this measure alone. We sought to reduce the likelihood of systematic response bias by implementing an array of procedural and statistical measures.

Regarding procedures, respondents were informed that their responses would remain confidential and be used solely for research purposes. The scale items were further phrased clearly and unambiguously to reduce response bias.

We performed statistical analyses, including confirmatory factor analysis (CFA) and heterotrait–monotrait ratio (HTMT). CFA results indicated adequate model fit, and HTMT values did not exceed recommended thresholds, supporting discriminant validity and mitigating concerns about common method bias across research constructs.

6.11 Confirmatory factor analysis:

The confirmatory factor analysis of the research variables aims to determine the relationships between the observations (questions) and the dimensions they represent. Additionally, it determines the correlations among the variables (dimensions) under study, thereby assessing the suitability of the researcher's model for the sample. After assessing the data's probability distribution using the Kolmogorov–Smirnov test, the results indicated that the data did not follow a normal distribution. Confirmatory factor analysis (CFA) was then conducted to evaluate the fit of the proposed research model (questionnaire) to the sample data. Because the maximum likelihood (ML) estimation method assumes multivariate normality, its use was not appropriate under these conditions. Consequently, an alternative estimation approach was adopted. Specifically, the unweighted least squares (ULS) method was employed, as it does not require normality assumptions and is therefore more suitable for analysing non-normally distributed data.

The saturation values (Factor Loading) (correlation) of the queries from each variable are depicted in Figure (6-5), along with the variable that indicates them. The single-headed arrow that connects the

question and the primary variable exemplifies this. In addition, the double-headed arrow illustrates the correlation coefficients for each pair of latent variables. The confirmatory factor analysis results demonstrated the researcher-developed model's significance and its alignment with the research sample model. The results of the indicators of goodness of fit in Table (6-22), which are based on the indicators of goodness of fit and acceptance limits used by most researchers and are presented in Table (6-21), indicate that all indicators are consistent, specifically within their acceptable limits. The standard regression coefficients (SRW-saturations) and non-standard regression coefficients, along with their corresponding probability values (P-values), are illustrated in Table (6-23).

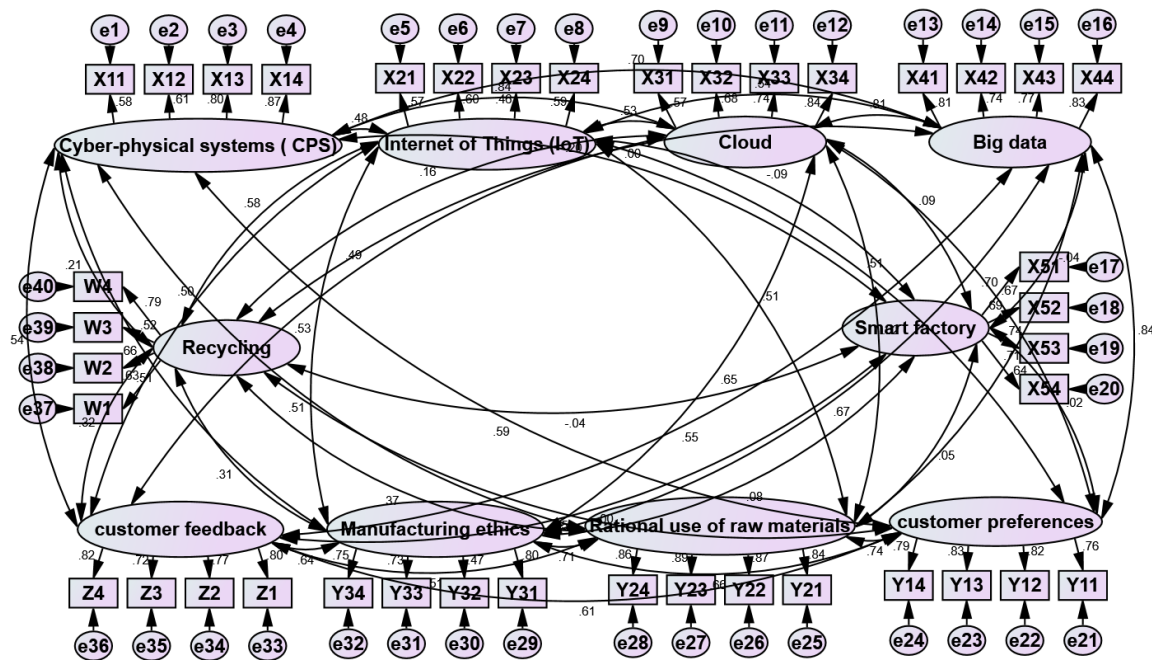


Figure 6 - 5 Confirmatory factor analysis of the dimensions of the research variables

Source: The researcher based on the statistical analysis results using AMOS V24 software. n=250

Table 6- 21 Goodness of fit indicators for confirmatory factor analysis.

Indicators	Value	Result
GFI	0.974	Identical
AGFI	0.969	Identical
PGFI	0.826	Identical
NFI	0.967	Identical
RFI	0.963	Identical
RMR	0.040	Identical

Source: Researcher based on statistical analysis results using AMOS V24 software, n=250.

Table 6- 22 lists the most important indicators of good conformity and their acceptance limits.

Indicator	Acceptance limits
Goodness of Fit Index (GFI)	If it is less than (0.90), this means that there is a weak fit. If it is equal to (0.90) or more, this indicates that the model is of good quality.
Adjusted Goodness of Fit Index (AGFI)	If it is greater than (0.85), it means an acceptable match, but if it is equal to (0.90) or more, it means a good match.
Normative Fit Index (NFI)	It indicates good model quality when it reaches (0.90) or more.
Parsimony Goodness of fit index (PGFI)	It indicates good model quality when it reaches (0.60) or more.
Relative Fit Index (RFI)	It indicates the good quality of the model and its conformity to the data when it reaches (0.90) or more.
Root Mean Square Residual (RMR)	This indicator indicates a good fit of the model when it reaches (0.08) or less.

Source: Hoyle, R. H., & Isherwood, J. C. (2013). Reporting results from structural equation modelling analyses in the Archives of Scientific Psychology. Archives of scientific psychology, 1(1), 14.

Table 6- 23 Standardised and non-standardised regression coefficient values for confirmatory factor analysis results.

Parameter	Estimate	L	U	SRW	P-value
X13 <---	1.693	1.101	2.568	.797	.009
X14 <---	1.986	1.367	2.956	.874	.006
X12 <---	1.145	.815	1.659	.612	.004
X11 <---	1.000	1.000	1.000	.583	.007
X23 <---	.892	.437	1.722	.463	.008
X24 <---	1.184	.819	1.787	.592	.007
X22 <---	1.144	.630	2.274	.600	.002
X21 <---	1.000	1.000	1.000	.569	.009
X33 <---	1.683	1.270	2.304	.744	.014
X34 <---	1.705	1.273	2.788	.839	.003
X32 <---	1.595	1.223	2.438	.680	.007
X31 <---	1.000	1.000	1.000	.567	.009
X43 <---	1.081	.841	1.400	.772	.011

Parameter		Estimate	L	U	SRW	P-value
X44	<---	1.187	.968	1.440	.830	.019
X42	<---	.933	.758	1.189	.738	.010
X41	<---	1.000	1.000	1.000	.805	.007
X53	<---	1.077	.688	1.569	.742	.012
X54	<---	1.158	.883	1.579	.707	.002
X52	<---	1.061	.698	1.514	.686	.009
X51	<---	1.000	1.000	1.000	.696	.004
Y13	<---	.985	.772	1.219	.827	.016
Y14	<---	.958	.782	1.153	.795	.006
Y12	<---	1.106	.880	1.369	.819	.010
Y11	<---	1.000	1.000	1.000	.756	.007
Y23	<---	1.044	.901	1.202	.893	.005
Y24	<---	1.032	.880	1.218	.860	.008
Y22	<---	1.036	.879	1.162	.867	.007
Y21	<---	1.000	1.000	1.000	.843	.012
Y33	<---	.727	.530	.937	.726	.009
Y34	<---	.791	.594	1.036	.747	.006
Y32	<---	.428	.249	.664	.471	.005
Y31	<---	1.000	1.000	1.000	.800	.005
Z3	<---	.782	.549	1.070	.716	.003
Z4	<---	1.057	.743	1.481	.821	.007
Z2	<---	.925	.631	1.266	.772	.008
Z1	<---	1.000	1.000	1.000	.801	.004
W3	<---	.736	.334	1.396	.520	.006
W4	<---	1.344	.733	2.841	.790	.004
W2	<---	1.085	.460	1.884	.662	.007
W1	<---	1.000	1.000	1.000	.629	.002

The most important indicator in Table (6-23) is the value of the standard regression coefficients (SRW), which represent the saturation (correlation) of the questions with the dimension they are on. Most of their values are supposed to exceed (0.50). From observing the results of the (SRW) values, we find that all saturations are greater than (0.50) and are significant because all the probability values

corresponding to the saturation values are less than (0.05) (Harlow, 2014). One of the indicators in this construct showed a standard regression weight slightly below the recommended limit of 0.50: X23. However, the load factor limits are guidelines rather than strict thresholds, and values above 0.40 are considered acceptable when supported by theory. The model construct demonstrated satisfactory internal consistency and composite reliability, and the loadings were statistically significant. Removing the item did not significantly improve the model's suitability or reliability; therefore, the item was retained to maintain content validity.

Most of the statistical tests used in the quantitative methodology were based on analysing data through exploratory factor analysis, reliability analysis, convergent validity testing via AVE, discriminant validity testing using the HTMT, and normality assessment using Skewness and Kurtosis statistics. This was followed by a common-method bias test, including full collinearity variance inflation factors, along with confirmatory factor analyses CFA and SEM for evaluation of the research model and measurement instrument. The choice of these statistical methods stems from the fact that our research model comprises not only several latent variables but also mediating relationships and theoretically interrelated dimensions, which require the simultaneous testing of both measurement quality and structural integrity.

While these procedures are suitable, there will still be a few methodological aspects to keep in mind. First, the study relies on cross-sectional, self-reported data, which can increase the risk of common method bias and social desirability effects and hinder the establishment of causal relationships between variables. Cross-sectional designs for descriptive and statistical solutions, however, remain limited to operationalising a snapshot of organisational change over time, despite implementations aimed at procedural or mechanistic remediation. Second, the conceptual framework is much more complex, with many constructs and mediating effects that require a sufficient sample size and statistical power. SEM models assume an adequate sample size (to provide parameter stability, model fit indices, and good estimates for mediation). Accordingly, the adequacy of the sample size was determined based on model complexity and average recommendations for SEM estimation. The choice of SEM was justified both theoretically and methodologically, given the study's objective: to test direct and indirect relationships simultaneously while controlling for measurement error among latent variables. In addition, it offers superior analytic capabilities compared to more traditional regression methods for testing complex mediation-based conceptual models (Memon et al., 2020). In addition, CFA and SEM together provide a unified mathematical framework for validating measurement models and their structural relationships.

However, different analytical methods may be useful depending on the research question and characteristics of the data. For instance, partial least squares structural equation modeling (PLS-SEM)

is typically well-suited for exploratory, prediction-oriented research designs with smaller sample sizes or for models that assume non-normality in the data distribution. At the same time, covariance-based SEM (CB-SEM) was deemed more suitable for meeting the research objectives, as the current study is theory-driven and aims to test an integrated conceptual model grounded in established theoretical foundations.

6.12 Hypothesis Testing: Structural Equation Modelling (SEM):

A quantitative method was used to address the research questions; each construct was defined within the proposed structural equation modelling (SEM) framework, and multiple items from previously validated scales were employed. The researcher must also test hypotheses. Therefore, in accordance with statistical principles, the researcher relies on hypothesis testing. There are two types of hypotheses: the null hypothesis (H_0) and the alternative hypothesis (H_1), which are essential elements in verifying research questions (Chigbu, U.E., 2019). The null hypothesis is that the independent variable does not affect the dependent variable. Any observed effect may be due to chance rather than to real factors (Szucs & Ioannidis, 2017). The alternative hypothesis is what you want to support or verify; it reflects the effect of the independent variable on the dependent variable or the difference you expect to find if your theory is correct (Phina et al., 2018). The null hypothesis is an assumption, not a proven fact, and the alternative hypothesis is what you are trying to demonstrate using facts and findings (Gilman, A., 2018).

Because Structural Equation Modeling (SEM) was used to analyse the data, a sample size was necessary to ensure the strength of the model estimates in AMOS V24. A sample of 250 valid responses was gathered, which is sufficient for SEM analysis and is recommended to be at least 250 (Teo, Tsai, and Yang, 2013; RVSPK & Megama, 2020). Prior to SEM testing, the data were screened for missing and extreme values. The Kolmogorov–Smirnov (KS) test was used as a normality test and is appropriate for large sample sizes. Normality testing is one of the most important assumptions of SEM because many estimation methods (e.g., maximum likelihood) rely on the normality of the variables. If this assumption is not met, alternative estimation methods can be used, including Generalised Least Squares (GLS), distribution-free, or Unweighted Least Squares (ULS). When normality cannot be assumed, normative tests can also be used. To measure the internal consistency of the measurement scales, the stratified alpha coefficient was used (Ursachi et al., 2015). Based on Greco et al. (2018), reliability coefficients were interpreted as follows: values above 0.70 indicate high reliability; values between 0.40 and 0.70 indicate moderate reliability; and values below 0.40 indicate low reliability.

6.11.1 Analysis of the effect relationship:

Regression analysis is employed to ascertain the direction and type of the causal relationship between one or more independent variables and a dependent variable. The value of the regression coefficient determines the direction of the link (direct or inverse). The significance of the impact is determined by examining the probability value (P-value) associated with the regression coefficient. If this number is below 0.05, it indicates that the independent variable has a significant influence on the dependent variable.

The first main hypothesis:

Null hypothesis H_0 : Industry 4.0 has no significant effect on the contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of industrial company workers.

Alternative Hypothesis H_1 : Industry 4.0 has a significant effect on the contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of industrial company workers.

Table (6-24) and Figure (6-6). The results show a strong, statistically significant positive effect of I4.0 on the contemporary vision of RSCs activities. The path coefficient ($\beta = 1.74$) is highly statistically significant ($p < 0.001$; C.R. = 7.408), underscoring the crucial role of I4.0 in the development of sustainable reverse supply chain practices. The low standard error (S.E. = 0.234) indicates the consistency and precision of the estimated correlation.

The model has high explanatory power, as the R^2 value is 0.82, indicating that I4.0 explains 82% of the variance in the contemporary vision of RSCs' activities. This degree of explained variance is quite high and demonstrates that the model can predict.

This is because of the high values of β and R^2 , which are justified both theoretically and methodologically. Theoretically, IoT, CPS, Big Data, Cloud Computing, and Smart Factory are I4.0 technologies that are radically redefining the contemporary vision of RSCs, enabling real-time tracking, instant decision-making, automatic recovery, and stakeholder coordination. These capabilities directly affect the processes of enhancing, developing, and controlling the contemporary vision of RSCs, and their correlation is strong.

The results are methodologically robust, as the validity of the measurement model and its structure was upheld. The model fit and validity criteria are within acceptable ranges. The HTMT results indicate that the model is discriminative, eliminating the possibility that structural redundancy or

multiple linear correlations are the cause of the strong effect. Thus, the value of t -statistics, which is great, and R^2 are not merely statistical inflation.

In general, the findings empirically confirm that I4.0 is an enabler of the current vision of RSCs, supporting its central role in the digital and sustainable transformation of these supply chains.

The quantitative analysis results in Table (6-24) show that I4.0 technology significantly affects the contemporary vision of RSCs activities. Specifically, I4.0 technology supports meeting customer preferences, enhances the rational use of raw materials, and aligns with manufacturing ethics practices. This combined integration contributes to waste reduction and promotes sustainability. Moreover, due to their direct effect, the results have reinforced the researcher's approach to establishing an integrative relationship between Industry 4.0 technology and the contemporary vision of RSCs activities.

Accordingly, reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1): there is a significant relationship between the independent variable, Industry 4.0, and the dependent variable, contemporary vision of RSCs activities. Moreover, the results of the first hypothesis provided an answer to the first research question, which included (How can I4.0 be integrated with the contemporary vision of RSCs activities by linking them). Industry 4.0 can be integrated with the contemporary vision of RSCs' activities through the use of emerging technologies. Industry 4.0 technology has effectively linked and integrated Industry 4.0 with the contemporary vision of RSCs activities.

Critical Interpretation and Assessment of the High Explanatory Power (R^2) of the Structural Model:

As for the direct relationship between Industry 4.0 technology and the contemporary vision of RSCs' activities, a model with high explanatory power ($R^2 = 0.82$) was presented, indicating that the independent variable explained around 82% of the variance in the dependent variable. Although such a high value is not impossible in structural equation modeling, it would be considered extraordinary in management and behavioral research, and thus calls for careful critical interpretation rather than blind acceptance.

A likely reason for this high R^2 is conceptual or structural convergence between the dependent and explanatory variables. If structures are theoretically very close (e.g., Industry 4.0 linkages or RSC activities in sustainability), there is a risk of overlapping conceptual boundaries, which may increase the explained variance but will not identify how processes lead to one another. This was addressed in this research through careful construct development, discriminant validity testing (HTMT), and confirmatory factor analysis (CFA), which showed that the constructs are statistically distinct from one another.

The second type of inflation is known as common-method variance and can occur when you use a single-source, self-report questionnaire. This bias can create spurious relationships between constructs. However, this concern was addressed through corrective measures (anonymity, confidentiality, and item clarity) and statistical diagnostics: the one-factor Harman test, confirmatory factor analysis model evaluation, and HTMT, which indicate that common-method bias does not appreciably distort the measurement model.

Only when items are similar in terminology or represent closely aligned conceptual elements would they increase a measure's explanatory power. Nonetheless, this research reduced the risk of measurement-driven inflation of variance by using validated measures, multi-item constructs, and precise item variation across motivational antecedents.

First, the confidence interval analyses and effect size indices in the structural model provide additional evidence of the robustness of the R^2 value from a statistical inference perspective. Tight confidence intervals around the path coefficients reflect the stability of the parameter estimates; large effect sizes indicate substantial practical effects on the dependent variables, not merely statistical correlations. These indicators work together to support the model's high explanatory power in practice.

Furthermore, the fit indices confirm that the model is not statistically inflated and demonstrate significant explanatory and predictive power. Therefore, the high R^2 value should be interpreted not as a systematic anomaly but as evidence of a strong theoretical relationship between Industry 4.0 technology and the contemporary vision of RSCs' activities. In conclusion, although an R^2 value of 0.82 is relatively high in management research, several robustness tests, including discriminant validity, common-method bias diagnostics, measurement validation, and effect size assessment, collectively support the reliability and thematic coherence of the results. Therefore, this diagnosis is interpreted as indicating a strong and significant explanatory relationship, rather than statistical inflation or modelling error.

Table 6- 24 Results of the effect of Industry 4.0 on contemporary vision of RSCs activities.

independent variable	Direction of effect	Dependent variable	Estimate(β)	S.E.	C.R.	R^2	P-value
Industry 4.0	→	Contemporary vision of RSCs activities	1.74	0.234	7.408	0.82	0.000

Table value ($t_{Tab} = 1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

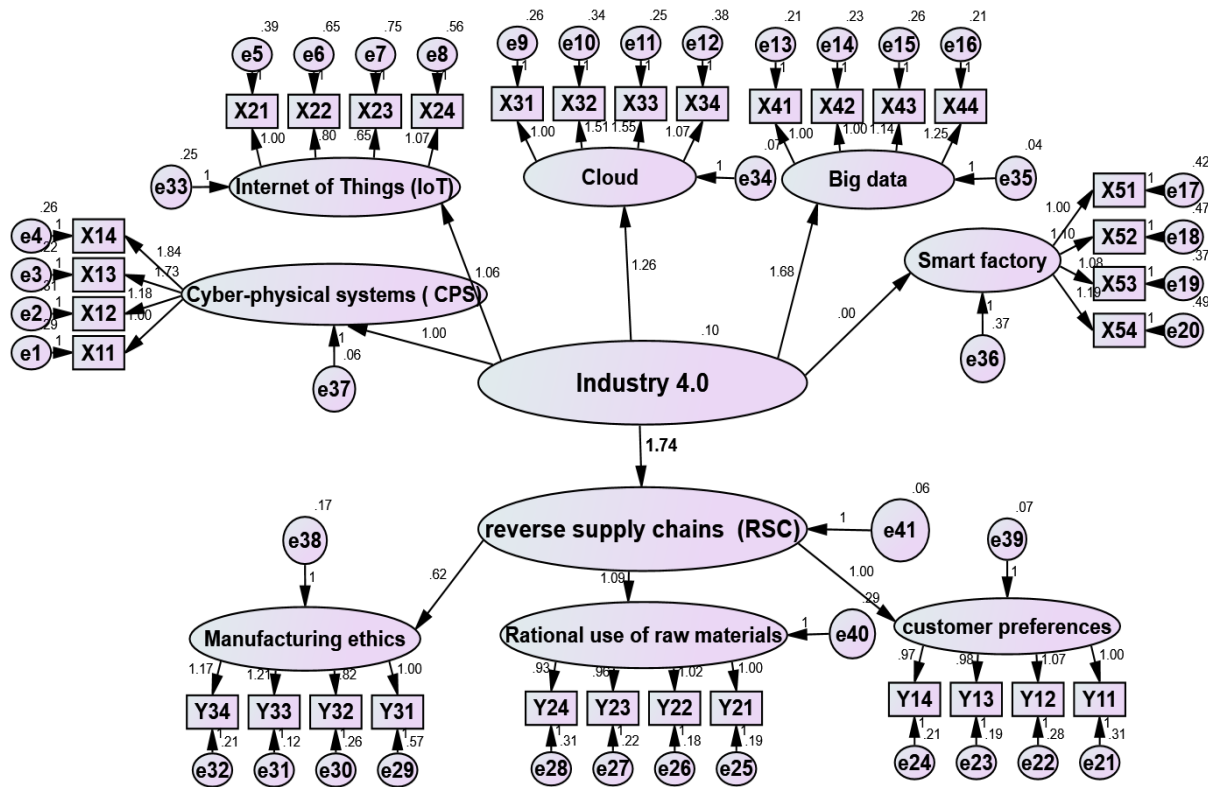


Figure 6 - 6 The effect of I4.0 on contemporary vision of RSCs activities

Source: Researcher based on the statistical analysis results using AMOS V24 software. n=250.

