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Smart Technologies in Reverse Logistics: A Simulation-Based Performance Analysis

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Abstract:

The growing integration of smart technologies is gradually transforming the supply chain by enhancing its efficiency, visibility and the quality of decision-making. Consequently, if implemented in reverse logistics – which involves managing returned, reused or recycled products – these technological solutions could significantly reduce the challenges associated with coordination, costs and sustainability, thereby improving efficiency. However, prior literature has largely examined these two concepts separately, leaving a significant research gap. With the aim of examining the effectiveness and potential impacts of integrating these technologies, this study uses a simulation model applied to the Moroccan automotive industry to compare different configurations of the reverse supply chain. The analysis begins with a conventional logistics chain operating without smart technologies, then compares this baseline with two smart configurations: one integrating AI-powered sorting (Scenario 2) and another deploying additive manufacturing (Scenario 3). The simulation results reveal performance variations ranging from -31.26% to +21.13%, illustrating the impact of these technologies on profitability, processing times, and environmental sustainability. Comparing the various integration strategies enables us to identify the most effective configurations for utilising smart technologies in the field of reverse logistics. These findings highlight the potential benefits of these innovations and offer food for thought for companies wishing to strengthen their sustainability initiatives whilst improving their operational performance. This study helps to expand the ever-evolving body of knowledge on the digital transformation of supply chain management and supports the development of data-driven strategies to promote circular economy initiatives.

Keywords: Reverse logistics, Industry 4.0, Simulation, system modeling, Moroccan automotive industry.
JEL Classification: L2, L25, O33, Q53.
Paper type: Empirical Research

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1. Introduction

In these last years, the Moroccan automotive industry has become a key driver of economic growth with major global manufacturers such as Renault, Stellantis, and numerous suppliers establishing more and more operations in Morocco. The sector has experienced significant expansion due also to the logistic hub and the proximity to the European market. However, the more vehicle production increases, so does the return thus increasing the challenge of managing reverse logistics-the process of handling returns, recycling parts, and ensuring the proper disposal or refurbishment of automotive components.
The main challenge faced in the reverse logistics is the uncontrollable and unpredictable nature of returned products hence the difficulty of having a precise forecast system in order to plan the return logistics. Also, when collecting the returned products, we have different options on how to integrate the returns into the production process.
RL adoption can help minimise the adverse environmental impacts through recycling and reusing end-of-life products. Other than that, it can have immense economic and social benefits as well (Shahparvari et al., 2021). To address these operational complexities within the specific regional framework, researchers and practitioners are increasingly turning to advanced technological solutions.
It has become common knowledge that the arising digital technologies could improve the efficiency of the operations of supply chains (SCs) worldwide (Govindan et al., 2018; Dubey et al., 2019). Both academia and practitioners have widely reported the potential benefits of the integration of digital technologies and SC management (Kamble et al., 2020). Implementing these novel technologies can help SCs to perform more efficiently (Chiappetta Jabbour et al., 2020). The operations and SC management could be restructured through Industry 4.0 (I4.0), named after the 4th industrial revolution. The name refers to the prevailing trend of exchange of data and automation in manufacturing technologies, like the Internet of Things (IoT), cyber-physical systems, and cloud computing, which could lead to forming smart factories (Govindan et al., 2018; Koot et al., 2021).
Industry 4.0 can offer insightful directions to promote the circular economy and RL (Dantas et al., 2021). The technologies have the potential to be used in different operations of the RL, like disassembly, recycling, recovery, and remanufacturing (Chiappetta Jabbour et al., 2020). I4.0 initiatives such as sensor-based infrastructure and big data can further boost efficiencies of product tracking, demand forecasting, and responsiveness of the RL (Manavalan & Jayakrishna, 2019). Hence, there could be good opportunities for companies looking for a higher sustainable profile through the adaption of I4.0 technologies in their RL system.
Using anonymised historical data from an automotive company in Morocco, this study evaluates the integration of smart technologies in reverse logistics. To answer a central question: How do different configurations (AI-powered sorting and additive manufacturing) affect key performance indicators (recovered value, cost, time and net gain) compared to a classical baseline?
Unlike prior conceptual works (Dubey et al., 2019; Govindan et al., 2018; Kamble et al., 2020), our simulation provides a data driven comparison of technological scenarios, offering unique empirical insights within the Moroccan automotive sector.
This paper is organised as follows. First, our literature review is presented in two sections. The first one presents the various studies treating reverse logistics. And the second one presents a detailed literature review of reverse logistics in industry. Then, we highlight our methodological approach to modeling and simulation of the different scenarios of reverse logistics implementations. In order to study the impact of new technologies on reverse logistics, we test different scenarios using our case study and then discuss the obtained results. We then conclude this article with a general conclusion and an outline of future research directions.