The results confirm the pivotal role of I4.0 as a key explanatory factor in shaping the contemporary vision of RSCs activities. The strength of the relationship reflects the fundamental impact of digital technology on the strategic orientation and operational integration of RSCs. At the same time, both the model's validity and discriminatory power support the robustness of this conclusion.

The second main hypothesis:

Null hypothesis (H₀): There is no significant effect relationship between Industry 4.0 and customer feedback at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

Alternative Hypothesis (H₁): There is a significant effect relationship between I4.0 and customer feedback at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

Table 6-25 shows the outcome of the structural relationship between I4.0 and customer feedback. The results indicate a statistically significant positive impact of I4.0 on customer feedback, as evidenced by an estimated path coefficient ($\beta = 0.90$) and a p-value < 0.001 , both well above traditional thresholds. The critical ratio (C.R. = 6.274) exceeds the suggested value of 1.96, confirming the strength of the relationship.

The standard error (S.E. = 0.144) is comparably low, indicating that the estimate of the path coefficient is stable and accurate. The model explains 35% of the variance in customer feedback ($R^2 = 0.35$), which is rather high. This implies that I4.0 is a significant contributor to customer feedback mechanisms, though there are other factors beyond I4.0 that could also affect customer feedback.

Overall, the findings provide empirical evidence of the intended relationship, showing that I4.0 implementation positively influences customer feedback by enhancing digital interaction, data collection, and real-time responsiveness.

The empirical test confirms that I4.0 technology, an independent variable, has a statistically significant impact on the mediating variable (customer feedback). This connection meets one of the fundamental requirements for inclusion in the research model, thereby demonstrating its role in linking I4.0 technology to the contemporary vision of RSCs' activities. This finding indicates that the adaptability of I4.0 technologies, when aligned with strategic practices in RSCs, may boost integration, operational effectiveness, and sustainability, thereby aligning I4.0 technologies with the contemporary vision of RSCs activities. This implies that it increases customer interaction with the company. Customer feedback enhances real-time data collection, communication, and responses. In practice, Industry 4.0 technologies enable organisations to collect, process, and act on customer feedback. This enables faster decision-making, thereby keeping pace with changing market demands through advanced production systems. Theoretically, the significant relationship between I4.0 technology and customer feedback empirically supports the assumption that digital transformation can strengthen demand-driven supply chain models. On the same note, in terms of management, the effect relationship can be stated as follows: advanced I4.0 technology fosters an environment rich in customer feedback, thereby increasing customer satisfaction and loyalty, and promoting an ethical and sustainable orientation in customer service work. Thus, the mediating role of customer feedback not only enhances the model's explanatory power but also clarifies the strategic direction of I4.0 technology in linking technological capabilities to customer-centric sustainability outcomes.

Based on the results of the second hypothesis, as shown in Table 6-25, and the significant relationship between the independent variable, Industry 4.0, and the mediating variable, Customer Feedback, we reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1). Moreover, the results of the hypothesis provided an answer to the second research question, including (Does Industry 4.0 technology link to (customer feedback and recycling) as intermediate variables?), as it showed an influential relationship between Industry 4.0 and Customer Feedback.

Table 6- 25 Results of the effect of Industry 4.0 on customer feedback:

independent variable	Direction of effect	Dependent variable	Estimate(β)	S.E.	C.R.	R ²	P-value
Industry 4.0	→	customer feedback	0.90	0.144	6.274	0.35	0.000

Table value ($t_{Tab} = 1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

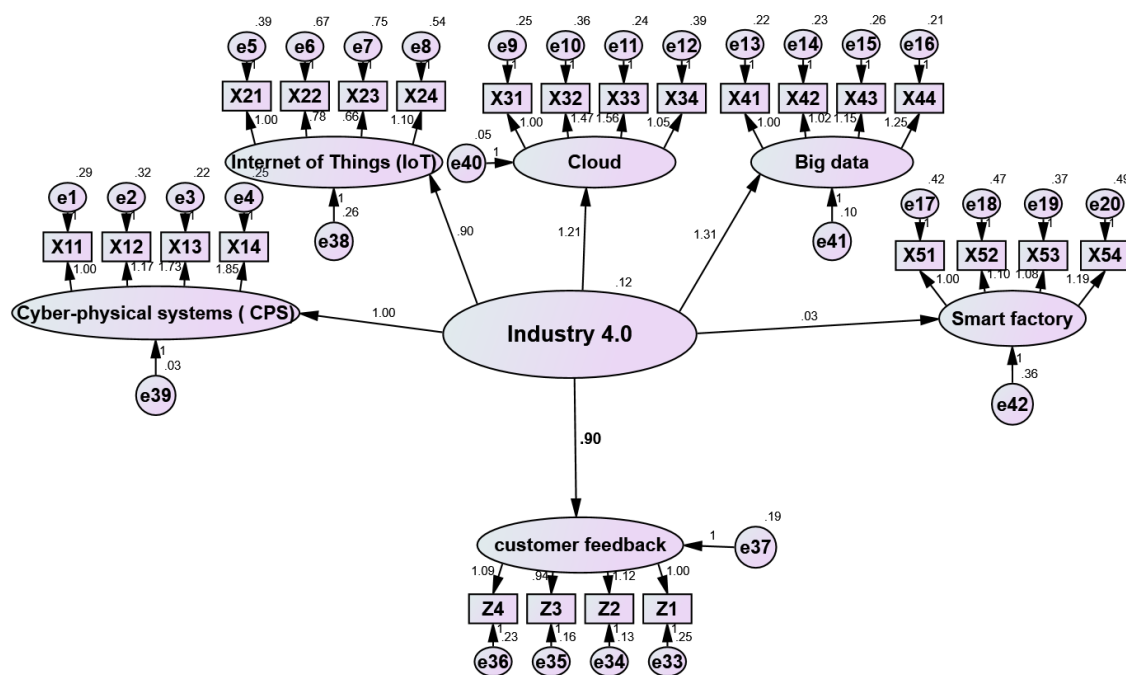


Figure 6 - 7 The effect of I4.0 on Customer feedback

Source: Researcher based on the statistical analysis results using AMOS V24 software. n=250.

The results demonstrate a positive and statistically significant effect of I4.0 on customer feedback, indicating that the adoption of I4.0 technologies meaningfully enhances firms' ability to capture, process, and utilise customer-related information. The strength of the relationship demonstrates that digitalisation and smart technologies are important factors in enhancing feedback processes and customer-firm interaction.

The described variance indicates a medium degree of predictive power, implying that although I4.0 is a significant predictor of customer feedback systems, other supplementary organisational, technological, or relational variables may also influence customer feedback results. In general, the

results support the idea that I4.0 is a critical facilitator of more responsive, data-oriented, and interactive customer feedback operations.

The third main hypothesis:

H₀: There is no significant effect relationship for Industry 4.0 in Recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

H₁: There is a significant effect relationship for Industry 4.0 in Recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

The relationship between I4.0 and recycling is structural as seen in Table 6-26. The findings show that there is a statistically significant positive impact of I4.0 on recycling activities based on the estimated path coefficient ($\beta = 0.32$), and the p-value (0.042) is statistically significant at the 5% level. The critical ratio (CR = 2.724) exceeds the lower bound of 1.96, indicating statistical causality in the relationship.

The standard error (SE = 0.117) is within a tolerable range of accuracy. Nonetheless, the R^2 value is 0.10, indicating a small amount of explained variance, implying that I4.0 accounts for only 10% of the variance in recycling practices. This means that I4.0 plays an important role in recycling, although other factors, including regulatory pressure, corporate commitment, infrastructure availability, and environmental awareness, also affect recycling outcomes.

Overall, the findings affirm that I4.0 has a positive impact on the recycling process. Nonetheless, the ability to explain this outcome variable is lower than that for other outcome variables, implying that it is regulated rather than dominant in this case. The findings of the third hypothesis show that there is a statistically significant impact of I4.0 technology as an independent variable on recycling as a mediating variable. This and important effect satisfies one of the conditions of the implementation of recycling as a mediating variable between I4.0 and the contemporary vision of the RSCs activities. This finding is corroborated by the central role of transformation in the development of circular economy practices, particularly in enhancing recycling processes across manufacturing systems.

I4.0 technologies can help companies streamline the recycling process, increase material recovery rates, and eliminate inefficiencies through real-time monitoring and tracking, intelligent data analytics, automation, and interconnected systems. These strengths will make recycling more flexible and responsive, tailored to customer preferences, and minimise the utilisation of raw materials and support ethical manufacturing. In theory, the mediating variable highlights the expansion of technological innovation beyond immediate operational advantages to sustainability-relevant practices, thereby closing the gap between technological capabilities and environmental performance. In manufacturing,

certain products have short life cycles and are subject to obsolescence due to technological change; flexible and adaptive recycling helps alleviate these effects.

From a management perspective, the intangible impact of I4.0 on recycling refers to companies' ability to leverage digital technology to enhance adaptability, reduce costs, and meet regulatory and environmental expectations for sustainable production. Thus, recycling emerges not only as a mediating variable but also as an organisational strategy through which I4.0 technology contributes to the contemporary vision of RSCs activities, focusing on resource-use efficiency, customer satisfaction, and ethical manufacturing practices in the context of manufacturing sustainability.

Based on the results of the third hypothesis, as shown in Table (6-26), and the significant relationship between the independent variable, Industry 4.0, and the mediating variable, recycling, we reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1). Moreover, the results of the hypothesis answered the second research question: “Does Industry 4.0 technology link to (customer feedback and recycling) as intermediate variables?” This demonstrated an influential relationship between Industry 4.0 and recycling.

Table 6- 26 Results of the effect of Industry 4.0 on Recycling.

independent variable	Direction of effect	Dependent variable	Estimate(β)	S.E.	C.R.	R²	P-value
Industry 4.0	→	Recycling	0.32	0.117	2.724	0.10	0.042

Table value ($t_{Tab} = 1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250.

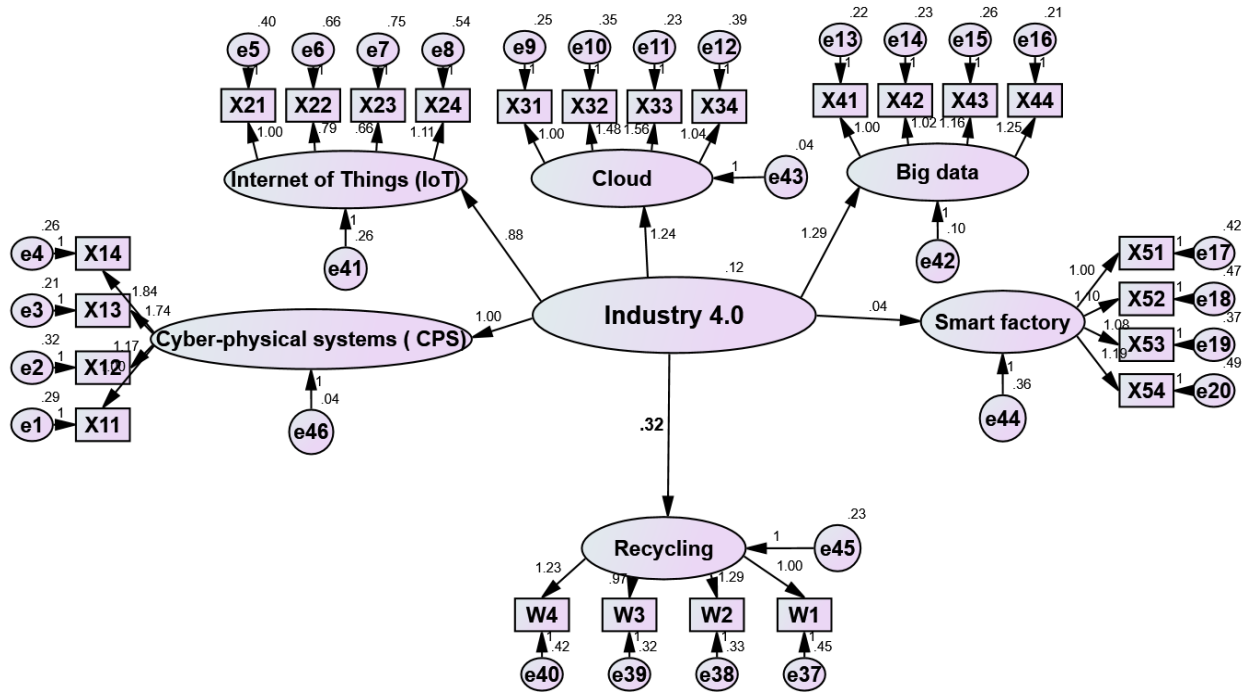


Figure 6 - 8 The effect of I4.0 on Recycling

Source: Researcher based on the statistical analysis results using AMOS V24 software. n=250

The results indicate that I4.0 exerts a positive but relatively modest influence on recycling activities, suggesting that digital technologies act as a supporting enabler rather than a primary driver of recycling outcomes, which is influenced by additional regulatory, organisational, and infrastructural factors.

Fourth main hypothesis:

H₀: There is no significant effect relationship between customer feedback and contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of workers in industrial companies.

H₁: There is a significant effect relationship between customer feedback and contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a specific sample of workers in industrial companies.

Table 6-27 presents the results of the relationship between customer feedback and the contemporary vision of RSCs activities. The findings indicate a positive, statistically significant effect of customer feedback on the contemporary vision of RSCs, as evidenced by the estimated path coefficient ($\beta = 0.72$) and a p-value < 0.001 .

The critical ratio (C.R. = 7.923) is substantially higher than the recommended value of 1.96, which proves the strength of the relationship. The standard error (S.E. = 0.091) is not large, which implies that the path coefficient is estimated with high precision. The contemporary vision of RSCs activities is explained by 47% ($R^2 = 0.47$), indicating a medium-to-strong effect. This implies that customer feedback is a major factor in defining the conceptualisation of implementing the contemporary vision of RSCs activities in organisations.

In general, the findings demonstrate that the functioning of efficient customer feedback systems is important in the development of the contemporary vision of RSCs activities. It enables more responsive, customer-oriented RSC strategies by giving organisations better insight into return-related issues, product recovery opportunities, and customer expectations. The empirical analysis demonstrates a significant relationship between the mediating factor, customer feedback, and the dependent variable, the contemporary vision of RSCs activities.

This supports the conclusion that customer feedback meets all requirements to serve as a mediating variable in the proposed model. In particular, the analysis demonstrates that: (1) the independent variable, I4.0 technologies, has an important impact on the dependent variable, the contemporary vision of RSCs activities. As postulated in the first main hypothesis, (2) the independent variable has a significant effect on the mediating variable, customer feedback, which is substantiated in the second hypothesis, and (3) the mediating variable, customer feedback, has a significant effect on the dependent variable. Therefore, the findings collectively establish the statistical significance of customer feedback as a valid mediator.

In addition to statistical confirmation, the findings indicate the essential functional importance of customer feedback within the contemporary vision of RSCs activities. I4.0 technologies will increase firms' capacity to integrate customer feedback into product development, resource management, and ethical production by streamlining the systematic capture of customer requirements and preferences. This dynamic supports demand-driven sustainability and enables organisations to respond very quickly and effectively to customer needs, while encouraging waste reduction and responsible consumption. Accordingly, customer feedback emerges not only as a mediating variable in the model but also as an organisational strategy, that links technological capability to a customer-centric, contemporary vision of RSCs activities and sustainability-oriented outcomes.

Based on the results of the fourth hypothesis, as shown in Table (6-27) and the existence of a significant relationship between the mediating variable customer feedback and the dependent variable contemporary vision of RSCs activities, reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1). Moreover, the results of the hypothesis provided an answer to the third research question, “Are the (customer feedback and recycling) intermediate variables linked to the

contemporary vision of RSCs activities”? As intermediate variables?), as it showed the existence of an influential relationship between customer feedback and contemporary vision of RSCs activities.

Table 6- 27 Results of the effect of customer feedback on contemporary vision of RSCs activities.

independent variable	Direction of effect	Dependent variable	Estimate(β)	S.E.	C.R.	R ²	P-value
customer feedback	→	contemporary vision of RSCs activities	0.72	0.091	7.923	0.47	0.000

Table value ($t_{Tab} = 1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

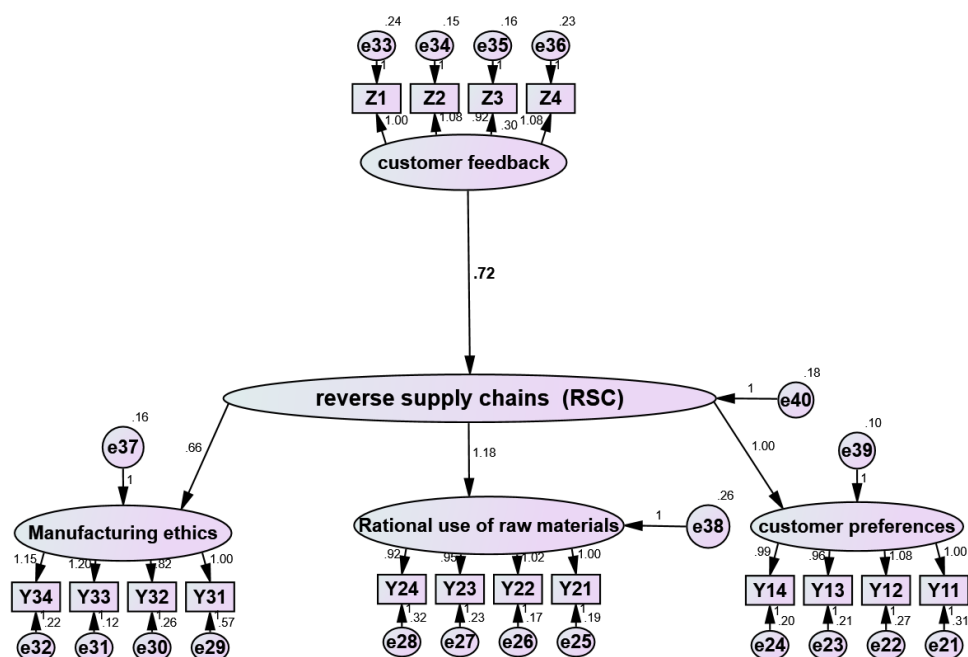


Figure 6 - 9 The effect of customer feedback in the contemporary vision of RSCs activities

Source: Researcher based on the statistical analysis results using AMOS V24 software. n=250

The results indicate customer feedback as a key explanatory factor shaping the contemporary vision of RSCs activities, underscoring its importance in guiding RSCs sustainable, adaptive, and strategically aligned practices.

The Fifth main hypothesis:

H₀: There is no significant influence relationship for recycling in the contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

H₁: There is a significant influence relationship for recycling in the contemporary vision of RSCs activities at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

The effect of recycling on the contemporary vision of RSCs activities, in Table 6-28. The findings indicate a statistically significant relationship between recycling and sustainability practices of RSCs ($\beta = 0.45$, p-value = 0.001, critical ratio (C.R.) = 4.449), indicating the reliability of the relationship. The R^2 of 0.16 indicates a low-to-moderate amount of explained variance, implying that recycling accounts for 16% of the variation in the contemporary vision of RSCs' activities. Although recycling is a significant factor, other aspects, such as the introduction of I4.0 or customer feedback, are probably more relevant in driving contemporary RSCs practice.

The outcome is inherently justified: recycling programs provide practical experiences in resource recovery, waste avoidance, and recycling, which illuminate sustainable and responsive approaches of organisations towards RSCs. Therefore, its influence is not strong, but recycling contributes to the development of a contemporary vision of RSCs' activities.

Hypothesis 5 was confirmed, indicating a significant relationship between the mediating variable, recycling, and the dependent variable, the contemporary vision of RSCs activities. This finding supports one of the key requirements for treating recycling as an intermediate variable in the study. Together, the statistical data demonstrate that recycling meets all criteria for mediation. In particular, (1) Industry 4.0 technologies are the independent variable that makes a strong impact on the dependent variable, the contemporary vision of RSCs activities. As postulated in the first main hypothesis, (2) I4.0 also has a significant effect on the mediating variable, recycling, as postulated in the third main hypothesis, and (3) recycling, in its turn, has a significant effect on the dependent variable, which supports its mediating role.

In addition to meeting the statistical requirements, such results highlight the organisational strategic significance of recycling in the contemporary vision of RSCs activities. Recycling can be seen as an essential process by which I4.0 technologies can transform digital capacity into material sustainability effects. Recycling enhances customer-oriented sustainability, thereby increasing resource recovery efficiency, minimising waste, and upholding manufacturing ethics. In more general terms, recycling is not merely a mediating variable in the model; it is also a key driver of the link between technological innovation and environmental performance. This highlights its role as an essential pillar in achieving

resource efficiency, regulatory compliance, and long-term supply chain sustainability within the framework of I4.0 technologies that support the contemporary vision of RSCs activities.

Based on the results of the fifth hypothesis, as shown in Table (6-28), and the existence of a significant relationship between the mediating variable, recycling, and the dependent variable, contemporary vision of RSCs activities, we reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1). Moreover, the results of the hypothesis provided an answer to the third research question, “Are the (customer feedback and recycling) intermediate variables linked to the contemporary vision of RSCs activities as intermediate variables”? It demonstrated an influential relationship between recycling and the contemporary vision of RSCs activities.

Table 6- 28 Results of the effect of Recycling on the contemporary vision of RSCs activities.

independent variable	Direction of effect	Dependent variable	Estimate(β)	S.E.	C.R.	R ²	P-value
Recycling	→	contemporary vision of RSCs activities	0.45	0.102	4.449	0.16	0.000

Table value ($t_{Tab} = 1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

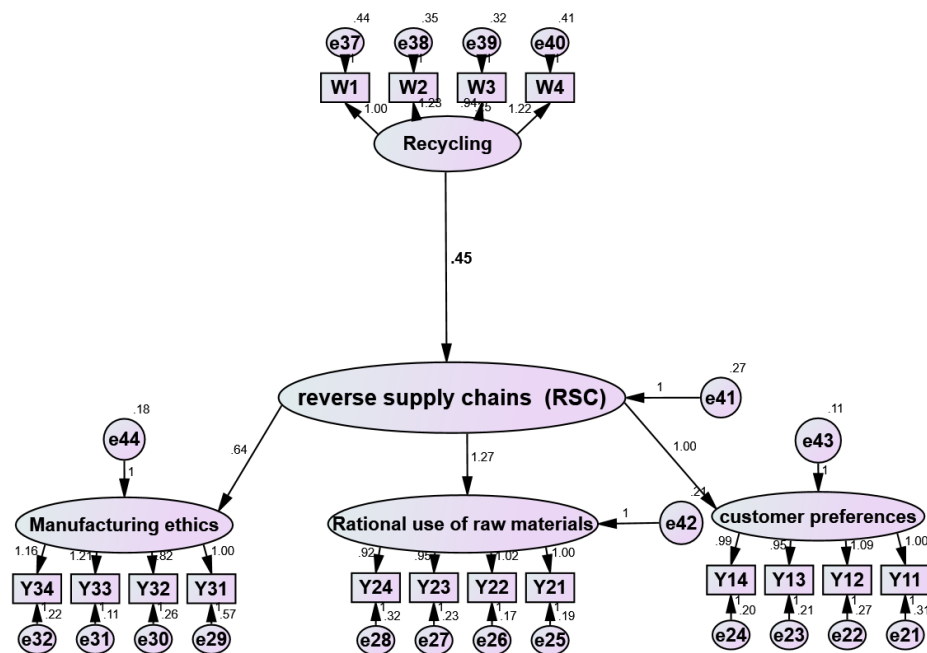


Figure 6- 10 The effect of Recycling in the contemporary vision of RSCs activities

Source: Researcher based on the statistical analysis results using AMOS V24 software. n=250

The results indicate that recycling positively contributes to shaping the contemporary vision of RSCs activities, highlighting its role as a practical driver of sustainability and adaptive strategies, even though its overall effect is moderate compared to other factors.

The sixth main hypothesis:

H₀: There is no significant effect relationship for Industry 4.0 in the contemporary vision of RSCs activities mediated by customer feedback as an intervening variable at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a sample of research.

H₁: There is a significant effect relationship for Industry 4.0 in the contemporary vision of RSCs activities mediated by customer feedback as an intervening variable at a statistical significance level ($\alpha \geq 0.05$) from the point of view of a sample of research.

In the sixth hypothesis, the mediating variable (customer feedback) was introduced to examine the influence of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities). Here, we will have three expected cases (Gunzler et al., 2013).

1. The mediating variable is customer feedback (a complete mediating variable). This case occurs when the effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) is insignificant. In contrast, the effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the mediating variable (customer feedback) is significant.
2. The mediating variable is customer feedback (a partial mediating variable) when:
 - The independent variable (Industry 4.0) effect on the dependent variable (contemporary vision of RSCs activities) is significant.
 - The effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the mediating variable (customer feedback) is significant.
3. The mediating variable, customer feedback, is (non-mediating) when:

The effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) is significant. In contrast, the effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the mediating variable (customer feedback) is not significant.

Table 6-29 shows the direct and indirect effects of I4.0 on the contemporary vision of RSCs activities, with customer opinions as a mediating variable.

Direct Effect:

The results show a statistically significant positive direct effect of I4.0 on the contemporary vision of RSCs activities, with a path coefficient of $\beta = 0.96$ and a p-value of 0.012. The confidence interval of 0.469 to 1.997 is nonzero, indicating a statistically significant and direct relationship. This finding indicates that I4.0 has a considerable influence on the design of strategies for the contemporary vision of RSCs activities.

Indirect Effect:

The indirect influence of I4.0 on the contemporary vision of RSC activities was also noted, with customer opinion as the mediating variable. The effect was statistically significant ($\beta = 0.159$, $p = 0.011$) and positively oriented. The indirect path confidence interval (0.049-0.414) does not include zero, indicating a significant mediating effect. This finding indicates that the mediating variable strengthens the relationship between I4.0 and the contemporary vision of RSCs activities, thereby reinforcing sustainable manufacturing practices.

Overall, the high direct and indirect effects mean a partial mediation model. Industry 4.0 has a direct impact on the present-day vision of RSCs' operations due to technological change and an indirect effect through the improvement of customer feedback procedures, which further results in the creation of adaptive, sustainable, and strategically aligned RSCs practices.

Theoretically, the result underscores the importance of demand mechanisms in closing the technological sustainability gap. Insofar as Industry 4.0 technologies offer advanced digital capabilities, they require customer feedback to translate these capabilities into concrete changes in sustainability-based practices. Customer feedback will help organisations align the innovation offered by I4.0 with customer needs, as well as ensure that resource efficiency, ethical production, and waste reduction are not overlooked, which are the main points of the contemporary vision of RSCs' activities. The partial mediation variable is important from a management perspective, as it underscores the strategic need to incorporate feedback systems into the I4.0 system. Rather than being used in a separate form, digital technologies are most effective for the contemporary vision of RSCs' activities when customer feedback systems influence the decision-making process and enhance the responsiveness and adaptability of processes to market conditions. Thus, customer feedback emerges not merely as a statistical mediator but as an operational and strategic driver that integrates I4.0 technologies with a sustainability perspective into the contemporary vision of RSCs activities, ultimately enhancing their performance and effectiveness.

Based on the results of the sixth hypothesis, as shown in Table (6-29) and the existence of a significant relationship between the independent variable Industry 4.0 and the dependent variable contemporary vision of RSCs activities, with the presence of the mediating variable customer feedback, reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1). Moreover, the results of the hypothesis provided an answer to the fourth research question: “How can customer feedback and recycling as intermediate variables integrate the relationship between I4.0 technology and the contemporary vision of RSCs activities”? It showed an influential relationship between Industry 4.0 and the contemporary vision of RSCs activities, with the presence of the mediating variable customer feedback.

Table 6- 29 Results of the effect of I4.0 on contemporary vision of RSCs activities with the presence of the mediating variable, customer feedback.

Independent variable	Mediating variable	Dependent variable	Estimate(β)	L	U	P-value
Industry 4.0	----	Contemporary vision of RSCs activities	0.96	0.469	1.997	0.012
	customer feedback		0.159	0.049	0.414	0.011

Table value ($t_{Tab} = 1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

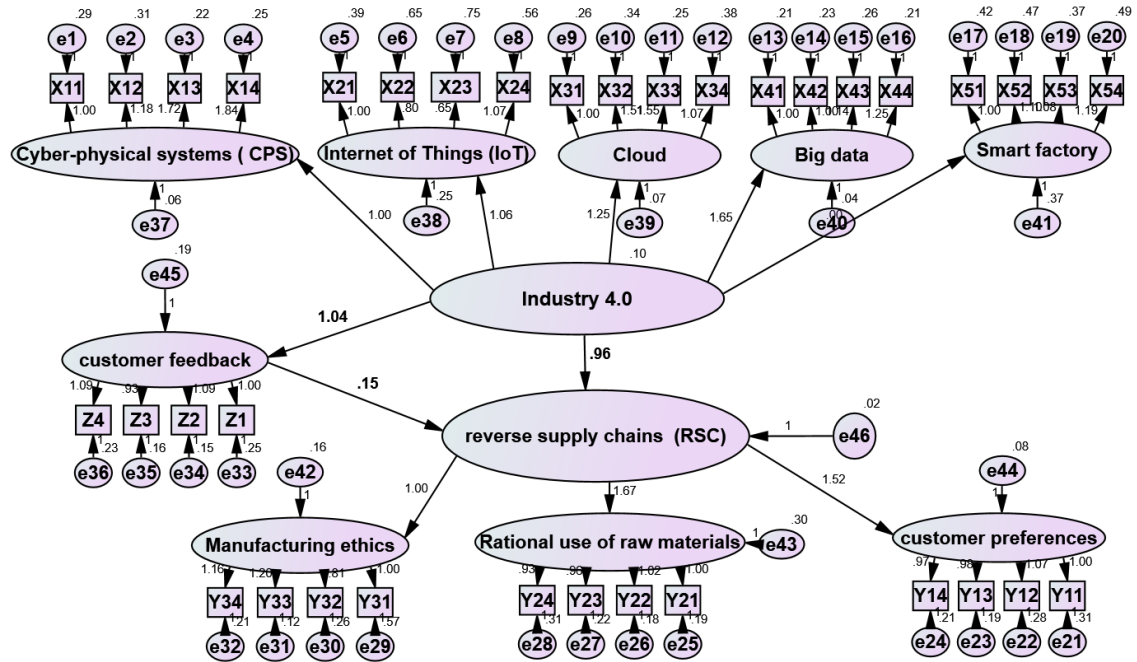


Figure 6-11. The effect of Industry 4.0 contemporary vision of RSCs activities with the presence of an intermediate variable customer feedback.

Source: Researcher based on the statistical analysis results using AMOS V24 software. n=250

The seventh main hypothesis:

H₀: There is no significant influence relationship for Industry 4.0 on contemporary vision of RSCs activities mediated by Recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

H₁: There is a significant influence relationship for Industry 4.0 on contemporary vision of RSCs activities mediated by Recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

In the seven hypotheses, we entered the mediating variable (recycling) into the effect relationship between the independent variable (Industry 4.0) and the dependent variable (contemporary vision of RSCs activities). Here, we will have three expected cases:

1. The mediating variable is recycling (a complete mediating variable). This case arises when the effect of the independent variable (Industry 4.0) on the dependent variable (a contemporary vision of RSCs' activities) is not statistically significant. In contrast, the effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the mediating variable (recycling) is significant.

2. The mediating variable is recycling (a partial mediating variable) when:
 - The independent variable (Industry 4.0) effect on the dependent variable (contemporary vision of RSCs activities) is significant.
 - The effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the mediating variable (recycling) is significant.
3. The mediating variable, recycling, is (non-mediating) when:

The effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) is significant. In contrast, the effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the mediating variable (recycling) is not significant.

Table 6-30 shows the direct and indirect effects of I4.0 on the contemporary vision of RSCs activities, with rotation as the mediating variable.

Direct Effect:

The results show a direct and statistically significant effect of I4.0 on the contemporary vision of RSCs activities. The estimated path coefficient is $\beta = 1.04$, with a p-value of 0.014, confirming statistical significance at the 5% level. The 95% confidence interval is 0.511-1.967, excluding zero, indicating the strength and stability of the direct relationship. The findings imply that I4.0 methods have a direct and significant effect on the formulation of sustainable RSCs strategies.

Indirect Effect:

The findings also show that I4.0 has a positive and statistically significant effect on the contemporary vision of RSCs activities mediated by rotation. This indirect effect has been estimated $\beta = 0.054$, $p = 0.026$. The confidence interval of (0.009 - 0.144) does not cover the value of 0.000, and this shows that the mediating effect is statistically significant. This finding suggests that the mediating variable (recycling) contributes to the relationship between the two, thereby helping formulate sustainable, closed-loop supply chain approaches.

The two statistically significant direct and indirect effects indicate a partial mediating effect. Direct Integrated digital technologies are directly influencing contemporary visions of RSCs activities and digitalisation, and indirectly by enhancing recycling practices to aid sustainability and circular economy objectives. Nevertheless, the mediating effect is less significant than the direct effect. It is still statistically significant, and it shows that recycling is a significant complementary process by which I4.0 influences the formation of sustainable RSCs.

Theoretically, the mediating position of recycling emphasises the key role of circular economy principles in I4.0 within a contemporary vision of RSCs' activities. Even though I4.0 technologies enable the implementation of more advanced features, including automation, connectivity, and data-driven decision-making, their practical effect on the contemporary vision of RSCs' activities lies in their ability to optimise recycling processes. Recycling, therefore, offers a channel through which digital transformation translates into material recovery, waste minimisation, and the responsible use of resources, the main aspects of the contemporary vision of RSCs' activities.

The outcomes support the managerial importance of implementing recycling as a mediating variable in I4.0-enabled supply chain models. Recycling also enhances operational effectiveness and harmonises technological innovation, ethical production, and sustainability laws. This underscores the appropriateness of the researcher's selection of recycling as a mediating variable, as it plays a pivotal role in integrating I4.0 technologies with the contemporary vision of RSCs activities to improve their overall performance and the operation of sustainability-driven goals, ultimately enhancing.

Based on the results of the sixth hypothesis, as shown in Table (6-30), and on the significant relationship between the independent variable, Industry 4.0, and the dependent variable, the contemporary vision of RSCs activities, with recycling as a mediator, reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1). Moreover, the results of the hypothesis provided an answer to the fourth research question: "How can customer feedback and recycling as intermediate variables integrate the relationship between I4.0 technology and the contemporary vision of RSCs activities"? They revealed a significant relationship between Industry 4.0 and the contemporary vision of RSCs activities, with recycling as a mediator.

Table 6- 30 Results of the impact of Industry 4.0 on the contemporary vision of RSCs activities with the mediating variable Recycling.

Independent variable	Mediating variable	Dependent variable	Estimate(β)	L	U	P-value
Industry 4.0	----	contemporary vision of RSCs activities	1.04	0.511	1.967	0.014
	Recycling		0.054	0.009	0.144	0.026

Table value ($t_{tab}=1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

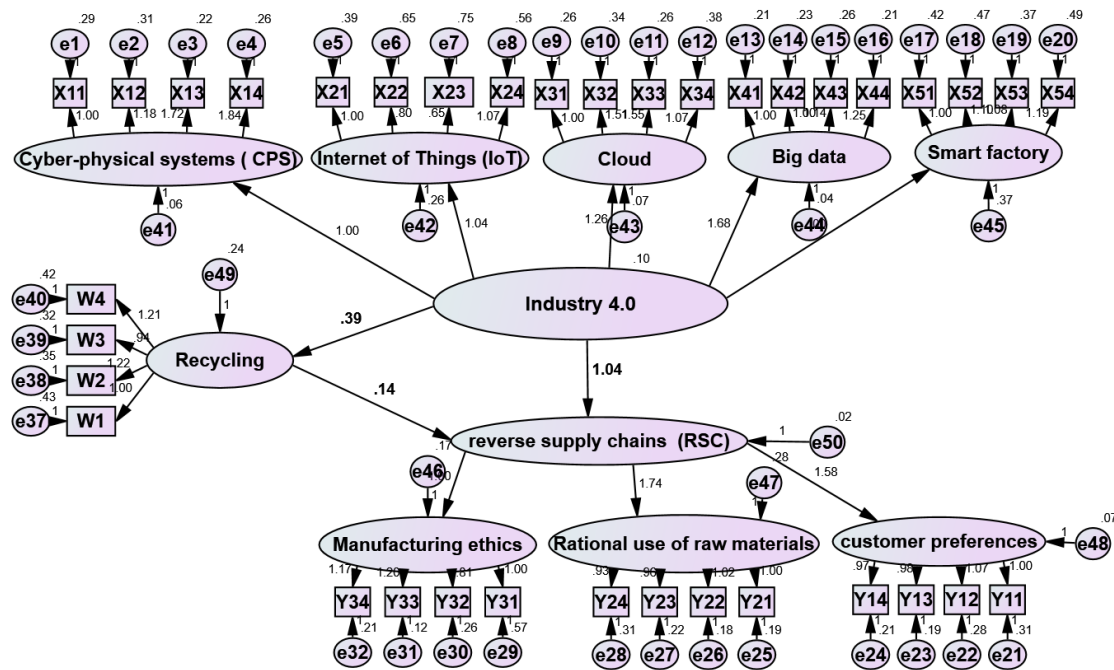


Figure 6 - 12 The effect of Industry 4.0 on contemporary vision of RSCs activities with an intermediate variable Recycling.

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

The eighth main hypothesis:

H₀: There is no significant influence relationship for Industry 4.0 on the contemporary vision of RSCs activities mediated by both customer feedback and recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

H₁: There is a significant influence relationship for Industry 4.0 on the contemporary vision of RSCs activities mediated by both customer feedback and recycling at a statistical significance level ($\alpha \geq 0.05$) from the point of view of the research sample.

The effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) was examined in the eighth hypothesis by incorporating two mediating variables (customer feedback and recycling). Three anticipated cases will be presented here: (Gunzler, et al., 2013).

1. The mediating variable is a complete mediating variable. This case arises when the effect of the independent variable (Industry 4.0) on the dependent variable (a contemporary vision of RSCs' activities) is insignificant. In contrast, the effect of the independent variable (Industry

4.0) on the dependent variable (contemporary vision of RSCs' activities) via the mediating variables (customer feedback and recycling) is significant.

2. The mediating variable is (a partial mediating variable) when:

- The independent variable (Industry 4.0) effect on the dependent variable (contemporary vision of RSCs activities) is significant.
- The effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the dependent variable (customer feedback and recycling) is significant.

3. The mediating variable is (non-mediating) when:

The effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) is significant. In contrast, the effect of the independent variable (Industry 4.0) on the dependent variable (contemporary vision of RSCs activities) through the mediating variable (customer and recycling) is not significant.

Table 6-30 presents the direct and indirect effects of I4.0 on the contemporary perception of RSCs activities, with customer feedback and recycling as mediating variables.

Direct Effect:

The results indicate a direct and statistically significant effect of I4.0 on the contemporary vision of RSCs activities. The estimated path coefficient $\beta = 0.95$, with a p-value of 0.018, indicating statistical significance at the 5% level. The direct relationship is strong as the 95 % interval is 0.474 to 1.786, which does not include zero. The outcome of this analysis is that I4.0 significantly influences the development of sustainable RSC strategies and does so independently.

Indirect Effect:

The indirect effect of I4.0 on the present vision of the RSCs operations, customer feedback, and recycling is positive and statistically significant. Its indirect effect is 0.18 with a p-value of 0.009. The 95 percent confidence interval (0.060 to 0.546) does not include zero, indicating that the mediating effect is statistically significant. It means that the relationship between I4.0 technology and the contemporary vision of RSCs activities is improved with the help of mediating variables. This common architecture helps in coming up with a modern, sustainable and flexible vision of RSCs activities.

All confidence intervals reported were derived from the empirical bootstrap distribution with 5,000 resamples using bias-corrected estimation in AMOS. This method enhances inference reliability by avoiding the normality assumptions underlying Sobel or delta-method tests, which are less robust for indirect effects in structural equation models.

The significant value of the direct and indirect effects indicates a partial mediation model. I4.0 has a direct effect on the contemporary vision of RSCs' activities, transforming technologies and integrating them digitally, and an indirect impact by advocating customer feedback and recycling, which aligns with customer responsiveness, sustainability, and a circular economy agenda. The indirect effect, albeit smaller than the direct effect, is statistically significant, indicating the complementary nature of customer-led mechanisms and recycling in converting I4.0 capabilities into policies that facilitate sustainability among RSCs.

Theoretically, the findings demonstrate that the mediators are two complementary aspects of I4.0 and the contemporary vision of RSCs activities. The demand-based aspect of feedback comes from customer feedback, whereby technological innovation is driven by shifting customer expectations, responsiveness, and ethical production. Recycling, in turn, represents the circular economy, with I4.0 capabilities applied to optimise resource consumption, minimise waste, and generate more environmentally friendly products. Taken together, these mediators depict how I4.0 technologies produce value by enhancing customer-centric sustainability and increasing material efficiency.