2. Literature review:

2.1. Definition and importance of reverse logistics:

The term “reverse logistics” is widely used in specialist literature to refer to the management of returns and the handling of recovered products. This term reflects the idea that logistics activities are carried out in the opposite direction compared to the regular supply chain operations. Given the growing interest in reverse logistics over the past decade, it is not surprising that the terminology surrounding it remains varied and somewhat inconsistent. In academic literature, reverse logistics is often examined within specific contexts. It may focus on activities such as product disassembly in electronic commerce or be studied through case analyses of particular types of returns. For instance, Thierry et al. (1995) refer to reverse logistics as Product Recovery Management (PRM), defining it as:
“The management of component products and materials-whether used or discarded-is the responsibility of the manufacturing company. The aim is to maximise the economic and environmental value of the products whilst minimising the amount of waste generated”. Similarly, Beaulieu et al. (1999) and Beaulieu (2000) describe reverse logistics as:
"A set of management activities aimed at reintegrating non-core assets into sectors with added value."
More recently, reverse logistics has been closely associated with the concept of the Closed-Loop Supply Chain (CLSC) (Ramezani et al., 2014; Govindan et al., 2015), which focuses on managing the recycling and recovery of end-of-life products (Guide & Van Wassenhove, 2009; Das & Posinasetti, 2015). A CLSC generally involves manufacturers overseeing the reverse logistics process, either by directly recovering returned goods or through intermediary channels (Ashayeri et al., 2015). These returned goods are then resold in primary or secondary markets after appropriate processing (Turrisi et al., 2013). A CLSC essentially broadens the traditional forward supply chain framework by incorporating reverse logistics activities such as product returns, recycling, recovery, reconditioning and reintroduction of products onto the market (He, 2015). Over the past decade, CLSC has emerged as a major focus in supply chain management literature, with increasing attention devoted to optimising, understanding and improving this structure (Adenso-diaz et al., 2012; He, 2015).
Post-2020 literature has expanded this concept, framing reverse logistics as a dynamic, data-driven system within smart circular supply chains where digital tracking enables real-time predictive recovery (Shahparvari et al., 2021).
In recent years, the integration of advanced technologies has significantly transformed reverse logistics and closed-loop supply chains (CLSCs). Artificial intelligence (AI) and machine learning (ML) are now employed to analyse return patterns, enabling businesses to predict and manage returns more effectively. Automation has expedited the sorting and processing of returned items, reducing errors and enhancing efficiency. The Internet of Things (IoT) facilitates real-time tracking of returned products, providing greater visibility and control over the reverse logistics process. Additionally, blockchain technology ensures secure and transparent transactions, fostering trust among stakeholders. Augmented reality (AR) is also being utilised to improve warehouse operations by providing real-time information to workers, thereby increasing productivity and accuracy. These technological advancements not only streamline operations but also contribute to sustainability efforts by promoting recycling and reducing waste.
While many Industry 4.0 technologies offer theoretical benefits, this study focuses specifically on AI-powered sorting and additive manufacturing, as they address two critical challenges in the sector: sorting efficiency and adaptable refurbishment.

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2.2. Smart Technologies in Reverse Logistics

Previous studies have focused on the underlying design principles of Industry 4.0 to achieve a circular economy (CE) by increasing production capability and improving product quality at an optimal cost (Abdul-Hamid et al., 2020). Lieder and Rashid (2016) emphasised the advantages of CE, including reduced environmental deterioration and increased social, economic, and sustainability benefits by incorporating the three Rs-reduce, reuse, and recycle-into the supply chain.

However, prior studies have also argued that CE has struggled to integrate with technological advancements necessary to effectively implement the 3Rs for sustainable production and consumption. For instance, Heyes et al. (2018) and Kinnunen and Kaksonen (2019) highlighted that technological advancements in CE remain relatively low, limiting the ability to recover resources and energy efficiently. On the other hand, Gigli et al. (2019) contended that, in the era of IoT advancements, leveraging technological capabilities can generate economic benefits for manufacturing firms while enhancing supply chain sustainability.