Regarding management, the relevance of both mediators makes it obvious that incorporating feedback systems and recycling habits into I4.0 and the contemporary vision of RSCs' activities is necessary. The customer response ensures agility and market responsiveness, whereas recycling conserves resources and promotes environmental stewardship. Their combined effect not only enhances the performance of the contemporary vision of RSCs activities but also advances broader goals of sustainable manufacturing, environmental conservation, and consumer welfare.

Based on the results of the eight hypotheses as shown in Table (6-31) and the existence of a significant relationship between the independent variable Industry 4.0 and the dependent variable contemporary vision of RSCs activities, with the presence of the mediating variables (customer feedback and recycling), reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1). Moreover, the results of the hypothesis provided an answer to the fourth research question: "How can customer feedback and recycling as intermediate variables integrate the relationship between I4.0 technology and the contemporary vision of RSCs activities"? As demonstrated, there was an influential relationship between Industry 4.0 and a contemporary vision of RSCs activities, with mediating variables including customer feedback and recycling.

Table 6- 31 Results of the effect of Industry 4.0 on contemporary vision of RSCs activities with the presence of the two mediating variables, customer feedback and recycling.

Independent variable	Mediating variable	Dependent variable	Estimate(β)	L	U	P-value
Industry 4.0	----	Contemporary vision of RSCs activities	0.95	0.474	1.786	0.018
	customer feedback and Recycling		0.18	0.060	0.546	0.009

Table value ($t_{Tab}=1.96$)

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

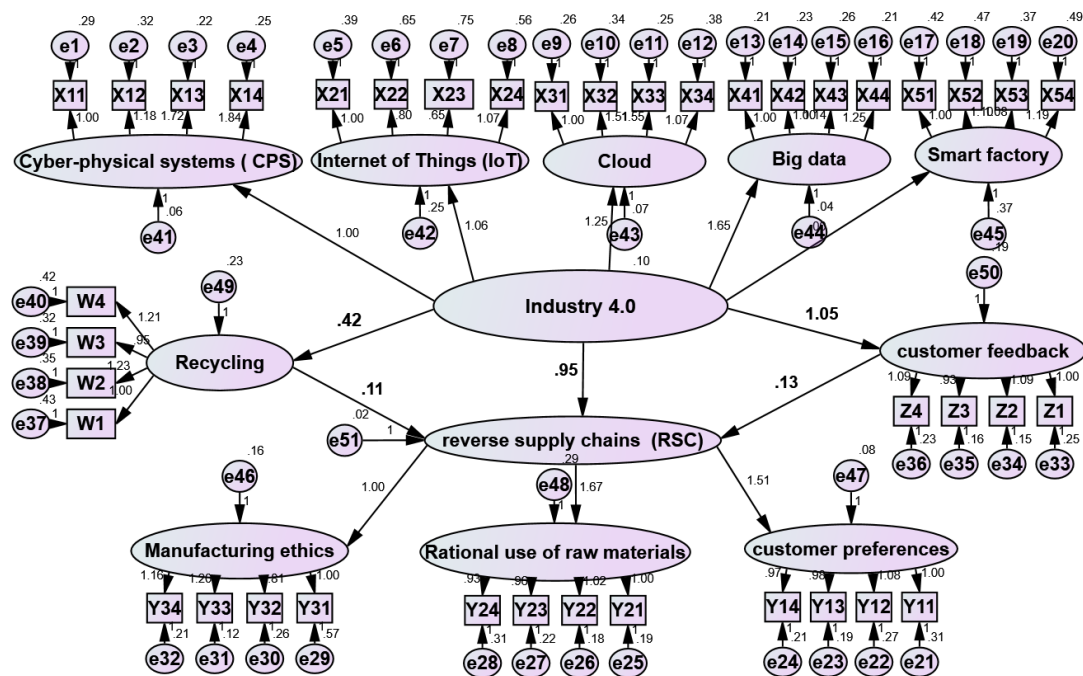


Figure 6 - 13 The impact of Industry 4.0 on the contemporary vision of RSCs activities with intermediate variables, customer feedback, and recycling.

Source: Prepared by the researcher based on the results of statistical analysis using AMOS V24 software. n=250

Chapter 7: Qualitative research methodology and thematic analysis

7.1 Introduction:

This chapter presents and analyses qualitative research findings from semi-structured interviews conducted as part of a mixed-methods approach. While the quantitative methodology provided statistical evidence of the direct and indirect relationships between I4.0 and contemporary RSCs activities and demonstrated the role of mediating variables, the qualitative approach aimed to deepen understanding of how these relationships operate and their underlying causes within the industry. Additionally, the relationship between them needs to be clarified in the presence of intermediate variables (customer feedback and recycling) to support the contemporary vision of RSCs activities through I4.0 technology. Therefore, the focus is on providing a contemporary vision of RSCs activities that include (customer preferences, rational use of raw materials, and manufacturing ethics) to effectively improve manufacturing sustainability, protect the environment, and benefit consumers.

Semi-structured interviews were used to supplement and confirm the survey results by documenting practitioners' and experts' practical knowledge and strategic insights, and to provide contextual interpretations that could not be fully captured in the surveys. Therefore, semi-structured interviews provide interpretive and confirmatory insights, contributing to a deeper understanding of the quantitative findings and to an assessment of their relevance to the industry context.

7.2 Purpose and Role of Qualitative Methodology:

The interviews aimed to enhance the research results and deepen the understanding of the mechanisms for integrating I4.0 technology and the contemporary vision of RSCs activities, mainly through:

- Find out how I4.0 technology is relevant to the modern perspective of RSCs operations.
- Illustrate the mediating variables (customer feedback and recycling) as organisational strategies to promote their integration.
- Furnish empirical evidence of how this integration can enable manufacturing to be sustainable, circular economy, and in accordance with ethical manufacturing practices.

Qualitative results within the mixed-methods research model will strengthen it by correlating statistical findings with interviewees' views, thereby increasing interpretive depth and analytical rigor.

7.3 Participant Selection and Qualifications:

Purposive sampling was used to ensure that participants in the semi-structured interviews had professional experience in the research area. Ten participants were chosen from three original equipment manufacturers (OEMs) involved in technology-based energy, renewable energy, and medical device manufacturing. The participants held senior management, supervisory, and technical

roles across various levels of forward and reverse logistics, including production, quality, research and development, logistics support, after-sales service, and maintenance. This diversity provided a broad range of perspectives on integrating Industry 4.0 and sustainable practices into RSCs activities, making it relevant to our research area.

The interviews took place between February and July 2024, during the quantitative survey period, and were conducted either face-to-face or online via Zoom. Ethical guidelines were followed in all interviews conducted as part of the scientific research. Appendix 5. Table of Interview Respondent Profiles.

7.4 Development of the Semi-Structured Interview Statement:

The interview statement was logically structured to align with the research questions, objectives, and the conceptual framework. Open-ended questions were designed in line with the widely accepted methodological approach to encourage detailed, thoughtful responses while also allowing room for further research and follow-up.

The interview questions were then developed in accordance with the research's key topics. The dimensions of the research variables and the intermediate variables, as well as each sub-dimension of the research variables, were reflected in a question drawn from the set of questions in that dimension used in the quantitative survey. This alignment enabled direct comparison and triangulation between the qualitative insights and quantitative results, thereby supporting integration with the quantitative data and enhancing methodological consistency.

The interview questions were based on four major areas:

1. Combining I4.0 technologies and sustainable RSCs operations.
2. The position of the particular I4.0 technologies (CPS, IoT, big data, cloud computing, and smart factories) within sustainable RSCs practices.
3. The importance of digital technologies in sustainable practices (customer preferences, reasonable usage of raw materials, manufacturing ethics).
4. The moderating position of customer views and recycling between I4.0 technology and the current vision of RSCs activities. Appendix 6. Table of Scope and Interview questions.

7.5 Thematic analysis coding of axes research:

The thematic coding approach was applied to the qualitative analysis, as it is the most popular method for identifying, organising, and interpreting patterns of meaning in interview data (Braun & Clarke,

2016). The method enabled the development of a robust analytical framework that connected participants' views to the research focus on I4.0 and sustainable practices in RSCs.

Rigor and transparency were maintained throughout the coding process, which followed a systematic, multi-step approach. First, the interview transcripts were analysed to develop a comprehensive understanding of the data. Codes were then derived from participants' responses and the theoretical literature. These initial codes contained important ideas and their scope, which were subsequently grouped into conceptual categories (second-order themes) based on semantic similarity and theoretical relevance. The categories were then grouped into broader thematic dimensions to define the research axes for the analysis.

The study's approach enabled it to move beyond descriptive statements toward higher-level implications that reflect the interactive dynamics between emerging manufacturing technologies and sustainability. Appendix 7. Axes of Thematic Coding of Research.

7.6 The consecutive stages of the coding procedure:

The qualitative data from semi-structured interviews were coded using a rigorous, systematic, and iterative procedure to improve precision, transparency, and theoretical integrity. The analysis would proceed through a series of steps aligned with best practices in qualitative research, converting raw empirical data into conceptually meaningful and relevant results.

Coding commenced with excellent preparation and interpretation of the interview data, including transcription, repeated reading, and reflective note taking. This preliminary move contributed to a close alignment between this research perspective and the participants' views, as well as to an inductive approach to the data. The analysis later moved progressively up the levels of abstraction, no longer analysing the language used by the participants at a basic (first-order) level, but rather interpreting it at a higher (second-order) level to discern crosscutting themes.

This comparative and iterative process enabled the identification of patterns, relationships, and underlying structures in the data while maintaining the empirical breadth of the original interview material. These steps promoted the use of a systematic coding procedure that increased product transparency by providing a clear traceability route from raw data to the experimental outcomes, with their theoretical explanations. Figure 7.1 provides a summary of the coding process and the stages involved.

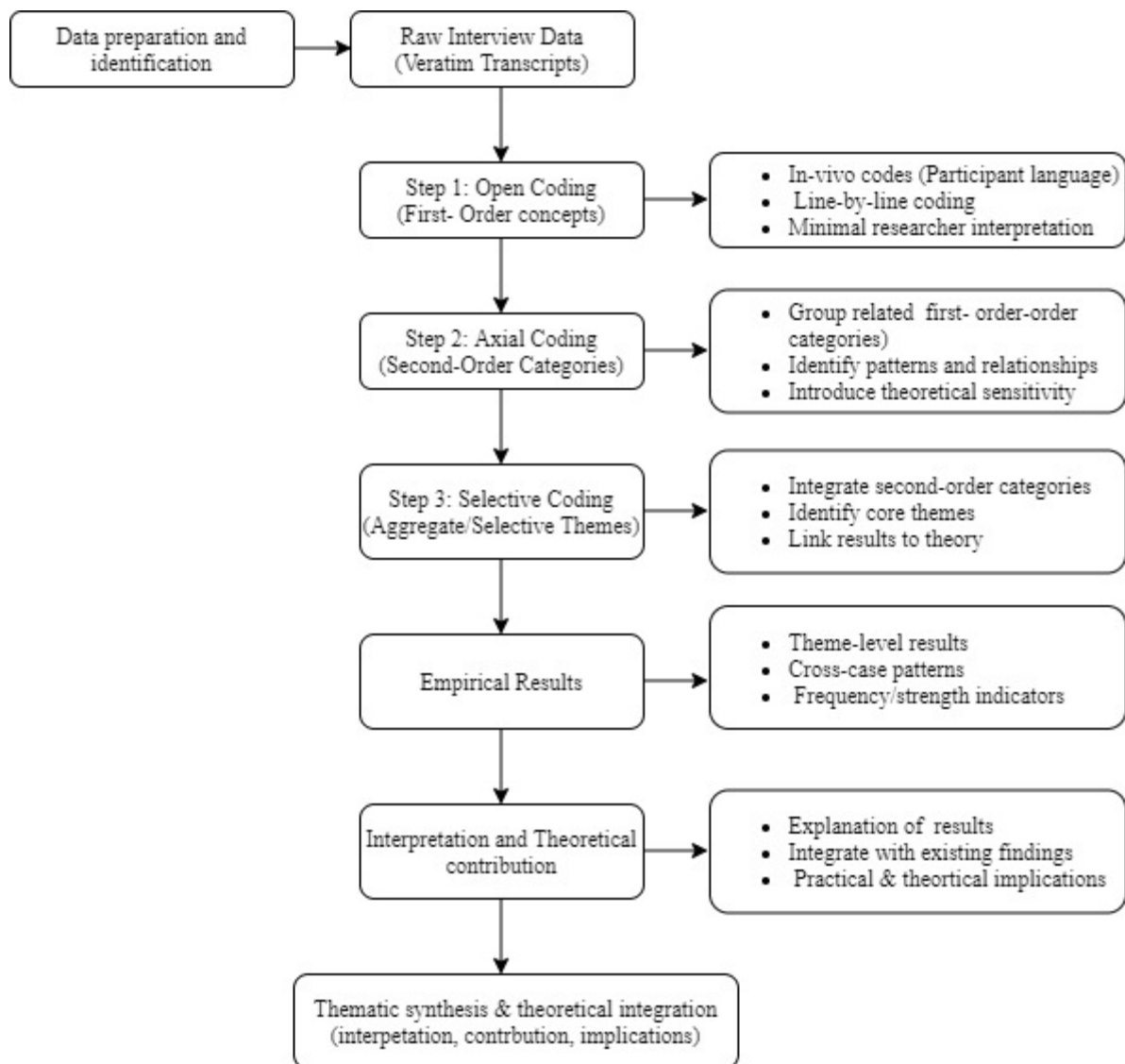


Figure 7- 1 Steps of the coding process

Figure 7-1 Demonstrates the steps of qualitative coding of data and data structure, the process of moving transcripts of interviews to main concepts, subcategories, general themes, and experimental findings to thematic synthesis and theoretical assimilation.

7.7 Representing the Relationship Between Participants' Responses and the Themes Identified in the Thematic Analysis:

To ensure that the themes selected during coding were grounded in participants' responses, this study employed a systematic, transparent thematic analysis, thereby maintaining a close connection between the primary data and the final themes.

1. Data preparation and identification:

The interview statement was formulated to represent the research perspective. The primary themes to be explored were divided into questions to elicit participants' opinions. This classification ensured scientific consistency and enabled the visualisation of subsequent coding processes. Moreover, it enabled addressing the research questions and, in the future, discussing the quantitative study's findings to inform the qualitative results.

2. Raw interview data (verbatim transcripts):

Once participants' responses were collected, the interview transcripts were read and reread to ensure a thorough understanding of their answers. This stage focused on repetitive utterances regarding I4.0 technologies, relationship integration, RSCs sustainable practices, and the moderating variables of customer feedback and recycling. The step above facilitated the categorisation of the research axes, thereby focusing the research on the main areas. This guaranteed rich feedback and ensured that subsequent coding was based on the interview transcripts rather than theory.

3. Generating First-order Codes from Primary Data (open coding):

The initial coding was conducted inductively, with first-order codes assigned to salient aspects of participants' responses. Wherever possible, the coding was done using the participants' own terms of the participants (e.g., "enhancing sustainability," "Waste reduction," "enhancing transparency," "Support for circular economy"), which means that the coding was based on empirical data in the real world and was not a mere abstract interpretation.

Participants' responses can be linked to each code, thereby establishing a verifiable positive correlation between interview transcripts and the analytical constructs. To explain this process in practice, the following are samples of the coding table and samples of the interview transcripts illustrating the coding process as follows:

Selective Theme	Second-Order Categories	First-Order Codes	Illustrative Interview Evidence
Integration of I4.0 Technologies into Sustainable Practices of RSCs activities	Strategic Purpose of Integration	Sustainability enhancement, Support for circular economy, Resource efficiency	"Integrating I4.0 technologies enhances manufacturing sustainability and contributes to a more circular economy".

"The participant also highlighted the role of emerging technologies for Industry 4.0 in supporting recycling and recovery processes that enhance the rationalisation of material use, reduce waste, improve the environment, and support manufacturing sustainability".

"Modern manufacturing technologies have effectively contributed to the development of the sector, and the integration of I4.0 technology and the contemporary vision of RSCs activities can contribute to enhancing manufacturing sustainability, which in turn significantly supports circular economy practices. In addition, the participant highlighted the role of various I4.0 technologies in supporting the contemporary vision of RSCs activities. The participant highlighted the enabling capabilities of modern technologies, such as CPS, to connect physical components into a network and enable remote control. Additionally, the IoT facilitates easy communication between humans and machines, as well as between machines. Additionally, big data and the cloud have played a crucial role in improving and streamlining processes, facilitating transparent monitoring of operations and production lines, and increasing manufacturing flexibility. All of these enabling factors have facilitated the integration process with the contemporary vision of RSCs activities, in line with enhancing manufacturing sustainability and the principles of the circular economy".

Similarly, regarding the answer to the question (Recycling processes supported by Industry 4.0 technology can be invested in achieving a contemporary vision of RSCs activities), the coding process was carried out as described below, based on the participants' responses.

Selective Theme	Second-Order Categories	First-Order Codes	Illustrative Interview Evidence
Mediating Mechanisms Linking I4.0 and RSCs	Recycling as a Mediating Variable	Support for closed-loop systems- Material recovery, Ethical operations	"I4.0-based recycling processes contribute to efficiency and provide more ethical processing".

"Adopting the I4.0 approach, based on modern technological applications, undoubtedly significantly improves the industry and enhances operations. It directly supports recycling processes and improves their performance, as evidenced by its high manufacturing flexibility, adherence to quality requirements, and ease of use. It provides successful solutions to meet customer preferences. In addition, modern technologies effectively reduce time and energy consumption, improving the process and promoting the rational use of raw materials. Utilising recycling processes to obtain raw materials protects the environment and supports sustainable manufacturing, thereby enhancing manufacturing ethics".

4. Definition Second-Order Categories through Pattern Recognition (Axial coding):

A comparison of first-order symbols across the texts was conducted to identify similarities and overlaps in concepts. Symbols with meaningful meanings were then categorised as second-order, such as strategic integration goals, operational improvements, and key text dimensions. This procedure was

carried out through an analytical abstraction that retained an empirical foundation, ensuring that the analysis remained aligned with the interview data.

5. Constructing Themes through Iterative Abstraction (Selective Code):

The selective themes are derived from the combination of the second-order categories that explain the impact of I4.0 technologies on RSCs sustainable practices. The themes were established with the aid of participants and other pertinent interview evidence.

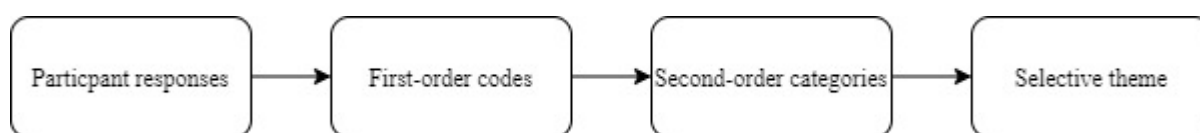
This iterative process ensured that the themes reflected a common empirical regularity rather than individual opinions.

6. Ensuring the Validity of Topics and Analytical Consistency:

Supporting the validity of topics through:

- Continuous comparison of topics and original texts.
- Using illustrative quotations to support the empirical foundation.
- Recording analytical observations to explain the reasons for decisions made during topic development.

The figure below illustrates the paths of the coding process:



The diagram above illustrates the analytical coding process, enabling clear and reliable tracking of each step.

Thus, each code is clearly grounded in participant responses, thereby ensuring methodological validity and rigor throughout the thematic analysis process and subsequent steps.