This debate highlights a key tension: while some regard Industry 4.0 as a driver of circularity (de Sousa Jabbour et al., 2018; Gigli et al., 2019), others highlight barriers such as high costs and limited technological readiness (Heyes et al., 2018). Our simulation addresses this by quantitatively weighing these benefits against operational costs.

This study is crucial in bridging these gaps, as Industry 4.0 could facilitate the implementation of the 3Rs in manufacturing processes. According to de Sousa Jabbour et al. (2018), advanced manufacturing technologies have the potential to enhance circularity within the supply chain. Disruptive technologies based on Industry 4.0 principles have now addressed many CE challenges, offering real-time information, tracking resource flow, monitoring parts/components, and improving performance. However, the connection between Industry 4.0 and CE remains only partially explored, as manufacturing industries are often reluctant to adopt Industry 4.0 due to high costs, lack of information, and a shortage of ubiquitous technologies for cleaner production (Su et al., 2013).

Industry 4.0 has the potential to pave the way for CE by tracking products post-consumption to facilitate remanufacturing and refurbishment. Since the technological benefits of Industry 4.0 remain underexplored, this has been identified as a significant research gap. Nevertheless, manufacturing industries are increasingly adopting advanced technologies that enable human-machine interaction on the shop floor and facilitate seamless communication between the cyber and physical worlds. Horváth and Szabó (2019) examined key elements of Industry 4.0 and CE to develop business models that focus on remanufacturing and recycling waste products. Similarly, Wang et al. (2017) demonstrated that reused products can function as new ones, with customer purchasing behavior remaining unchanged even without green incentives. Their study further indicated that remanufactured components serve as effective substitutes for newly manufactured products.

Although some researchers have analysed the relationship between reverse logistics (RL) and Industry 4.0, these two concepts have largely been studied separately from different perspectives. An integrated CE-RL network within Industry 4.0 could serve as a decision-making platform for enhancing resource circularity in supply chains. Additionally, it would create value from discarded products and waste through remanufacturing and refurbishment processes. Thus, product returns play a crucial role in enabling manufacturing industries to design and maintain sustainable operations. Table 1 summarises prior works on smart reverse logistics and highlights this study's contribution.

Table 1. Comparative summary of prior works on smart reverse logistics

Authors	Focus / Technologies	Methodology	Key Findings / Limitations
de Sousa Jabbour et al. (2018)	Industry 4.0 & Circular Economy	Literature Review	Identified key success factors; lacked quantitative validation.
Horyáth & Szabó (2019)	Industry 4.0 & CE Business Models	Qualitative Analysis	Examined barriers; noted high cost and complexity as major hurdles.
Wang et al. (2017)	Remanufactured Components	Analytical Modeling	Shown substitution effects; did not simulate operational SC flows.
This Study (2026)	AI-Sorting & Additive Manufacturing	Arena Simulation	Quantifies operational trade-offs (time, cost, value, net gain) using real case data.

Source: Author's elaboration

2.3. Conceptual framework and research propositions:

To summarise the expected relationships between the selected Industry 4.0 and the reverse logistics performance indicators, we propose the following conceptual mapping:

Figure 1: Conceptual framework of smart reverse logistics

- **AI-powered sorting** ⟶ Direct impact ⟶ **Reduce processing time and Logistic cost** (Operational efficiency)
- **Additive manufacturing** ⟶ Direct impact ⟶ **Increases Recovred Value and Net gain** (Value maximisation)

Source: Author's elaboration

Based on this conceptual framework we formulate two research propositions to be tested quantitatively through our simulation model:

- Proposition 1 (P1): AI-powered sorting reduces reverse logistics processing cost and time, despite potential value losses due to misclassification.
- Proposition 2 (P2): Additive manufacturing increases recovered value, despite higher processing times and operational costs.