To practically illustrate the previous steps in the thematic analysis process according to the interview transcripts, the researcher reversed those steps according to the following diagram:

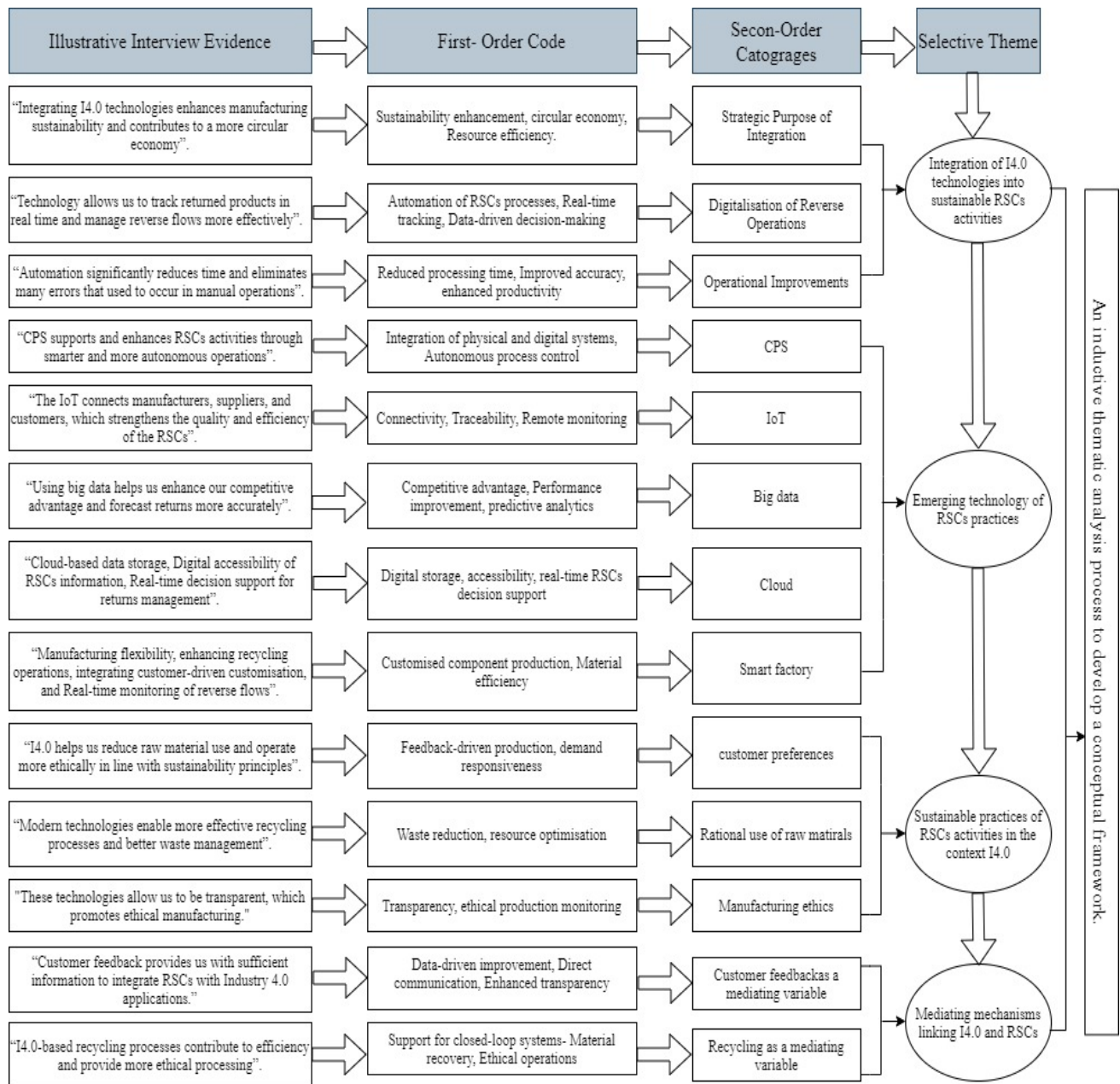


Figure 7- 2 Thematic analysis used in the qualitative methodology.

7.8 Data Analysis Methodology: Thematic Analysis:

Thematic analysis was used to analyse qualitative data, and the coding process was conducted systematically and transparently. The method enabled the detection, categorisation, and understanding of patterns common across the interview transcripts. The analysis included several steps, as follows:

1. Acclimatisation to the data by repetitions of the transcripts.
2. Early coding by both inductive (data-based) and deductive (theory-based) methods.
3. Putting first-order codes into second-order categories by conceptual affinity.

4. Formulation of general themes (research axes) that were in line with the research conceptual framework.

This process helped move the description toward higher-level analytical interpretations and relate practitioners' experiences to theoretical aspects of I4.0, sustainable manufacturing practices, and the circular economy.

7.9 Key Themes and Findings:

7.9.1 Intellectual combination of I4.0 processes and contemporary vision of RSCs activities:

The analysis of participants' perspectives indicates that companies do not adopt Industry 4.0 technologies primarily to boost operational efficiency. Instead, they plan to integrate digital technologies to support their manufacturing sustainability goals, particularly those related to the circular economy and resource efficiency in sustainable RSCs.

Study respondents also linked improved sustainability outcomes, such as reduced waste, increased resource efficiency, higher recycling rates, and better decision-making in sustainable manufacturing, to the integration of automation, real-time data, and analytics.

To provide a more analytical explanation, this I4.0 technology adoption suggests it is primarily a facilitator rather than merely a means of incremental process improvements. The benefits of integrating I4.0 digital technology into RSCs operations include being better positioned to operate systematically and achieve sustainable manufacturing goals, such as energy savings, resource optimisation, and process improvements, thereby extending the product lifecycle and improving environmental practices.

Nonetheless, participants did not deny the current difficulties, particularly in monitoring expired goods, recovering expired materials, and fully integrating digital technologies into recyclable supply chains. These results indicate a discrepancy between potential and actual use of technology. The participants' answers were short fragments, as shown below.

The participant, who works at a manufacturing company that relies on modern technology in its industry and holds the position of Standardisation and Quality Control Officer, added: "Industry 4.0 technology is extremely important for improving processes, as it provides great flexibility in production, which has significantly increased the company's ability to meet the needs of different customers. Given the capabilities of modern technology, the integration of hardware components, and the smart factory's ability to reduce costs and time, the company seeks to make optimal investments in Industry 4.0 technologies. Moreover, in order to comply with international legal standards, the company has developed its remote service centers (RSCs)."

An interview was conducted with the Production and Operations Department Director at a factory specializing in energy and renewable energy equipment, affiliated with a leading global company. The factory uses Industry 4.0 technology in its production and has an effective reverse supply chain. In addition, the interview participant (from the non-random sample) has experience and knowledge of Industry 4.0 technologies. The interviewer presented the question (Integrating Industry 4.0 technologies with reverse supply chains enhances manufacturing sustainability and contributes to a more circular economy) to the interviewee. The participant indicated, “The Company has adopted Industry 4.0 technology in its operations over the past ten years and gradually, according to strategic plans and feasibility studies prepared by its relevant departments. The factory currently relies primarily on modern technology in its operations. The participant also explained that Industry 4.0 technology plays a significant role in improving operations and provides excellent flexibility in production, thereby enhancing the company's ability to keep pace with diverse customer requirements. It also considers the potential of modern technology and networking between physical parts, and the capabilities of the smart factory in saving costs and time, and for optimal investment in Industry 4.0 technology. Furthermore, to keep pace with international legal legislation, the company worked on developing its reverse supply chains.”

“The participant also indicated that there are still obstacles preventing I4.0 technology from being integrated into the contemporary vision of RSCs activities, such as recovering expired materials, closely monitoring their collection and recovery mechanisms to rationalise the use of raw materials.” The participant's response contributed to answering the first research question: (How can I4.0 technologies be effectively integrated into the contemporary vision of RSCs activities?). Additionally, the participant's response supported the first hypothesis and the research objective: how I4.0 technologies can be integrated into RSCs activities.

7.9.2 The Role of Specific I4.0 Technologies:

IoT, CPS, big data analytics, cloud computing, and smart factories were identified as key enablers of sustainable RSCs. CPS and IoT will enable instantaneous communication among physical objects, operators, and systems, thereby making systems responsive to customer preferences and optimally utilising resources. Decision-making, transparency, and process optimisation can be enhanced by big data and cloud computing, and the manufacturing flexibility required for recycling and reprocessing can be provided by smart factories.

Based on the presented responses of the participants, I4.0 digital technologies contribute greatly to a holistic perception of RSCs activities. This increased visibility enables companies to maintain

continuous awareness of returned products, assess their condition earlier, and plan recovery operations more efficiently.

The participants reported that processing time was lower, their handling errors decreased, and the quality of their decision-making improved directly due to greater transparency and tracking. The transparency that digital technologies provide has overcome the uncertainty surrounding RSCs, thereby explaining the participants' insights. RSCs are highly dynamic, unlike conventional supply chains, where the timing, volume, and condition of returned goods are predictable. Analyses indicate that I4.0 technology can minimise this variability and uncertainty by converting scattered return flows into open monitoring, tracking, and management systems.

The presented mechanism explains how digital technology can translate into performance improvements and sustainable practices within RSCs, as digital visibility and tracking can facilitate decision-making and minimise unnecessary operations and material losses. The following is a brief excerpt of participants' answers.

Regarding questions related to the (role of Industry 4.0 technology in supporting RSCs activities). One of the participants, who works for a leading energy and renewable energy company, and holds the position of engineer in the research and development department, pointed out that "the company relies on all of this technology in its operations and interconnecting its components, in addition to connecting workers and physical components through cyber-physical systems and the Internet of Things. Big data enables the optimal analysis and management of operations, and the ease of accessing and storing big data using cloud technology helps all stakeholders securely and quickly access the required data". In the same context, and through verbal intervention, the participant pointed out, "there are some technical challenges facing us in linking Industry 4.0 technology with RSCs activities".

In response to the same question, one participant works at a modern medical device manufacturer. In addition, the manager of the maintenance and calibration department within the company's reverse logistics activities answered, "The Company relies on this technology in its operations and the connection of its components, in addition to connecting workers and physical components through CPS and the IoT. CPS can support the response to customer preferences through the electronic networking of physical components and the capabilities of the smart factory, enabling rapid response to changes and high flexibility, thereby helping meet customer preferences, rationalising the use of raw materials, and saving energy".

Moreover, the participant added, "There are some technical and organisational challenges facing the company in integrating I4.0 technology into the contemporary vision of RSCs activities."

7.9.3 Sustainability Dimensions in RSCs:

Participants affirmed that I4.0-enabled RSCs directly contribute to sustainability outcomes by:

- Meeting customer preferences through feedback-driven production.
- Optimising raw material use by reducing waste, recycling, and minimising defects.
- Ethical manufacturing by ensuring transparency, traceability, and good after-sales service.

The participants' opinions indicate a modern vision of RSCs, in which I4.0 technologies create an integrated socio-technological system rather than a set of individual tools. The CPS and IoT systems are also envisaged as core mechanisms for digitalising physical assets, human resources, and organisational processes, enabling smart factories to respond quickly to changes in customer preferences with high operational flexibility.

According to the participants interviewed, real-time digital coordination enhances electronic networking, data sharing, and responsiveness to customer preferences in RSCs, enabling companies to adapt their recovery, remanufacturing, and recycling operations quickly. This receptiveness is also directly linked to maximising raw material utilisation and energy efficiency, demonstrating that sustainability outcomes are achieved through process adjustments rather than by predetermined efficiency indicators.

In addition, the participants also relate IoT-enabled communication platforms and big data analytics to ethical manufacturing practices. Transparency, incorporation of feedback, and sound decision-making in product development develop ethical considerations. Cloud computing serves as an enabling infrastructure that facilitates the high-speed, secure sharing of information among all stakeholders, thereby improving discipline and coordination in sustainable RSCs activities.

Nevertheless, recognition of technical and organisational challenges offers a more analytical perspective, as it means that the realisation of this contemporary vision of RSCs activities depends on companies' willingness and the feasibility of integrating their systems. This indicates that the digital transformation of RSCs is not only a technical issue but also an organisational and managerial one. An example of a participant's response is provided below.

The firm has aimed to establish communication pathways with its customers by using digital technologies to gather information about their responses to products, as well as suggestions and preferences regarding product customisation and performance. The company listens to customer feedback to satisfy customer preferences.

Given that many customer requests are specialised, a company must conduct a feasibility study and other procedures before investing in them.

The following are citations from participants' answers. The interviewer interviewed a reverse logistics support officer at a medical device manufacturing company. Since the participant is a reverse logistics specialist, the interview question was asked in the context of his work, including the statement, "Customer feedback in RSCs provides sufficient information about customer preferences, which can be met through Industry 4.0 technologies." The participant indicated, "The Company pays special attention to RSCs. Specifically, the company has specialised departments distributed across multiple geographic regions in several countries to provide after-sales services, including maintenance, repair, and other services, as well as contribute to the recovery of expired materials for recycling. Furthermore, the company has worked to open communication channels with customers, using digital technologies, to learn about their reactions to its products, suggestions, and desires for product customisation and performance efficiency. The company pays attention to customer feedback to address their preferences." The participant also indicated, "Modern Industry 4.0 technologies, especially smart factories, have played a significant role in meeting changing customer demands, given their flexibility in responding to changing market requirements and enhancing the company's competitive advantage." During the interview, the interviewer asked a side question regarding the company's obstacles in this context. The participant indicated, "Some of the requests they receive from customers relate to specific specialisations that require feasibility studies and other measures from the company to invest in."

7.9.4 Mediating the Customer Feedback and Recycling:

Customer feedback serves as a mediator, converting the adoption of digital technologies into effective operational decision-making in RSCs. Whereas I4.0 technology provides the framework for integration, customer feedback provides the content that enables it.

By using network technologies that enable customer feedback, companies manage the feedback flow to align returned products with customer expectations, leading to increased product acceptance, less unnecessary reprocessing, and better resource use. This mediation clarifies that an integrated relationship directly enhances sustainability outcomes by enabling informed decisions aligned with customer needs and sustainability.

Analytically, customer feedback does not, in and of itself, drive sustainable manufacturing practices. However, it influences the effectiveness of relationship integration by ensuring that integrated data flows are meaningful and relevant to decision-making.

Another aspect that emerged among the participants was recycling as a factor in the correlation between I4.0 and sustainable manufacturing practices. Digital technology improves monitoring, automation, and process optimisation through data. The technologies combine internal operations with stakeholders in recycling and recovery.

Recycling has often been associated with the effective use of raw materials, waste minimisation, energy conservation, and the promotion of environmentally friendly practices.

The process-based intermediary of recycling helps combine digital technology to achieve sustainability outcomes. CPS, IoT, and cloud platforms enable stakeholders in RSCs to connect through relationship integration.

Nevertheless, sustainable manufacturing is not possible without the integration of effective recycling. The digital connectivity of relationships enables stakeholders better to channel recycled products into appropriate recycling or recovery operations, thereby facilitating sustainable production and minimising the environmental footprint.

Thus, recycling improves relationships by translating relationship and information integration into material performance gains, such as more efficient use of raw materials and energy savings. This is an excerpt from participants' answers.

The company listens to customers, uses customer feedback to assess its products, and undertakes production changes in response to evolving customer needs. The company also maintains ongoing contact with its customers and provides electronic evaluation forms to assess the company's performance and product quality. That is, customer feedback may serve as one of the strategic instruments of connecting I4.0 technology with the contemporary vision of RSCs activities.

The following are excerpts from participant responses. To understand the company's focus on customer feedback and its role in linking and integrating forward and reverse logistics, the coordinator posed a question to a participant working in post-marketing monitoring and feedback at an energy and renewable energy company: "Can customer feedback be a tool for linking and integrating Industry 4.0 technology and the contemporary vision of RSCs activities?" The participant explained, "The Company pays attention to customer feedback and considers it an evaluation of its products, and works to implement any production improvements to meet changing customer requirements. The company also maintains continuous communication with its customers and provides electronic evaluation forms to assess its performance and product quality. In other words, customer feedback can be a strategic tool for linking Industry 4.0 technology and the contemporary vision for reverse supply chain activities."

Additionally, an interview was conducted with the production manager at one of the company's factories, which specialises in energy solutions. The factory produces several types of alternative energy systems and uses modern technology. After confirming that the factory recycles its products, the researcher also found that most of its products are designed to be recyclable and that it has an effective RSCs management system. The interview questions were presented to the participant: (Recycling processes supported by Industry 4.0 technology can be invested in to achieve a

contemporary vision of RSCs activities). The participant indicated, “Adopting the I4.0 approach, based on modern technological applications, undoubtedly significantly improves the industry and enhances operations. It directly supports recycling processes and improves their performance, as reflected in high manufacturing flexibility to meet quality requirements and ease of use. It provides successful solutions to meet customer preferences. In addition, modern technologies effectively save time and energy, improving the process and supporting the rational use of raw materials. Utilising recycling processes to obtain raw materials protects the environment and supports sustainable manufacturing, thereby enhancing manufacturing ethics”.

The participants' responses also help address the fourth research question, whereas the quantitative findings substantiate the eighth hypothesis. Moreover, they reinforce the research model's structure and demonstrate its practicality in real-world contexts.

7.9.5. The Customer Feedback and Recycling Role of Combined Mediation:

Participants' impressions indicate that the mediating variables are sequential and complementary in their roles. Customer feedback helps build relationships at the decision-making level, thereby informing the redesign of products, their remanufacturing, or their recycling. Recycling, in turn, is a factor at the operational level, as it defines the actual recovery and reuse of materials.

All these intervening variables reveal the underlying reasons why relationship integration driven by I4.0 technology can yield sustainable results for RSCs, without necessarily having a direct linear impact. Instead, sustainability enhancement arises from informed choices (customer feedback) and digitally enhanced recovery procedures (recycling).

In the context of the participants' responses, the interviewer interviewed a leading renewable energy solutions company. The interviewer spoke with one of the participants, an expert engineer in the quality and quality control department. The following question was posed: "A smart factory offers manufacturing flexibility that meets customer preferences, supports recycling, and can be integrated with the contemporary vision of RSCs activities." The participant explained, "A smart factory possesses high manufacturing flexibility, enabling it to respond quickly to changing customer requirements. Therefore, it can meet customer preferences and respond to market demands. Modern technologies also offer advanced capabilities for integrating forward and reverse logistics, and the smart factory effectively supports and improves recycling processes. The company continuously strives to develop ways to integrate its products and services to ensure the superiority of its offerings and provide practical support to customers." During the interview, the interviewer also asked the participant about big data and cloud computing technology, the company's investments in its operations, and the participant's role in enhancing RSCs. The participant explained, "The Company

uses big data and cloud computing technologies, particularly in research and development and at the plant scale, and they are mainly used to improve the process. These technologies can enhance RSCs activities with a contemporary vision by managing customer feedback, which contributes to meeting their actual preferences according to quality standards and in the required quantities, and supporting RSCs."

7.10 Sample Adequacy and Data Saturation:

The qualitative research methodology was based on ten semi-structured interviews with specialists and experts in Industry 4.0 technology, RSCs, and sustainable manufacturing. The number of interviews was based on purposive sampling and data-rich analysis rather than on statistically representative data. This technique contributed to the data's saturation and adequacy for the specific research purposes.

The adequacy of the research sample was assessed using the concept of data saturation, defined as the point beyond which no new topics, insights, or conceptual patterns relevant to the research topic and objectives emerge. The semi-structured interviews demonstrated a high degree of homogeneity in the data across the specific research contexts. Subsequent interviews did not yield new interpretive patterns or conceptual dimensions beyond those indicated in the previous interviews; at this point, the qualitative data had reached saturation within the context of our research.

In accordance with the research methodology, the semi-structured interviews were not intended to generalise the results. Moreover, it enriches the interpretation and clarifies the organisational mechanisms and realities that cannot be fully explained by quantitative results alone, but require a deeper understanding of the actual work environment. Qualitative findings, derived from an objective analysis of participants' responses, corroborated the quantitative results in the research context. They revealed insightful perspectives on implementation issues, sustainability practices, ethical manufacturing, and the practical integration of digital technologies into RSCs activities. Thus, the qualitative methodology enhanced the explanatory depth and methodological soundness of the multidisciplinary research.

7.11 Relation to Quantitative Findings:

The qualitative results provide a good explanation for the quantitative results provided in the preceding chapter. The interview findings reveal statistically significant relationships between I4.0 technologies and sustainable RSCs activities, and point to contextual issues and trade-offs that could not be quantified.

7.12 Credibility and Accuracy:

The research has utilised purposive sampling and experienced participants to enhance credibility and reliability through systematic, objective analysis, and has validated the findings with quantitative data and the available literature. The extensive contextual description facilitates the generalisability of the findings to a broader scope, whereas the clarity of the analysis documentation facilitates their verifiability. The researcher had detailed initial transcripts of participants' responses and all interview details.

7.13 Chapter Summary:

In this chapter, the role and use of I4.0 technologies in the contemporary vision of RSCs' operations are demonstrated, and the manner in which their combination enhances manufacturing sustainability and the circular economy's aims is discussed. Although I4.0 has high enabling potential, the results indicate that certain technical and organisational issues remain, and further research is necessary on successful implementation mechanisms.

Chapter Eight

Discussion of Research Results

This chapter summarises and discusses the research results. The findings of the research were anchored in providing independent responses to the research questions and objectives, in accordance with the identified research problem and gap. This section of the study presents the numerical findings of the statistical analysis and provides a clear, objective interpretation. It also presents the qualitative findings and discusses them objectively, in accordance with the participants' opinions. The investigator used descriptive and inferential statistics to analyse quantitative outcomes from pre-designed surveys. Additionally, the researcher conducted semi-structured interviews with pre-set questions to obtain qualitative information from participants' responses, reflecting their views and visions of reality in their workplaces. The results are discussed and summarised as follows:

1. The contemporary vision of RSCs activities is directly affected by Industry 4.0 technologies. The initial hypothesis indicated a strong association between Industry 4.0 and reverse supply chains. The findings of the semi-structured interviews also confirmed that Industry 4.0 technologies are key to providing a contemporary vision of RSCs activities. The findings of the initial primary hypothesis demonstrate the role of advanced technologies in Industry 4.0 in enhancing the interdependence between Industry 4.0 and the contemporary vision of RSCs activities. The combination of the contemporary vision for RSCs activities and their integration with the latest industrial technologies would be beneficial for manufacturing sustainability.

Moreover, the findings of the research support prior studies, as Baccarelli et al. (2017) reported that Industry 4.0 technology has the potential to enhance recycling and workflows systematically throughout the value chain. The researchers also showed that the new route to sustainability in manufacturing could be based on waste reduction, in which a new logistics business model recycles and reuses waste to convert it into new, higher-value-added products through reverse supply chain operations (Leader & Rashid, 2016).

Moreover, the findings of the first hypothesis can answer the first main research question (how the integration of Industry 4.0 technologies can be integrated into the contemporary vision of RSCs activities). Supporting emerging technologies can enhance integration between I4.0 and the contemporary vision of RSCs activities, improving their performance in achieving greater manufacturing sustainability. The results of the hypothesis also reinforce the research objectives of integrating I4.0 technology with the contemporary vision of RSCs activities, which, in turn, enhances manufacturing sustainability and waste reduction.

Although the first main hypothesis addressed the impact of Industry 4.0, as an integrated technological architecture, on the contemporary vision of RSCs' activities, discussions of the individual impacts of its constituent technologies (CPS, IoT, cloud computing, big data, and smart factories) are essential for both theoretical and analytical purposes. Industry 4.0 is a multidimensional architecture in which each technology contributes through distinct operational mechanisms and capabilities. Therefore, analysing the individual impacts of these technologies provides a deeper understanding of how the overall effect of Industry 4.0 is generated and identifies the specific contributions of each technological component to supporting customer preferences, the rational use of raw materials, and manufacturing ethics. At the same time, testing their collective effect shows that RSCs' activities are not driven by isolated technologies but by the synergistic integration of complementary digital capabilities within the broader Industry 4.0 architecture. This approach enhances the explanatory power of the research model and offers a more comprehensive interpretation of the empirical findings.

2. The quantitative results demonstrate that Cyber-physical systems directly support the contemporary vision of RSCs activities. The results of the first hypothesis indicate a significant effect of cyber-physical systems on the contemporary vision of RSCs activities. Additionally, qualitative findings from semi-structured interviews corroborated the survey results, as responses from industry participants demonstrated the role of CPS in advancing the contemporary vision of RSCs activities.

3. The quantitative results demonstrate that the Internet of Things influences the contemporary vision of RSCs activities. This technology can effectively improve the performance of the contemporary vision of RSCs activities. Additionally, qualitative findings from semi-structured interviews complemented the quantitative results, as participants demonstrated the role of IoT in improving the contemporary vision of RSCs activities, grounded in industry realities.

4. The quantitative results showed that the cloud influences the contemporary vision of RSCs activities. This suggests that the cloud plays a crucial role in supporting the contemporary vision of RSCs activities. Furthermore, qualitative findings from semi-structured interviews supported the quantitative results, with responses from industry practitioners demonstrating the active role of cloud in shaping the contemporary vision of RSCs activities.

5. The quantitative results showed the effect of big data on the contemporary vision of RSCs activities. Big data is fundamental to meeting the contemporary vision of RSCs activities. Similarly, qualitative findings from semi-structured interviews supported the quantitative results, as participants' responses reflected industry realities and demonstrated the effective role of big data in enhancing the contemporary vision of RSCs activities.

6. The results of the quantitative method showed direct influences of the smart factory on the contemporary vision of RSCs activities. A smart factory with flexible manufacturing can help meet customer preferences, reduce energy consumption, and enhance overall process efficiency. This is reflected in the rationalisation of material use, which is consistent with manufacturing ethics. On the other hand, qualitative findings from semi-structured interviews supported the quantitative results, as participants' responses reflected industry realities and demonstrated the effective role of smart factories in enhancing the contemporary vision of RSCs activities.

The results from (2-6) represent the effect of industrial technology on the contemporary vision of RSCs activities. Industry 4.0 technology played a significant and effective role in integrating Industry 4.0 with the contemporary vision of RSCs activities. This will effectively improve the performance of contemporary RSCs activities, which, in turn, will be reflected in reduced waste and optimal investment.

The results of the first hypothesis support previous literature, demonstrating a significant impact of cyber-physical systems on the contemporary vision of RSC activities. The research by Dave et al. (2020) examines the potential advantages of using cyber-physical systems (CPS) technologies in remanufacturing and recycling household products. Their study combined Industry 4.0 CPS technology with a web-based resource planning system to manage real-time data and determine reorder points using inventory measurement sensors. Moreover, Perez et al. (2022) demonstrated the potential of integrating systems and technologies into smart factory systems (CPS). This system architecture is compatible and open to integration within the contemporary vision of RSCs activities. Moreover, the Internet of Things (IoT) is implemented as a cyber-physical system. The smart factory, in this context, reflects the core characteristics of Industry 4.0 and is used to ensure manufacturing sustainability (Mueller et al., 2017).

Conversely, the findings of the former sub-hypothesis revealed that the Internet of Things (IoT) affects the contemporary vision of RSCs' activities. Conversely, the qualitative results of the semi-structured interviews corroborated the quantitative data, as participants' responses reflected industry realities and demonstrated the success of smart factories in advancing the contemporary vision of RSCs activities. This technology can successfully enhance the performance of supply chain activities involved in RSCs. The study is consistent with past authors' trends, as Garrido-Hidalgo et al. (2020) emphasised the use of the Internet of Things (IoT) to facilitate reverse supply chain and integration strategies, guided by IoT communication protocols, for managing waste electrical and electronic equipment using machine learning. Moreover, RSCs can be greatly assisted by the Internet of Things (IoT), which helps increase

visibility, automate manual operations, optimise inventory, and trace product cycles. This is to make sure that the regulations are followed and to improve sustainability (Manavalan & Jayakrishna, 2019). Besides, IoT technology can be used to collect, track, and analyse real-time data, helping companies employ more effective, transparent, and cost-efficient reverse logistics practices and make manufacturing more sustainable (Gopakhlloo et al., 2023). Similarly, big data influences reverse supply chain operations (customer preferences, the rational use of raw materials, and manufacturing ethics). Big data is necessary to satisfy customer preferences, rationalise use, and uphold manufacturing ethics. The study results validated Edwin et al. (2022) findings, which showed that big data provides information on manufacturing processes and resource sourcing for RSCs systems that can support productivity, enhance sustainability, and make them more responsive to consumer and market needs. The concept of big data can be successfully applied to improve RSCs activities and address issues that could impede the integration of I4.0 technology and RSCs systems, leveraging real-world empirical knowledge to enhance integration mechanisms.

Moreover, cloud computing significantly contributes to the contemporary vision of RSCs activities. Cloud technologies can enable real-time data collection and analysis, helping the company understand customer preferences and respond to them (Giannakiset et al., 2019). It also encourages rational utilisation of the raw materials by enhancing recovery and recycling. With centralised access to data, companies can trace product life cycles, thereby reducing waste and rationalising the use of raw materials (Govindan et al., 2015). In addition, the cloud improves ethical practices in manufacturing by providing a clear view of sourcing, manufacturing, and returns (Tiwari et al., 2018). Such transparency helps with ethical decision-making and increases consumer confidence in sustainable operations.

The hypothesis outcomes indicate a direct influence of the smart factory on the contemporary vision of RSCs activities. A flexible manufacturing smart factory can help satisfy customer preferences, save energy, and optimise processes, as evidenced by the rational use of materials and adherence to manufacturing ethics. According to the previous literature, smart factory technologies can facilitate the contemporary vision of RSCs' activities through automated sorting and processing. The smart factory also includes the Internet of Things, artificial intelligence, and robotic sensors that automatically sort and categorise returned products by condition (Mehrpouya et al., 2019). This supports decision-making regarding whether to refurbish, recycle, or dispose of them in an environmentally friendly manner. Smart factories also contribute to the circular economy by enhancing material reuse and rationalisation (Lin, 2018), reducing waste, and supporting a more circular supply chain, thereby enhancing environmental sustainability. Furthermore, according to Dev et al. (2020),

smart factories are equipped with adaptive manufacturing systems that can quickly adjust to changes in quantity and quality requirements in reverse logistics.

Based on the results above. This represents the effect of industrial technology on the contemporary vision of RSCs activities. It can be shown that Industry 4.0 technology has played an influential and effective role in integrating Industry 4.0 with the contemporary vision of RSCs' activities, thereby improving the performance of these activities. This, in turn, is reflected in waste-reduction initiatives and their optimal investment, thereby enhancing manufacturing sustainability.

The results of the first hypothesis can help answer the first research question: How do key Industry 4.0 technologies contribute to the integration and enhancement of RSCs' activities? Through advanced networking and integration capabilities, these technologies have effectively enhanced the integration between Industry 4.0 and reverse supply chains, significantly improving their performance. Furthermore, the results of the hypothesis support the research objectives of demonstrating the role of Industry 4.0 technology in integrating reverse supply chain activities.

7. There is a significant relationship between Industry 4.0 technology and customer feedback. This result indicates that one of the conditions for introducing the mediating variable (customer feedback) in the relationship between Industry 4.0 and the contemporary vision of RSCs activities has been met. Respondents' responses in semi-structured interviews also highlighted the enabling capabilities of Industry 4.0 technology for rapid response to customer feedback and its potential as a strategic tool for integrating forward and reverse logistics to enhance sustainability.

8. Industry 4.0 technology effectively supports recycling. The results of the third hypothesis clearly show a significant relationship, indicating that one of the conditions for introducing the mediating variable (Recycling) has been met. The results for the second and third hypotheses also addressed the research question (to what extent Industry 4.0 technology is related to customer feedback and recycling as mediating variables). Participants' responses to the semi-structured interviews also indicated the potential of I4.0 technology to support and enhance recycling, thereby improving recycling performance.

9. The results of the fourth hypothesis indicate that customer feedback affects the contemporary vision of RSCs activities. The results of this hypothesis also fulfilled another condition for introducing the mediating variable (customer feedback). In addition, the results of the fourth hypothesis contributed to answering the research question (Are the mediating variables customer feedback and recycling related to the reverse supply chain?). The findings of the hypothesis led to the discovery of a strong connection between customer feedback and the contemporary vision of RSCs activities. This means that the mediating variable can strengthen the correlation between Industry 4.0 and the contemporary vision of

RSCs' activities. In addition, the semi-structured interview instrument helped reinforce the quantitative results by prompting participants to respond. The participants also identified customer feedback as one of the main value chain practices for effectively supporting customer preferences, rational utilisation, and ethical manufacturing activities.

10. The results of the fifth hypothesis indicate that there is a strong correlation between recycling and the contemporary vision of RSCs activities. The outcomes of the hypotheses (1-5) indicate that all requirements for introducing intermediate variables into the research model were met, suggesting that the research model will achieve higher levels of accuracy and reliability in hypothesis testing. In addition, the findings of the fifth hypothesis helped in answering the research question (Are the mediating variables customer feedback and recycling related to the reverse supply chain?). Moreover, participants in semi-structured interviews stated that recycling is crucial to advancing the contemporary view of reverse supply chain activities, as it fulfils customer expectations, rationalises the use of raw materials, and ensures ethical manufacturing, thereby facilitating sustainable manufacturing.

The findings for hypotheses (2-5) were consistent with the existing literature. According to previous literature, Customer feedback may be a valuable source of information for producers, enabling them to understand why materials are sent back, assess product quality, and identify customer preferences. Moreover, it has been shown that customer feedback has considerable diagnostic value, helping define product design, avoid flaws, and satisfy expectations (Moldavska & Welo, 2017). According to Govindan et al. (2015), combining customer feedback with reverse supply chains can make the manufacturing process more efficient and sustainable. Redesign is a way to reduce waste and improve resource utilisation. In addition, Industrial 4.0 technology has helped industrial companies gather and analyse customer feedback and invest it in the most efficient way (Zhang et al., 2020).

Moreover, amid rapid technological breakthroughs, Industry 4.0 digital technologies are instrumental in the recycling process, helping create a sustainable global economy (Kurniawan et al., 2022). Technological advancements help the industry develop practical solutions for waste treatment and recycling, resulting in long-term benefits for society. Industry 4.0 technology has proven its role in recycling as a growth engine for value creation by enhancing the efficient operation of resource recovery and reducing operational costs, possibly through tracking waste flows (Zhang et al., 2023). Consequently, industrial users are gradually shifting from a linear to a circular economy in waste management. This promotes resource recovery through recycling recovered materials for consumers and reduces the negative impacts of the linear economy. For this reason, identifying new opportunities and challenges in recycling, reuse, and recovery (3Rs) is essential. Modern industrial technologies can

effectively support these activities (Kurniawan et al., 2022). The goal of Industry 4.0 is to maximise the closed flow of materials while retaining the fundamental value that circulates via technological innovation across the reverse supply chain (Rajput & Singh, 2021).

On the other hand, and in the same context. The results of the semi-structured interviews confirmed the interview question (Recycling supported by Industry 4.0 can be invested in achieving customer preferences, rational use of raw materials, and manufacturing ethics), as the results showed an effective role for Industry 4.0 technologies in meeting customer preferences, supporting rationalisation of consumption, and enhancing manufacturing ethics. Additionally, the quantitative and qualitative findings reinforced prior literature in this field.

The semi-structured interviews' results supported the survey results through the interview question (Can customer opinions be one of the tools for integration between Industry 4.0 and contemporary vision of RSCs activities). The participants acknowledged the crucial and effective role of customer feedback in providing Industry 4.0 technology with information and insights that help improve and develop processes according to customer preferences, which, in turn, is reflected in the integration of Industry 4.0 with the contemporary vision of RSCs' activities.

11. The mediating variable (customer feedback) strengthened the relationship between Industry 4.0 technology and the contemporary vision of RSCs activities. Based on the results of the sixth hypothesis, customer feedback directly affects the relationship between Industry 4.0 and the contemporary vision of RSCs' activities. That is, testing the relationship between Industry 4.0 and a contemporary vision of RSCs' activities had a greater effect in the presence of the mediating variable, customer feedback, indicating that the mediating variable effectively strengthened the integration between Industry 4.0 and a contemporary vision of RSCs activities.

12. The mediating variable (recycling) strengthened the relationship between Industry 4.0 technology and the contemporary vision of RSCs activities. The findings of the seventh hypothesis show that the mediating variable (recycling) enhances the connection between Industry 4.0 technology and the contemporary vision of RSCs activities, implying its role in mediating the relationship between the independent variable and the dependent variable.

13. The intermediate variables (customer feedback and recycling) are combined into two intermediate variables to support and strengthen the integration relationship between Industry 4.0 technology and the contemporary vision of RSCs activities. According to the results of the eighth hypothesis, we observe that the intermediate variables play a significant and effective role in enhancing the integration between the independent variable (Industry 4.0) and the dependent variable (contemporary vision of

RSCs activities). The results of the eighth hypothesis also contributed to answering the research question (How can customer feedback and recycling, as intermediate variables, integrate the relationship between Industry 4.0 and the contemporary vision of RSCs activities?). Helps with Industry 4.0 technology, which is optimally integrated with the intermediate variables. This, in turn, enhanced integration with the independent variable (a contemporary vision of RSCs activities), thereby achieving optimal results in meeting customer preferences, rational use of raw materials, and manufacturing ethics, thereby reducing waste and optimising investment in line with the research gap.

On the other hand, and in the same context. The results of the semi-structured interviews confirmed the interview question (Recycling supported by Industry 4.0 can be invested in achieving customer preferences, rational use of raw materials, and manufacturing ethics), as the results showed an effective role for Industry 4.0 technologies in meeting customer preferences, supporting rationalisation of consumption, and enhancing manufacturing ethics. Additionally, the quantitative and qualitative findings reinforced prior literature in this field.

14. The semi-structured interviews' results supported the survey results through the interview question (Can customer feedback be one of the tools for integration between Industry 4.0 and contemporary vision of RSCs activities?). The participants acknowledged the crucial and effective role of customer feedback in providing Industry 4.0 technology with information and insights that help improve and develop processes in line with customer preferences, which, in turn, is reflected in the integration of Industry 4.0 with the contemporary vision of RSCs activities.

8.1 Critical Interpretation, Theoretical Implications, and Methodological Considerations of the Findings:

Our findings show consistent results between the quantitative and qualitative analyses. The results mostly support the hypothesis that Industry 4.0 technologies significantly contribute to the contemporary vision of RSCs activities, both directly and indirectly. However, some meaningful insights can be derived from the results, which should be considered to improve scientific design and methodology.

Results: First, the results provide strong evidence of direct and indirect positive relationships between Industry 4.0 technologies and the contemporary vision of RSCs activities. They also provide substantial empirical support for the integrated theoretical framework informed by Sustainability-Oriented Innovation (SOI) and Resource Orchestration Theory (ROT). Direct relationships, especially those with an $R^2 > 0.80$ obtained in this study after stability testing the predictive capability of the structural model (e.g., Industry 4.0 technologies affecting the contemporary vision of RSCs activities), may be conceptual neighbours offering similar value through dimensions or operations. This, however,

does not automatically entail construct redundancy, particularly given that CFA and HTMT testing showed that the constructs were empirically distinct. However, the results indicate that real structural connectedness may exist between digital transformation and sustainability-oriented RSCs practices within advanced manufacturing contexts.

Second, although the results largely confirm previous studies, this research expands the existing literature by demonstrating how combining Industry 4.0 technologies can improve the contemporary vision of RSCs activities and by providing insights into innovative measures for RSCs activities (e.g., customer preferences, rational use of raw materials, and manufacturing ethics). As a result, this theoretical observation is fascinating if only because extant studies are almost universally organised around the goals of operational efficiency, automation, and waste reduction. In contrast, this research notion extends its scope to strategic sustainability paradigms and facets of ethical manufacturing harmony. That is, the findings suggest avenues in which SOI theory could provide a more expansive explanation beyond technological innovation, encompassing change and enabling sustainability-focused organisational transformation.

Third, the mediating variables' role of customer feedback and recycling offer a significant theoretical contribution because they are, to some degree, connected to Industry 4.0 technologies rather than being directly driven by or acting solely through technology. Instead, these results indicate the centrality of organisational and informational orchestration mechanisms as mediators between technology absorptive capacity and sustainable RSCs outcomes. This result supports the structure of ROT by suggesting that sustainability practice relies not only on possession but also on orchestration, in both stakeholder information and resource recovery operations. Both yield finding that contradict technology-deterministic perspectives often encountered in the literature concerning Industry 4.0, which mostly assume that technological implementation itself will automatically produce sustainability outcomes.

These results also reveal theoretically relevant insights from the qualitative research. Participants emphasised implementation-related aspects, mainly organisational integration, the transition of manufacturing systems under Industry 4.0 conditions, and the trade-off between the technology uptakes required for its functioning and sustainability expectations. While these issues did not statistically invalidate the proposed relationships, they also indicate that the practical success of Industry 4.0 integration within RSCs may depend on higher-order contextual organisational competence and two additional lower-level aid factors, namely genuine managerial readiness or strategic alignment, which were not fully captured by the quantitative model used in this research. Thus, future research may need to investigate moderating organisational variables such as digital maturity, sustainability culture, or institutional pressures.

Results also indicate an important conceptual distinction between reverse logistics and the broader contemporary vision of RSCs activities. Filling the gaps identified in the literature that has primarily focused on reverse logistics as a green supply chain mechanism. These findings demonstrate that sustainability-oriented RSC activities are strategic and transcend product or component remanufacturing; they include recycling and incorporate customer integration within circular economy objectives aimed specifically at optimising resource consumption by closing many loops across the entire scope of supply chains. This helps address conceptual confusion surrounding prior work while supporting the vision of RSCs as integrated sustainability systems rather than standalone end-of-life logistics functions.

Nonetheless, several methodological limitations must be considered when assessing the robustness of our results. The research has some limitations, as it mainly relied on self-reported data from questionnaires, which may increase the likelihood of social desirability bias and subjective estimate effects. While we employed procedural and statistical remedies, including assurances of anonymity, Harman's single-factor test, CFA on all items independent from their respective underlying factors, and HTMT analysis indicating that common method bias was not a substantial concern, we cannot rule out the presence of common method bias.

Non-continuous measures: First, the data in this cross-sectional study were collected at a single time point, thus precluding causal inference among variables. Hence, the findings should be viewed primarily as tests of robust associations for a putative causal structure rather than as Permanent Effects that exist in the long term. Longitudinal studies could therefore offer more certain insights into the dynamics of Industry 4.0 diffusion in systems RSCs.

The results have limited generalisability to other industrial sectors or to lower-technological-maturity organisations due to purposive sampling, which targeted specialists and professionals working in advanced manufacturing and Industry 4.0 environments as informants. While the respondents in the current study came from a wide range of countries and industrial sectors, it is still more applicable to advanced manufacturing.

Conclusions: Finally, these mixed methods provided crucial triangulation by combining quantitatively validated indicators with qualitative depth. The qualitative component was not intended to create an independent theory-based model, but rather to supplement the model and add depth. Hence, subsequent qualitative research could establish a baseline understanding and examine the organisational barriers and theoretical tensions associated with the implementation dynamics of Industry 4.0-enabled RSCs activities.

Further, the theoretical connections between practical aspects, which collectively form an integrated SOI and ROT framework, are validated. It also underscores the importance of organisational

orchestration mechanisms, contextual implementation conditions, and sustainability-oriented managerial capabilities in explaining how Industry 4.0 technologies can foster an effectiveness-based contemporary vision of RSCs activities and their updated prioritisation strategies.