3. Methods

Our objective in this study is to measure the effectiveness of integrating new technologies in reverse logistics in order to facilitate the reintegration of returned products into the production process. The main challenges that we face in reverse logistics in comparison to the standard supply chain are:

Table 2. Differences between traditional logistics and reverse logistics

Aspects	Traditional Logistics	Reverse logistics
Prediction	Relatively simple	More difficult
Product volume/Flow	One to many	Many to one
Destination/ route	Uniform	Non uniform
Options available	Uniform	Non uniform
Price	Defined	Indefinite
Importance of speed	Clear	Undefined
Layout	Relatively uniform	Depending on several factors
Distribution cost	Recognised	Not considered a priority
Inventory management	Easily identifiable	Less readily identifiable
Life cycle of product	Consistency	Inconsistency
Negotiation	Easy to manage	More complex to manage
Marketing methods	Directly between the parties	Complicated
Visibility of the process	Although known	Complicated by several factors
packaging state	More transparent	Less transparent

Source: Adapted from the Reverse Logistics Executive Council (RLEC) (Rogers & Tibben-Lembke, 1999).

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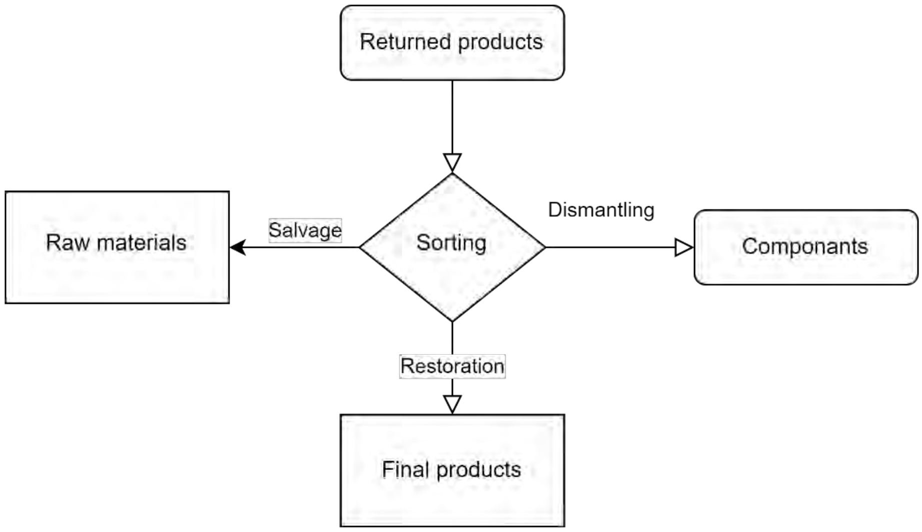
In order to face those challenges, we see new technologies as a way to automate the integration of reverse logistics with minimal perturbations on the supply chain. In order to measure the effectiveness of this integration, we propose the use of simulation of different scenarios to evaluate the impact of new technologies in reverse logistics and on the global process.
Arena Rockwell simulation software was chosen over alternatives like AnyLogic or FlexSim due to its superior efficiency in modeling discrete-event stochastic systems, and its built-in templates for modeling detailed queuing networks and resource constraints in reverse logistics.
The studied industry is characterised as follows:

- Industry comprises producing a product from different components.
- The production of the product is continuous unless the stock is loaded.
- Supply of raw materials occurs if the stock level falls to 10% of maximum stock.

In reverse logistics, the enterprise collects returned products from clients and sorts them based on the necessary treatments to maximise their value:

- Different levels of repair and refurbishment to restore the product.
- Dismantling the product to collect components.
- Salvage to collect raw materials.
- Disposing of the product.

Figure 2. Returned products treatment



Source: Prepared by the authors

Simulation input use 12 months of anonymised automotive partner data (2024-2025). Stochastic return arrivals follow a Poisson process (beta=2.4 hours), validated against historical logs with deviations under 4.2%. Robustness is ensured via 150 Monte Carlo replications per scenario (95% confidence level, error < 2.5%).
In order to study the impact of smart technologies on reverse logistics, we propose different scenarios for the same company in the automotive sector:

- ✓ scenario 1: Classic reverse logistics;
- ✓ Scenario 2: Reverse logistics with AI-powered image recognition to classify returned items on their way to the company;
- ✓ Scenario 3: Reverse logistics with additive manufacturing (3D printing).

The objective is to compare the results obtained from these scenarios and study the impact of each smart technology on the reverse chain logistics.

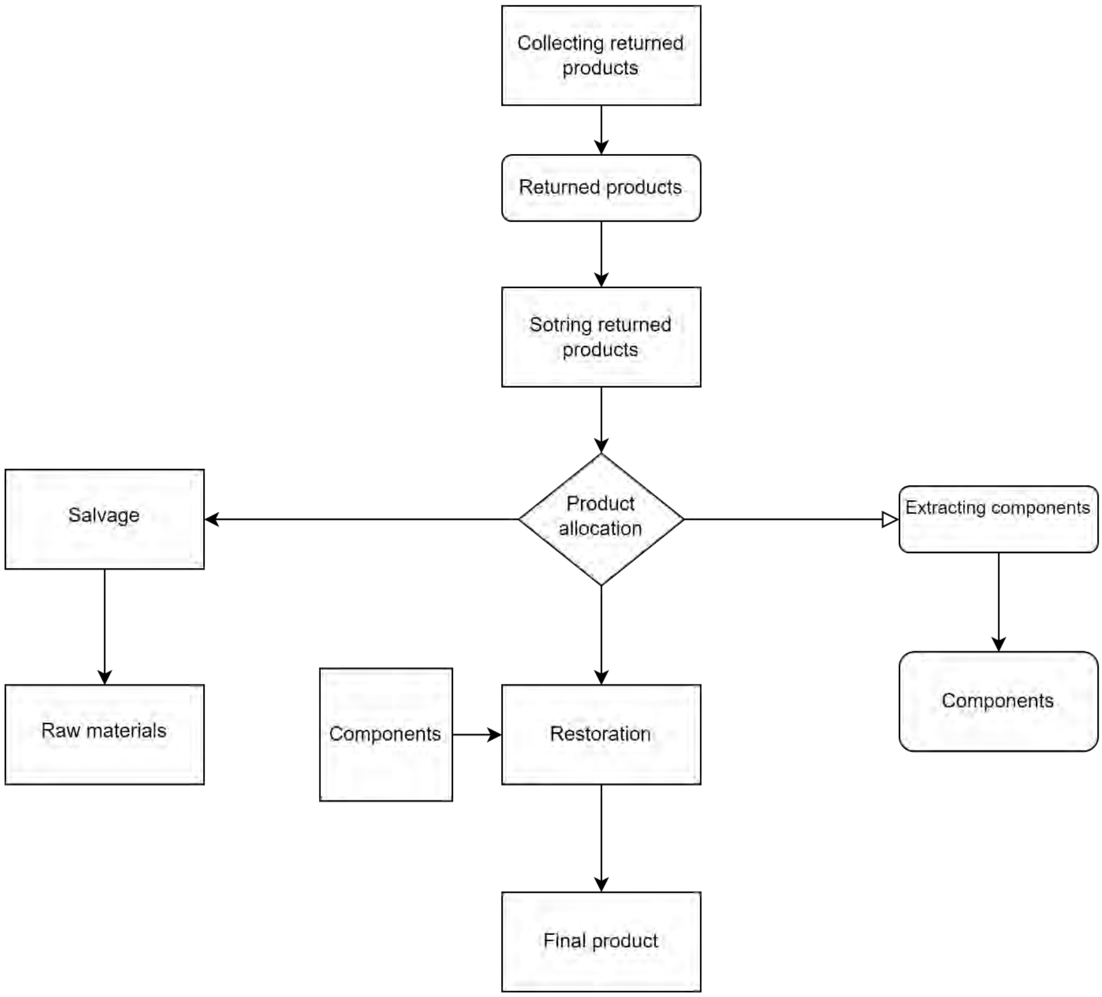
Key factors for comparison:

- ✓ Time needed for returned products
- ✓ Cost of reverse logistics
- ✓ Recovered value
- ✓ Net gain

- ***Scenario 1 : Classic reverse logistics***

In this scenario, we will simulate the classical reverse logistics:
Our source of returned products will be the collect mainly after client's demand. Once the products reach the company, there will be a manual sorting operation in order to identify the state of each collected product.
The first scenario will be used as the base of comparison to study the impact of new technologies.

Figure 3. First scenario model



Source: Prepared by the authors

- ***Scenario 2: Reverse logistics with AI-powered image recognition to classify returned items on their way to the company***

In order to gain time in the sorting process, we propose to implementing AI-powered image recognition to classify returned items on their way to the company. Once a product is collected, its image will be sent and analysed to identify the needed treatment.