8.2 Theoretical and practical contributions of the research:

The study significantly advances both the theoretical and empirical literature by creating a conceptual framework that integrates Industry 4.0 technologies with the contemporary vision of RSCs activities. The mediating constructs in the framework include customer feedback and recycling, with the Sustainability-Oriented Innovation (SOI) theory used to establish direct connections and the Resource Orchestration Theory (ROT) to explain the mediating processes. This approach moves beyond just theoretical assumptions to develop a relevant model that assesses both direct and indirect relationships between digital technologies and sustainable manufacturing practices.

Theoretically, the conceptual framework can make a difference by integrating SOI and ROT into a single explanatory framework that demonstrates how I4.0 technologies (CPS, IoT, cloud computing, big data analytics, and smart factories) serve as system-level facilitators of sustainable manufacturing through RSCs practices. In contrast to sustainability-oriented innovation, which has traditionally aimed to integrate environmental and social goals into innovation processes, this study broadens the scope by demonstrating how digital manufacturing infrastructures can realise system-level sustainability. The conceptualisation of I4.0 is therefore not just a technological extension, but an eco-friendly digital platform that meets consumer preferences, encourages the effective use of materials, and promotes ethical manufacturing at the RSCs.

At the same time, the research advances the ROT theory by integrating customer feedback and recycling into the resource coordination process. Rather than treating these factors as peripheral management operations, the framework positions them as organisational strategies that translate technological capabilities into sustainable manufacturing practices. Ongoing customer feedback provides continuous information to help align production systems with evolving sustainability expectations. Recycling is also a material coordination process that ensures a cyclical flow of resources. The model can incorporate digital stakeholder engagement and material recovery as strategic coordination competencies by including these intervening variables.

Among the most notable theoretical contributions is the systematic development of a testable conceptual framework for integrating digital technologies, intermediary mechanisms, and sustainable practices in RSCs. This framework provides a methodological basis for analysing direct and indirect effects, advancing the view of manufacturing sustainability as a dynamic outcome of interactions and integrated operational capabilities, rather than a linear by-product of technology adoption. The model

is developed in its approach, describing RSCs as efficient sustainability systems enabled by I4.0 technology, rather than as passive end-of-life processes.

In practice, the research provides an evidence-based conceptual framework that helps companies and professionals use I4.0 technologies to achieve sustainable manufacturing goals. The framework focuses on the use of customer feedback systems and organised recycling procedures in digital manufacturing settings as critical to achieving the greatest sustainability impact. As a result, managers and policymakers will have a clear roadmap to align technology investment with RSCs strategies to enhance resource efficiency, ethical production, and customer-focused sustainability.

Moreover, the combined research methodology enhances the model's practical applicability by demonstrating the quantitative associations and situating them within the qualitative understanding. This two-sided stance demonstrates that the introduction of I4.0 technologies supports a contemporary vision of RSCs' activities, thereby contributing to the model's relevance across a variety of manufacturing settings.

In general, this study can be regarded as a continuation of current theories into a viable, empirically based concept that explains how I4.0 technologies, both directly and indirectly, facilitate sustainable RSC practices through intermediaries. Therefore, the study not only advances theoretical understanding but also serves as a basis for further investigation and implementation of digital technologies as facilitators of a contemporary vision of RSCs' activities.

The researcher's contribution is a genuine effort that is theorised, empirically tested, and supported by practical experience in an industrial setting. It will focus on embedding I4.0 technology and the contemporary vision for RSCs' activities, thereby making manufacturing more sustainable and less wasteful. The researcher develops a theoretical framework for the research variables and their sub-dimensions, which have not been previously tested in the literature. The study will provide a contemporary vision of RSCs' activities within the framework of I4.0 technology, offering a more detailed, consistent, and forward-looking perspective on how I4.0 can transform them. The development of the conceptual framework for the research was based on the idea, reinforced by theories. Enhancing sustainability does not lie solely in possessing digital tools, but rather in investing in them optimally through integrated mechanisms grounded in harmonious organisational strategic visions, represented by the introduction of intermediate variables (customer feedback and recycling) and the utilisation of available resources from RSCs practices as strategic tools. These tools enabled the integration of I4.0 technology with the contemporary vision of RSCs activities, which, in turn, is reflected in improved sustainability, aligned with the rapid developments in manufacturing, including meeting customer preferences, the rational use of raw materials, and manufacturing ethics.

Chapter Nine

Conclusion and Future Research

9.1 Conclusion:

The conclusion chapter represents a final synthesis statement of this doctoral dissertation research. It presents the study's key findings and contributions. It also points out the main research question, objectives, and cognitive contributions of this research. The significance of the study lies in its scholarly and practical dimensions, encompassing the identification and discussion of prior work and the justification of the findings in their broader context. This study will adhere to time and space constraints to investigate knowledge and its utilisation in the industrial sector. Moreover, the research employed both quantitative and qualitative methods, which strengthen the findings regarding theory and practice by drawing on existing knowledge. The study also provides recommendations for future research, identifies areas requiring further analysis, and outlines how subsequent scientific research can be conducted.

The research question is whether waste levels are increasing despite companies and institutions' efforts to minimise them. Consequently, more research and studies are required to come up with effective mechanisms to meet the rapid changes in the manufacturing processes that are causing growing waste owing to the growing consumption and swift obsolescence of commodities due to rapid technological change in the manufacturing process. The study will provide a mechanism to reduce waste and optimise investment, thereby making manufacturing more sustainable. The vision of the research is to use I4.0 technology to facilitate reverse supply chain activities, which is a modern trend, respond to customer demands, and enable the rational use of raw materials while embedding ethical manufacturing practices. These factors form critical pillars of waste minimisation and investment, which will help improve sustainability, as evidenced by earlier research and emphasised throughout the researcher's work on different facets of his present study. The vision of the researcher rests on the investigation of organisational approaches to the inclusion of forward and reverse logistics based on the main research question (How can Industry 4.0 technologies be successfully implemented to the contemporary vision of RSCs activities) and investigates the connection between I4.0 and the contemporary vision of RSCs activities. The research question is as follows: (How do customer feedback and recycling affect the relation of Industry 4.0 technologies and contemporary vision on RSCs activities?). Enforce the organisational strategic aspect, which aims to invest available resources (customer feedback and recycling) as strategic enablers to promote the integration of I4.0 technologies and the modern vision of RSCs activities, as postulated by Resource Orchestration Theory (ROT) by Sirmon, Hutt, and Ireland (2007). Quantitative and qualitative research findings, supported by real-life

industry experience, demonstrated the effectiveness of intermediate variables (customer feedback and recycling) in enhancing the interconnection between I4.0 technology and the contemporary vision for RSCs activities. This was informed by the notion that a company's only asset is modern technology, which does not necessarily lead to improved sustainability, but that strategic mechanisms are needed to harmonise all components.

The researcher introduced a theoretical framework for the research variables and their sub-dimensions through a literature review, drawing on a contemporary perspective that accommodates the dynamic nature of rapidly evolving manufacturing processes. Furthermore, the research questions were developed through a comprehensive examination of practical theories, which in turn led to the formulation of research hypotheses. These hypotheses informed the development of a research conceptual framework and a research model, which were repeatedly and consistently constructed and served as the foundation for research methodologies grounded in well-founded principles.

The research's parallel contribution is a forward-looking theoretical framework that integrates a contemporary vision of RSCs activities into the broader scope of developing sustainable, digitally enabled manufacturing systems. It discusses how I4.0 technologies could be combined with the contemporary vision of RSCs' activities, taking a particular approach that uses logistics centre practice as a mediating factor to manifest their contribution to the integration of forward and reverse logistics. This way, it offers a holistic picture that connects technological capabilities to the strategic orientation of logistics companies' practices. This expresses the reinforced social aspect, represented by the satisfaction of customer preferences; the environmental aspect, represented by the rational utilisation of raw materials; and the ethical aspect of production, combined with the research structure. This broadens knowledge, overcomes obstacles, and opens the way to how Industry 4.0 technologies can reorganise RSCs operations with a new vision to meet the fast-changing demands of manufacturing technology. The outcomes are reflected in manufacturing sustainability, waste reduction, and optimal investment in the same.

9.2 Future research:

Further studies may improve on the present results to manage the issues and consider the previously uncharted areas that can improve the combination of forward and backward logistics in manufacturing. Testing and working out interdisciplinary approaches and implementing new tools to analyse the results will enrich the knowledge and improve the results of research. Furthermore, emphasis should be placed on translating theoretical developments into practical applications, thus bridging the gap between empirical findings and practical application. Based on the results of this research, the findings highlight the impact of I4.0 technology on contemporary vision of RSCs activities, as well as the direct

role of customer feedback and recycling in enhancing the integrated relationship between them. Accordingly, the researcher proposed several recommendations to address the research problem of waste treatment and optimal investment to enhance manufacturing sustainability. The researcher proposed several recommendations to address and limit the research problem. In presenting his research proposals, the researcher sought to provide practical and theoretical guidance for researchers, stakeholders, etc., which could contribute to improving manufacturing sustainability and preserving the environment, as shown below:

1. Further research and investigation in the field of research variables (Industry 4.0 and reverse supply chains), as they are essential elements in the scope of manufacturing and are accompanied by continuing developments. Thus, they require ongoing research and exploration to enhance manufacturing sustainability.

A research idea can stem from a research question:

How do reverse supply chain practices aided by Industry 4.0 evolve in facilitating manufacturing sustainability and circular resource management?

The present research was a hypothetical cross-sectional study, and the findings describe relationships at a single point in time rather than their longitudinal development. Future longitudinal studies could examine how the relationship among Industry 4.0 technologies, customer pressure on recycling, and sustainable RSCs changes across stages of digital transformation and sustainability implementation. This would strengthen causal interpretation and broaden the dynamic aspect of Sustainability-Oriented Innovation (SOI).

2. Expansion and research exploration to identify additional opportunities for developing RSCs activities and fully integrating them into a networked manufacturing system. A research idea is developed based on a research question that revolves around:

What is the interplay between ethical manufacturing practices and digital technologies in influencing sustainable RSCs governance?

Research results show that manufacturing ethics is a key component of a contemporary vision of RSCs' activities; at the same time, existing Industry 4.0 studies offer relatively sparse conceptual integration in this area. Thus, future research may leverage sustainability-focused manufacturing theory and explore ethical governance frameworks, transparency systems, and digital accountability mechanisms as possible extensions in the era of Industry 4.0.

3. New initiatives by researchers and specialists in this field aim at addressing research problems related to reducing waste and investing it optimally, focusing on the optimal use of raw materials as a crucial element in reducing waste and preserving the environment.
4. Given the rapid pace of technological advancement in the RSCs domain, there is a noticeable gap in the literature concerning the evolving concept of manufacturing ethics. Few studies have addressed the need to update ethical considerations in manufacturing in light of emerging technologies. There is a need to extend research in this field to ensure that ethical systems remain up to date and aligned with technological advances.
5. Pay attention to the contribution of other technologies to Industry 4.0. Our current study failed to consider or demonstrate the extent to which they influence the various operations of reverse supply chains.
6. Carry out research and study of other integration mechanisms of Industry 4.0 systems that include reverse supply chain activities that will be effective in improving sustainability and minimising wastage. To further explore our research findings, a research question can be examined that includes:

How do the organisational factors, specifically digital maturity, sustainability culture, and managerial readiness, moderate RSC activities?

Finally, the current study established robust direct links between Industry 4.0 technologies and the contemporary vision of RSCs activities. Yet, qualitative insights revealed that organisational readiness and operational capabilities could hinder effective integration across organisations. This would expand the ROT perspective in future studies by addressing how internal organisational conditions enable technological capabilities to evolve towards sustainable operational consequences.

7. One of the potential directions of future research would be to investigate how customers perceived the degree to which the adoption of I4.0 technologies to facilitate the activities of RSCs assisted in addressing their expectations. These might also be of interest to managers and industry professionals who want to demonstrate the efficiency of I4.0-based strategies in real-world settings.

In light of our research findings, the role of mediating variables in promoting the integration of Industry 4.0 technology and the contemporary vision for RSCs activities has been identified. Based on this, we propose exploring other mediating factors that could enhance sustainable manufacturing practices. Knowledge in this area can be further developed through a research question that includes:

What supplementary mediating or moderating mechanisms can augment the link between Industry 4.0 technologies and sustainable RSCs activities?

The Current study considered Customer feedback and Recycling as mediating variables. Other strategic mechanisms (e.g., knowledge sharing, AI-based decision-making, stakeholder collaboration, and circular business models) may also be investigated in the future to determine whether they further explain or strengthen the integration of advanced digital technologies with sustainability-oriented RSC activities.

Researchers should make future contributions that consider the short-, medium-, and long-term impacts of Industry 4.0 technologies and apply best practices for integrating them with reverse logistics in the manufacturing industry, thereby surmounting the major challenges of their implementation. Finally, the combination of forward logistics, a concept embodied by Industry 4.0, and reverse logistics, a concept embodied by reverse supply chain activities. Not only will it help make manufacturing more sustainable, but also its impacts will directly translate into waste reduction, more sustainable investment, environmental preservation, and benefits to consumers, thus improving the welfare of society.

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Appendices:

Appendix No. 1: Research Ethics

Ethics and Risk Management Guidance

This note gives guidance on getting ethical and risk management permission for your project. All students must apply for permission irrespective of the nature of the project.

This guidance applies to all “standard” projects carried out by Management Science except those dealing with vulnerable groups (e.g. patients, children, drug users, etc.) or involving the collection of personal confidential data. If you doubt whether your project is a “standard” one then discuss this with your supervisor (for example, a Management Science student might be part of a larger project that involves carrying out medical tests on humans). If you are dealing with a non-standard project, or one that involves vulnerable groups or the collection of personal data, then you may have to obtain approval from the University Ethics Committee in advance. Otherwise, you would gain approval from the Departmental Ethics Committee. In all cases, you should complete the approval form below as a first step.

A participant is someone who provides any kind of input to your project (but not the problem owner), for example, someone you observe, interview, or give a questionnaire. Data includes any kind of information they give you, including verbal information. Your work should conform to normal professional practice, the Data Protection Act as well as to University Ethics Policy.

Participants in your project should:

a) Know

- what the project is about,
- how their data is to be used,
- how the data is stored,
- whether their data will be used anonymously, and
- which organisations are involved with the project.

b) Not be placed at risk through participation in the study.

c) Be able to contact someone else (e.g. the Head of Department) if they have any issues they would like to raise.

d) Be able to withdraw from the study and remove data that has been submitted (where this has not been anonymised).

e) All information should be in plain language that can be easily understood by the participant.

Normally we would expect:

- That you produce an information sheet for participants that provides the above information. If possible you should give this in written form for them to read. If this is not appropriate (e.g. on the telephone) then it should be clearly explained, and you should have a script that you will use.
- That data collected should be held on the university server on your own password protected account.
- That information will be used anonymously. However, bear in mind that if you are interviewing a small group of people then it is difficult to maintain anonymity because someone might be recognizable from the opinion that they give. Hence people should be made aware of this possibility. Under some circumstances it is not appropriate to keep information anonymously, for example because the person involved is providing information as an expert.
- That, when dealing with participants in a workplace, you have been given permission by their management to take part, and that the participants know this.

All students carrying out management science projects should gain approval from the departmental ethics committee using the form attached, and should also include

- a) The information sheet or script that you use to inform participants about the project.
- b) The participant consent form.

Standard formats are available for the information sheet and consent form, but these require you to complete specific information relevant to your project.

Management Science

Ethics & Risk Management Project Approval Form

Student Name: Wisam Ibrahim Mousa

Project Name: Reverse supply chain in Industry 4.0.

Supervisors: Mouhamad Ali Agha

External Organisations Involved:

Start Date: 2021

Expected Finish Date: 2024

Nature of interaction with participants: Questionnaire, Interviews

Questionnaire, Focus Groups, Interviews:

Other (Specify): No

Nature of participants (e.g. service users, office staff): A sample of workers in the field of forward and reverse supply chains

Are there any participants who could be considered vulnerable (e.g. patients, children): No.

What do you consider to be the main ethical issues in this project?

The nature of the questions should be appropriate and not interfere with the company's issues.

Are there any significant risks to the participants (e.g. releasing confidential information)?

There are no risks for the participants.

Are there any significant risks to the University, the student, or staff, from participation in this project?

There are no risks.

Does this project involve the NHS or external funding to the University?

No.

Is any information sought that might be considered personal? If so, explain what the nature of this information is, why it is needed for the project, how it will be stored and will it will be anonymised?

There is no personal or confidential information.

Attach: Participant Information Sheet and Consent Form

Is any information sought that might be (personally or commercially) confidential? If so, explain what the nature of this information is, why it is needed for the project, how it will be stored and how it will be desensitised prior to use in non-confidential settings.

There is no confidential, commercial or personal information, but the nature of the questions is

Signed

Student: Wisam Ibrahim Mousa

Supervisor: Mouhamad Ali Agha

Please return the completed and signed form to mansci-ethics@strath.ac.uk.

OFFICE USE ONLY

Feedback Form DEC

Remit of DEC: Yes ☐ No ☐

Risks not significant and does not involve NHS or External Funding: Yes ☐ No ☐

If yes to both, HoD or nominee can sign off Risk Management Approval

Decision DEC

Ethics Approval : Choose 1

- ☐ Approved
- ☐ More information required for the reasons given below
- ☐ Not Approved, for the reasons given below ;

Reasons:

Risk Management Approval: Choose 1

- ☐ Approved for risk management purposes and the University is the sponsor.
- ☐ Not Approved

Signed:

Convenor of DEC (on behalf of HoD)

**Invitation:**

Thank you for agreeing to participate in this research survey looking at (Reverse Supply Chains in Industry 4.0).

This project aims to explore the role of Industry 4.0 technologies in supporting reverse supply chains in the industry.

However, before agreeing to participate, you must read the following information thoroughly and understand the process in which you will be involved.

Introduction, study objective, and outputs:

I am a Ph.D. researcher at the University Strathclyde of Glasgow Business School and am currently doing research (Reverse Supply Chains in Industry 4.0). In the field of manufacturing, with a particular focus on Industry 4.0 technology in supporting reverse supply chains, as well as exploring activities for reverse supply chains in the field of meeting customer preferences, rational use of raw materials, and manufacturing ethics.

The results of my Ph.D. study may be published and may be contributed to other academic outputs such as papers in relevant conferences and journals.

Search methods:

The research will consist of an online questionnaire and some online interviews. This can be done on any computer or other communication device connected to the Internet. Moreover, the answer needs a short time to complete it.

Aim and layout of the questionnaire:

The aim of the questionnaire is the extent to which Industry 4.0 technology can support reverse supply chains in the field of industry and the mechanisms of integration between them, the purpose is to improve sustainability in manufacturing by meeting customer preferences, rational use of raw materials and standards of manufacturing ethics.

Participant monitoring and withdrawal:

Participation is voluntary. You may withdraw from the survey at any time before final submission without giving any specific reason.

Research ethics:

This research is subject to the University of Strathclyde of Glasgow standards of ethics. The university ethics committee approved this questionnaire. Full details of the ethical review are available by contacting the researcher via the researcher's email address indicated on the form.

Confidentiality of the information:

The questionnaire form will not include mentioning the names of the participants or accurate information indicating the identity of the participants, and the participant's answers were used only for scientific research while maintaining the confidentiality of the information.



Further Information, Problems, and the Complaints Procedure:

If you wish for further information, or complaints or concerns, the principal researcher, Wisam Ibrahim,

Can be contacted by email at: **wisam.alshihmani.2020@uni.strath.ac.uk**

If you do not wish to contact the researcher personally, then you may contact the supervisor for the Ph.D., Dr. Mouhamad Ali Agha, by email: **mouhamad.s.ali-agma@strath.ac.uk**

Project Oversight and Ethical Review:

The University Strathclyde of Glasgow oversees this research. The University's Ethics Committee has approved this research. The full details of the ethical review are available by contacting the researcher.

Thank you for taking the time to read this Participant Information Sheet



Questionnaire

Dear participants

Good greeting...

This questionnaire is part of a PhD thesis at the University of Strathclyde, Business School, Department of Management Sciences titled (Reverse Supply Chains in Industry 4.0).

Please kindly answer the questions in the questionnaire as objectively and accurately as possible, knowing that the information collected is only for scientific research and does not bear any other capacity. Thank you for your cooperation with us.

Researcher: Wisam Ibrahim Musa

Department of Management Sciences

Email: wisam.alshihmani.2020@uni.strath.ac.uk

Strathclyde Business School

University of Strathclyde

199 Cathedral Street

Glasgow,

G4 0QU

Participant information

1- Gender:

Male		Female	

2- Age:

Less than 25 years		25- 35 years		36-45 years		46 years and over	

3- Qualification:

Primary		Preparatory		Bachelor's		Master's / Ph.D.	

4- Scope of works:

Forward supply chains		Reverse supply chain	

The first variable Industry 4.0						
No.	Items	Strongly Disagree	not agree	neutral	Agree	Strongly Agree
Cyber-physical systems (CPS)						
1	The company adopt (CPS) technology in manufacturing.					
2	Play Cyber-physical systems have a role in manufacturing operations.					
3	Cyber-physical systems link the physical world to the virtual optimally.					
4	Cyber-physical systems have benefits in process improvement					
Internet of Things (IoT)						
5	The company adopt Internet of Things technology in its operations.					
6	The Internet of Things plays a role in supporting manufacturing operations.					
7	The Internet of Things achieved the optimal link between the supplier, the producer, and the customers.					
8	The Internet of Things brings economic and social benefits.					
Cloud						
9	The company adopts cloud technology in its operations.					
10	The cloud allows for optimal storage and sharing of information.					
11	The cloud saves time and costs in sharing information.					
12	The cloud has a role in manufacturing operations.					
Big data						
13	The company relies on big data to save its information.					
14	Big data helps companies understand market requirements and needs.					
15	Big data a competitive advantage for companies?					
16	Big data have a role in manufacturing operations.					
Smart factory						
17	The company uses the smart factory in its manufacturing processes.					
18	The smart factory provides a competitive advantage for companies.					
19	The smart factory supports sustainable manufacturing.					

20	Smart factories have a role in production flexibility.					
The second variable reverse supply chains (RSC)						
customer preferences						
21	The company takes care of reverse logistics.					
22	The company cares a series to meet the preferences of the customer.					
23	Reverse supply chains provide sufficient information about customer preferences.					
24	The company is constantly developing reverse supply chain activities.					
Rational use of raw materials						
25	The company is interested in the rational use of raw materials.					
26	The rational use of raw materials is an activity of the reverse supply chains.					
27	The rational use of raw materials reduces costs and preserves the environment and the sustainability of manufacturing.					
28	Modern technology has contributed to the rational use of raw materials.					
Manufacturing ethics						
29	The company is committed to the standards of manufacturing ethics.					
30	Manufacturing ethics add a competitive advantage to the company.					
31	Customers care greatly about manufacturing ethics when purchasing goods and services.					
32	Manufacturing ethics contribute to sustainability.					
The mediating variable of customer feedback						
33	Customer feedback helps in manufacturing decisions.					
34	Customer feedback is a link between the product and the consumer.					
35	Customer feedback is a reverse supply chain activity.					
36	Customer feedback is of interest to the company.					
The mediating variable Recycling						
37	The company is interested in recovering obsolete materials and recycling operations.					

38	Recycling operations have increased due to modern industrial technology.					
39	Recycling is a core activity of reverse supply chains.					
40	Recycling brings economic, social and environmental benefits.					

Appendix No. 2: Electronic questionnaire.

Revers supply chain in Industry 4.0

Start of Block: Participant information

[Participant information and consent.pdf](#) Please find attached regarding questionnaire information.

I Gender

- ☐ Male (1)
 - ☐ Female (2)
-

II Age

- ☐ Less than 25 years (1)
 - ☐ 25- 35 years (2)
 - ☐ 36-45 years (3)
 - ☐ 46 years and over (4)
-

III Qualification:

- ☐ Primary (1)
 - ☐ Preparatory (2)
 - ☐ Bachelor's (3)
 - ☐ Master's / Ph.D. (4)
-

IV Scope of works:

- ☐ Reverse supply chain (1)
- ☐ Forward supply chains (2)
-

V Do you work in the field industry 4.0 or reverse supply chain.

- ☐ Yes (9)
- ☐ No (10)
-

VI Do you have expertise in Industry 4.0 technology (cyber-physical systems, Internet of things, big data, cloud, smart factories) and reverse supply chains?

- ☐ Yes (1)
- ☐ No (2)
-

VII Company Name:

Page Break

Now, you can move on to answering the survey questions.

End of Block: Participant information

Start of Block: The first variable, Industry 4.0 / Cyber-physical systems (CPS)

1 The company adopts Cyber-physical systems technology in manufacturing.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

2 Play Cyber-physical systems have a role in manufacturing operations.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

3 Cyber-physical systems link the physical world to the virtual optimally.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

4 Cyber-physical systems have benefits in process improvement.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The first variable, Industry 4.0 / Cyber-physical systems (CPS)

Start of Block: The first variable, Industry 4.0 / Internet of Things (IoT)

5 The company has adopted the Internet of Things technology in its operations.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

6 The Internet of Things plays a role in supporting manufacturing operations.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

7 The Internet of Things achieved the optimal link between the supplier, the producer, and the customers.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

8 The Internet of Things brings economic and social benefits.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The first variable, Industry 4.0 / Internet of Things (IoT)

Start of Block: The first variable, Industry 4.0 / Cloud

9 The company adopts cloud technology in its operations.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

10 The cloud allows for optimal storage and sharing of information.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

11 The cloud saves time and costs in sharing information.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

12 The cloud has a role in manufacturing operations.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The first variable, Industry 4.0 / Cloud

Start of Block: The first variable, Industry 4.0 / Big data

13 The company relies on big data to save its information.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

14 Big data helps companies understand market requirements and needs.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

15 Is big data a competitive advantage for companies?

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

16 Big data have a role in manufacturing operations.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The first variable, Industry 4.0 / Big data

Start of Block: The first variable, Industry 4.0 / Smart factory

17 The company uses the smart factory in its manufacturing processes.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

18 The smart factory provides a competitive advantage for companies.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

19 The smart factory supports sustainable manufacturing.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

20 Smart factories have a role in production flexibility.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The first variable, Industry 4.0 / Smart factory

Start of Block: The second variable, reverse supply chains (RSC) / customer preferences

21 The company takes care of reverse logistics.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

22 The company care about meeting the preferences of the customer.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

23 Reverse supply chains provide sufficient information about customer preferences.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

24 The company is constantly developing reverse supply chain activities.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The second variable, reverse supply chains (RSC) / customer preferences

Start of Block: The second variable, reverse supply chains (RSC) / Rational use of raw materials

25 The company is interested in the rational use of raw materials.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

26 The rational use of raw materials is an activity of the reverse supply chains.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

27 The rational use of raw materials reduces costs and preserves the environment and the sustainability of manufacturing.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

28 Modern technology has contributed to the rational use of raw materials.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The second variable, reverse supply chains (RSC) / Rational use of raw materials

Start of Block: The second variable, reverse supply chains (RSC) / Manufacturing ethics

29 The company is committed to the standards of manufacturing ethics.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

30 Manufacturing ethics add a competitive advantage to the company.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

31 Customers care greatly about manufacturing ethics when purchasing goods and services.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

32 Manufacturing ethics contribute to sustainability.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The second variable, reverse supply chains (RSC) / Manufacturing ethics

Start of Block: The mediating variable of customer feedback

33 Customer feedback helps in manufacturing decisions.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

34 Customer feedback is a link between the product and the consumer.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

35 Customer feedback is a reverse supply chain activity.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

36 Customer feedback is of interest to the company.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The mediating variable of customer feedback

Start of Block: The mediating variable Recycling

37 The company is interested in recovering obsolete materials and recycling operations.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

38 Recycling operations have increased due to modern industrial technology

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

39 Recycling is a core activity of reverse supply chains.

- ☐ Strongly disagree (1)
 - ☐ Somewhat disagree (2)
 - ☐ Neither agree nor disagree (3)
 - ☐ Somewhat agree (4)
 - ☐ Strongly agree (5)
-

40 Recycling brings economic, social and environmental benefits.

- ☐ Strongly disagree (1)
- ☐ Somewhat disagree (2)
- ☐ Neither agree nor disagree (3)
- ☐ Somewhat agree (4)
- ☐ Strongly agree (5)

End of Block: The mediating variable Recycling

**Appendix No. 3: Link to search database, according to software SPSS V26,
linked to Amos V24.**

<https://1drv.ms/u/c/2baabb10b815392e/IQCZL7nvDr0pQaO46CZMc5ZJAb2TXa4TQorhZJcmpDsyGU8?e=O5Yp2A>

Appendix No. 4: Provides detailed information on the measurement indicators.

Indicators that the questionnaire questions aim to diagnose:

1. Independent Variable: I4.0

The objective is to assess the extent of adoption of I4.0 technologies and their role in manufacturing operations.

CPS (X11–X14): Measures the extent of a company's adoption of CPS technologies, their role in operations, their effectiveness in connecting physical and virtual systems, and their contribution to process improvement.

The CPS dimension is represented by four questions on a five-point Likert scale, each of which is considered important for accurately describing the dimension. The first indicator diagnoses adoption, reflecting its actual use in operations. The second indicator addresses effectiveness, assessing whether it is optimally utilised in the company's operations. The third indicator assesses its contribution to process improvement, which reinforces the dimension's tangible results in efficiency and responsiveness. The fourth indicator relates to strategic value, focusing not only on CPS as an operational tool, but also as a recognised driver of strategic mechanisms for linking and integrating operations.

These indicators were chosen to represent the dimension, ensuring logical consistency and conceptual completeness. Together, they enable the dimension to be measured as both a technological application and a transformative capability.

Representing the dimension with four carefully selected questions is appropriate for methodological purposes, as it ensures content validity and the possibility of measuring the measurement tool's consistency and reliability.

IoT (X21–X24): Assesses the adoption of IoT, its role in operations, its ability to connect front-end and back-end actors, and its economic and social benefits.

The IoT dimension was measured using four questions to identify its key aspects: adoption represents the use of the technology in the operational and organisational practices of the surveyed companies; connectivity effectiveness assesses the extent to which this technology is invested in real-time integration between systems; and economic and social benefits expand the scope of the assessment beyond technical performance to tangible outcomes. This indicator is based on the literature, as IoT not only reduces costs and enhances efficiency (economic benefit) but also improves meeting customer expectations and promotes ethical manufacturing practices through transparent traceability, which is

reflected in enhanced sustainability (social benefit). Thus, this indicator reflects organisational value and broader societal impact. Our selection of this dimension underscores its importance not only as a technological enabler but also as a driver of sustainable manufacturing and social responsibility.

Cloud (X31–X34): Assesses the use of cloud computing technology, the efficiency of storing/sharing information, time and cost savings, and its role in operations.

Key indicators for cloud computing highlight its organisational importance. Its role in operations reflects its ongoing contribution to operational integration. Data storage and sharing ensure accessibility and scalability, while its role in manufacturing focuses on flexibility, scalability, and efficiency. This represents the cloud not just as an infrastructure but also as a strategic enabler of digital transformation.

Big Data (X41–X44): Measures the adoption of big data, its role in understanding customer requirements, competitive advantage, and its contribution to operations.

The four indicators of this dimension are crucial because they fully capture the organisational significance of this dimension. Adoption demonstrates the technological integration between the five technologies of (I4.0), effectiveness is achieved through optimal investment in this technology, and the contribution indicator reflects the tangible added value of this technology in improving operations and decision-making. Big data is also an important intangible strategic resource for companies, enhancing their competitive advantage. These indicators ensure that the dimension is optimally expressed as a technical capability and a driver of organisational advantage.

Smart Factory (X51–X54): Measures a company's adoption of smart factories, its competitive advantages, and its support for sustainability and production flexibility.

Objective: To monitor the integration of I4.0 technologies into company operations and their expected benefits.

Smart factory measurement indicators indicate that adoption establishes a company's use of integrated smart factory technologies. Competitive advantage represents its role as a source of distinction and position in the market. Its contribution to sustainability represents a cycle of waste reduction and improved resource utilisation. Flexibility embodies the ability to adapt and respond quickly to customer requirements. These indicators provide a comprehensive definition of the smart factory as both a technological and strategic framework.

2. Dependent Variable: RSCs

The objective is to assess how RSCs perform in terms of sustainability, efficiency, and alignment with customer needs.

Customer Preferences (Y 11-14): To measure the extent to which reverse logistics and reverse supply chains respond to customer needs and evolve.

The indicators capture this dimension comprehensively. Logistics focus indicates the company's adoption and operational engagement with these activities. Customer engagement measures customer preferences, which reflect the company's ability to respond quickly to these preferences. The availability of customer information reflects transparency and the integrity of feedback. Continuous improvement reflects the company's commitment to adapting to its internal and external environments. Together, these indicators validate this dimension as a practical and strategic concept, enabling us to explore how I4.0 technology affects customer preferences as a RSCs activity.

Rational Use of Raw Materials (Y 21-24): To assess how reverse supply chains contribute to resource efficiency, cost reduction, environmental conservation, and sustainability.

The core indicators of this dimension embody multiple, complementary perspectives. The efficiency index indicates a company's commitment to resource efficiency, and the inclusion of RSCs activities reflects rationalisation and resource efficiency practices. It assesses the impact on cost reduction, manufacturing sustainability, and tangible environmental practices. The contribution links the role of I4.0 technology in improving resource utilisation. Together, these indicators operationalise the rational use of raw materials as a strategic and operational concept oriented toward sustainability, enabling the evaluation of theoretical insights into empirical findings on how technology can contribute to promoting responsible and sustainable manufacturing.

Manufacturing Ethics (Y 31-34): To monitor adherence to ethical standards, the competitive advantage of ethics, customer sensitivity to ethics, and their role in sustainability.

Objective: To identify the role of RSCs in customer preferences, rational use of raw materials, and manufacturing ethics.

The key indicators for this dimension cover a comprehensive representation: organisational commitment assesses a company's commitment to ethical manufacturing standards, competitive advantage reflects the strategic value of this dimension, customer concern assesses the importance customers place on manufacturers, and contribution demonstrates the importance of the dimension in promoting long-term sustainability and environmental and social practices. Together, these indicators operationalise manufacturing ethics as a multifaceted concept, integrating operational, strategic, and

societal perspectives, enabling us to measure how I4.0 technologies affect ethical practices and connect them to RSCs activities.

The survey indicators play a pivotal role in advancing sustainability-oriented innovation (SOI) theory by translating its abstract focus on economic, environmental, and social integration into measurable practice. For I4.0, indicators such as adoption, effectiveness, and strategic value position digital technologies as catalysts of sustainability, demonstrating that innovation becomes sustainability-oriented when its impact on efficiency, responsiveness, and competitiveness is explicitly assessed. For RSCs, indicators like customer engagement, rational material use, and ethical practices embed sustainability within organisational processes, demonstrating that SOI emerges from the interaction between technological capabilities and responsible operational practices. Thus, the indicators not only operationalise SOI but also expand it, making the link between innovation and sustainability empirically observable and theoretically more robust.

3. Mediating Variable: Customer Feedback (Z11-Z14)

The objective is to measure the role of customer feedback as a link between consumers and manufacturing.

Indicators include the role of feedback in decision-making, the link between producer and consumer, its integration into RSCs, and the extent of the company's interest in it.

Objective: To test whether customer feedback enhances the relationship between I4.0 adoption and efficient RSCs.

The indicators cover this dimension optimally, as the impact of manufacturing decisions is measured by their operational implications. Based on the development of resource orchestration theory ROT, the use of the company's available resources, represented by customer feedback, was activated. A research model was developed to understand the intermediary mechanisms that enhance the dynamic interaction between the research variables, utilising a sustainability-oriented consumer SOC approach to demonstrate the potential impact of customer feedback on supporting sustainable manufacturing practices. The link between the producer and the consumer also reflects the informational and relational importance. The integration of I4.0 and RSCs activities enables the integration of customer feedback into organisational strategies, and the importance assessment reflects the company's vision in setting strategic priorities. Together, these indicators activate customer feedback as an intermediary construct, enhanced by I4.0 technologies, to promote responsible and sustainable manufacturing practices.

4. Mediating Variable: Recycling (W11-W14)

The objective is to measure recycling as a key sustainability activity in RSCs.

Indicators include the company's interest in recycling, technological advances in recycling, its central importance in RSCs, and its economic, social, and environmental benefits.

Objective: To test whether recycling enhances the relationship between I4.0 adoption and RSCs sustainability outcomes.

The key indicators for this dimension reflect its comprehensive representation, as recovery of old materials and recycling directly measure their operational and strategic impact. Based on the development of resource orchestration theory ROT, recycling is an organisational strategy through which I4.0 technology enhances resource utilisation and process efficiency. The model interacts dynamically, enhanced by advanced technology, facilitating integrations between model constructs to measure the potential impacts of these constructs in promoting sustainable practices. By integrating recycling into RSCs activities, the model demonstrates how technology adoption enables sustainable manufacturing practices that generate economic, social, and environmental value. Evaluating recycling in terms of these multidimensional benefits reflects a company's strategic commitment to sustainability, highlighting the role of advanced technologies in enabling responsible and resource-efficient production. Together, these indicators embody recycling as a technology-based intermediary mechanism linking I4.0 and sustainable manufacturing outcomes.

The key indicators of the survey questions aim to examine how the adoption of I4.0 technologies directly affects the contemporary vision of RSCs activities, and to demonstrate its indirect effect through the presence of intermediary mechanisms such as customer feedback and recycling.

In short, these survey questions aim to transform abstract variables (I4.0, Contemporary vision of RSCs activities, customer feedback, and recycling) into measurable indicators, allowing the researcher to test statistically the relationships among them.

The survey's structural indicators contribute to the development of IOS and ROT. By integrating technology, enhanced with content that characterises efficiency and contribution, sustainability-oriented innovation emerges and is empirically tested, which is developing IOS. The indicators also expand measures related to customer perceptions and recycling practices from items that document technological adaptation and organisational strategy into a research model that considers the dynamic interactions between its components, systematically integrating sustainability, thus supporting ROT across the product lifecycle.

Appendix 5: Table of Interview participant profiles.

Participants	Scope of work	Participants profile
Manager	Forward supply chain (I4.0)	Production and Operations Manager.
Manager	Forward supply chain (I4.0)	Quality Department Manager.
Logistics support	Reverse supply chain	Reverse Logistics Support Officer.
Supervisor	Forward supply chain (I4.0)	Operations Officer.
Manager	Forward supply chain (I4.0)	Production department manager in one of the company's factories.
Logistics support	Reverse supply chain	After-sales service department manager.
Research and Development (R&D)	Forward supply chain (I4.0)	Engineer in the R&D Department.
Quality Assurance (QA) and Quality Control (QC)	Forward supply chain (I4.0)	Senior Engineer in Quality and Quality Control Department.
Reverse logistics	Reverse supply chain	Post-Market Surveillance and Feedback Collection.
Maintenance and Calibration	Reverse supply chain	Maintenance and Calibration Department Manager

Appendix 6: Scope and the interview questions.

Participants	Scope of work	Participants profile
Manager	Forward supply chain (I4.0)	Production and Operations Manager.
Manager	Forward supply chain (I4.0)	Quality Department Manager.
Logistics support	Reverse supply chain	Reverse Logistics Support Officer.
Supervisor	Forward supply chain (I4.0)	Operations Officer.
Manager	Forward supply chain (I4.0)	Production department manager in one of the company's factories.
Logistics support	Reverse supply chain	After-sales service department manager.
Research and Development (R&D)	Forward supply chain (I4.0)	Engineer in the R&D Department.
Quality Assurance (QA) and Quality Control (QC)	Forward supply chain (I4.0)	Senior Engineer in Quality and Quality Control Department.
Reverse logistics	Reverse supply chain	Post-Market Surveillance and Feedback Collection.
Maintenance and Calibration	Reverse supply chain	Maintenance and Calibration Department Manager

Appendix 7: Thematic Coding of Research Axes.

Selective Theme	Second-Order Categories	First-Order Codes	Illustrative Interview Evidence
Integration of I4.0 Technologies into Sustainable Practices of RSCs activities	Strategic Purpose of Integration	Sustainability enhancement, Support for circular economy, Resource efficiency	“Integrating I4.0 technologies enhances manufacturing sustainability and contributes to a more circular economy”.
	Digitalisation of Reverse Operations	Automation of RSCs processes, Real-time tracking, Data-driven decision-making	“Technology allows us to track returned products in real time and manage reverse flows more effectively”.
	Operational Improvements	Reduced processing time, Improved accuracy, enhanced productivity	“Automation significantly reduces time and eliminates many errors that used to occur in manual operations”.
Emerging technology of Enhanced RSCs Practices	CPS	Integration of physical and digital systems, Autonomous process control	“CPS supports and enhances RSCs activities through smarter and more autonomous operations”.
	IoT	Connectivity, Traceability, Remote monitoring	“The IoT connects manufacturers, suppliers, and customers, which strengthens the quality and efficiency of the reverse chain”.
	Big Data	Competitive advantage, Performance improvement, predictive analytics	“Using big data helps us enhance our competitive advantage and forecast returns more accurately”.
	Cloud computing	Digital storage, accessibility, real-time RSCs decision support	“Cloud-based data storage, Digital accessibility of RSCs information, Real-time decision support for returns management”.
	Smart factory	Customised component production, Material efficiency	“Manufacturing flexibility, enhancing recycling operations, integrating customer-driven customisation, and Real-time monitoring of reverse flows”.
Sustainable Practices of RSCs activities in the Context of I4.0	Customer preferences	Feedback-driven production, demand responsiveness	“I4.0 helps us reduce raw material use and operate more ethically in line with sustainability principles”.
	Rational raw material use	Waste reduction, resource optimization	“Modern technologies enable more effective recycling processes and better waste management”.
	Manufacturing ethics	Transparency, ethical production monitoring	“These technologies allow us to be transparent, which promotes ethical manufacturing”.

Mediating Mechanisms Linking I4.0 and RSCs	Customer Feedback as a Mediating Variable	Data-driven improvement, Direct communication, Enhanced transparency	“Customer feedback provides us with sufficient information to integrate RSCs with Industry 4.0 applications.”
	Recycling as a Mediating Variable	Support for closed-loop systems- Material recovery, Ethical operations	“I4.0-based recycling processes contribute to efficiency and provide more ethical processing”.