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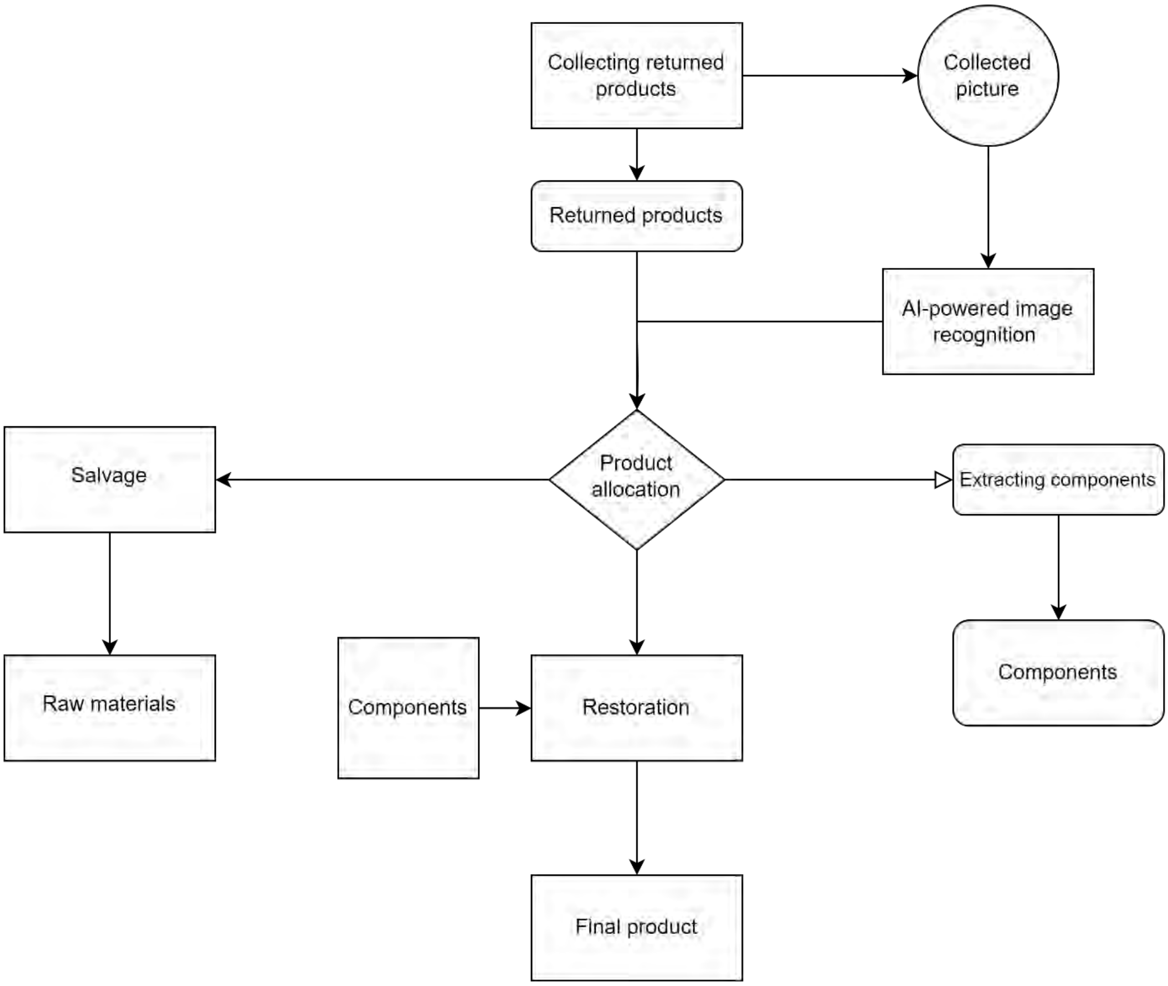
The AI sorting accuracy was parameterised at 92%, with the remaining 8% representing misclassification errors leading to sorting losses.

The objective of this scenario is to study the precision of the AI-powered sorting by also taking into consideration the extra cost generated by loss due to sorting that could be generated by misclassification.

Figure 4. Second scenario AI powered sorting



Source: Prepared by the authors

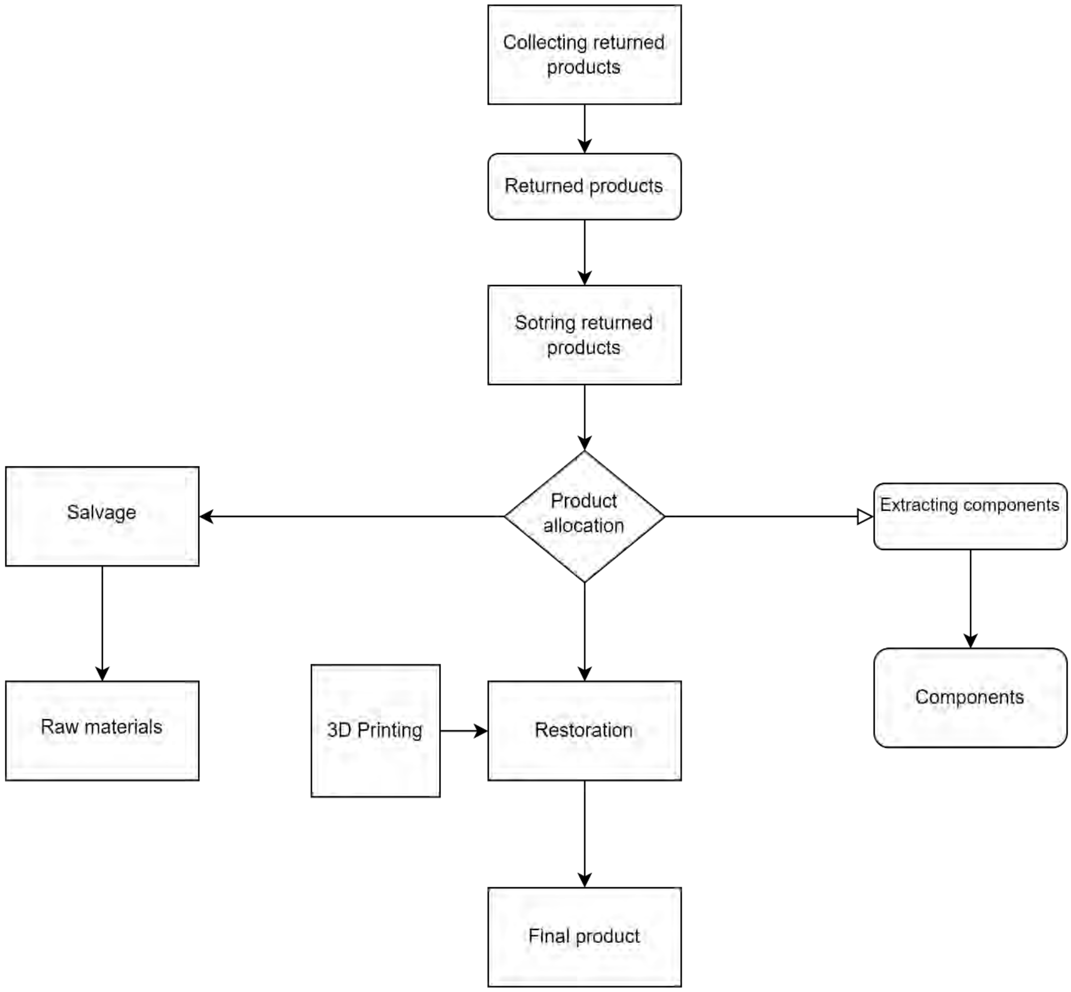
- ***Scenario 3: Reverse logistics with additive manufacturing (3D printing)***

In order to offer more flexibility in treating returns, we propose to implement additive manufacturing in order to increase the restoration rate of products and offer more gain and flexibility of returned products.

The additive manufacturing unit was modeled with a processing cost of $15/unit and a triangular repair cycle time (min=0.5h, mode=1.2h, max=2.0h).

The objective of this scenario is to study the gain that could be generated from implementing additive manufacturing and reduce the impact on the component's stocks.

Figure 5. Third scenario additive manufacturing



Source: Prepared by the authors

4. Results and Discussion

We used Rockwell Arena Simulation software to study the three scenarios. Since our input data was generated using random distribution due to the randomness nature of returned products, we used the Monte Carlo method with 150 replications per scenario to ensure statistical robustness (95% confidence level, margin of error < 2.5%).
Since our objective is to analyse the impact of the smart technologies in reverse logistics, we analysed the variation of the integration of smart technologies:

Table 3. Simulated performance results and variations:

Performance Indicator	**Scenario 1 (Baseline)**	**Scenario 2 (AI Sorting)**	**Scenario 3 (AM Repair)**
Time needed (Hours)	45.2 (±3.1)	31.1 (±2.4)* [-31.26%]	54.7 (±3.8)* [+21.12%]
Reverse logistics' cost ($)	1250 (±85)	1060 (±72)* [-15.23%]	1446 (±98)* [+15.71%]
Recovered value ($)	2150 (±130)	1865 (±115)* [-13.25%]	2604 (±165)* [+21.13%]
Net gain ($)	1500 (±95)	1759 (±110)* [+17.26%]	1772 (±125)* [+18.12%]

Note: Parentheses show standard deviations (150 runs); brackets show relative variations. Asterisks (*) indicate significant t-test differences (p<0.01) against the baseline.

Source: Authors' own elaboration

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The comparative analysis of Scenarios 2 and 3 relative to Scenario 1 reveals distinct strategic trade-offs in reverse logistics performance. Scenario 2 demonstrates a significant reduction in processing time (–31.26%) and reverse logistics costs (–15.23%), leading to a net gain increase of +17.26%, despite a decrease in recovered value (–13.25%) due to misallocation by the AI-powered sorting. This was due to the lack of data to improve the AI machine learning algorithm, which could be improved by increasing the input data to train the learning algorithm for a better efficiency. The drop in recovered value (-13.25%) in Scenario 2 represents the technological readiness barriers noted by Heyes et al. (2018), who observed that low technological maturity frequently constrains the efficient recovery of resources. This suggests that Scenario 2 emphasises operational efficiency and cost reduction, potentially by simplifying recovery processes or improving logistics flow.

In contrast, Scenario 3 exhibits an increase in both processing time (+21.12%) due to the slow nature of 3D printing and reverse logistics costs (+15.71%), but achieves a substantial improvement in recovered value (+21.13%) since it could achieve a more precise reparation via additive manufacturing, resulting in a slightly higher net gain of +18.12%. This value maximisation (+21.13%) aligns with the de Sousa Jabbour et al. (2018) and Gigli et al. (2019), showing how Industry 4.0 supports circular economy principles through component restoration. This scenario appears to prioritise the enhancement of product recovery outcomes, possibly through more advanced treatment and refurbishment methods.

Overall, both alternative scenarios outperform the baseline (Scenario 1) in terms of net gain, albeit through different approaches: Scenario 2 leverages cost and time optimisation, while Scenario 3 focuses on value maximisation from returned products. The choice between the two scenarios depends on the strategic orientation of the enterprise-whether the emphasis is placed on operational efficiency or on maximising the economic value of reverse logistics.

Sensitivity analysis on AI accuracy (80%-98%, baseline 92%) reveals that each 1% increase in sorting accuracy improves recovered value by 1.45% and net gain by 0.85%, highlighting the role of continuous algorithm training. Moreover, while transposable to other high-volume return sectors (e.g., electronics), product life-cycle speed remains a key sector-specific limitation.

5. Conclusion

This study highlights the significant potential of smart technologies in improving reverse logistics performance. The comparative analysis of three scenarios demonstrates that smart technology integration can lead to notable enhancements in either operational efficiency (as seen in Scenario 2) or value recovery (as seen in Scenario 3), both contributing to increased net gains compared to the baseline scenario. These findings suggest that smart technologies-specifically AI-powered sorting and additive manufacturing-can serve as powerful enablers for more sustainable and cost-effective reverse logistics systems. Theoretically, this research bridges the gap between Industry 4.0 and circular economy. Practically, it provides a decision-making guide for managers to select technologies based on strategic priorities.

However, several limitations must be acknowledged. First, the scenarios are based on simulated or case-specific data, which may not fully capture the complexity and variability of real-world supply chains and lacks empirical validation. Second, the study did not model the combined multi-technology scenario originally announced, and focuses primarily on quantitative indicators without exploring qualitative impacts.

Third, the upfront investment and organisational changes required for technology adoption were not integrated into the model.

Future research should aim to validate these findings through empirical case studies across diverse industries and geographical contexts. Additionally, expanding the analysis to include

long-term return on investment modeling and multi-criteria decision models incorporating social performance indicators would provide a more holistic understanding of next-generation systems.
Future efforts should focus on developing strategic partnerships between government, academia, and industry to support the digital transformation of reverse logistics.

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