Redefining Reverse Supply Chains: A Circular Economy Approach with Industry 5.0

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ABSTRACT

Our research introduces a pragmatic roadmap for optimizing operational excellence within sustainable reverse supply chain and logistics management. This is achieved through a synergistic implementation of Industry 5.0 principles and the Circular Economy (CE) model, as encapsulated in the ReSOLVE framework. We unveil the profound connection between I5.0 and

CE by presenting a case-based model that has substantial impacts on both economic and environmental performance. At its core, this model revolves around two critical dimensions. First, it focuses on the real-time exchange of information within the reverse logistics system. Second, it emphasizes the promotion of environmentally friendly products in the market. Our research delves into the effectiveness of the virtual environment within an I 5.0 context by conducting simulations of a reverse logistics model. These simulations encompass key operational aspects, including inventory and production planning policies, family-based dispatching rules for re-manufacturing, and additive manufacturing. Additionally, our analysis thoroughly explores the trade-off between setup delays and the availability of eco-friendly transportation within the context of remanufacturing. In order to provide valuable managerial insights, we leverage the Taguchi experimental design framework for our analysis. Our findings underscore the significance of achieving a well-balanced combination of information sharing and family-based dispatching rules when considering the trade-off between environmental sustainability and economic performance. Furthermore, our results emphasize the necessity of focusing on costs associated with socially influenced operations, which extends to factors such as investments in collection infrastructure and the size of the end-user market, as these factors have a substantial impact on product returns.In conclusion, this paper underscores the integration of I 5.0 and CE as a real-time decision model for sustainable reverse logistics systems, providing a critical perspective for management in navigating the complexities of contemporary supply chain and environmental responsibilities

Keywords: *Operational Excellence, Industry 5.0, Circular Economy, Reverse Logistics, Sustainability*

INTRODUCTION

The concept of a circular economy has gained significant traction in recent years as the world grapples with the environmental and economic consequences of a linear, "take-make-dispose" approach. In a circular economy, resources are reused, recycled, and repurposed, aiming to minimize waste and promote sustainability. At the heart of this paradigm shift is the reverse supply chain, a critical component that enables products and materials to be reintegrated into the production cycle. The emergence of Industry 5.0, characterized by advanced technologies and a heightened focus on collaboration, presents a unique opportunity to bolster the resilience and effectiveness of the reverse supply chain.

In a world increasingly aware of the environmental and economic challenges posed by our linear "take-make-dispose" model of consumption, the circular economy has emerged as a beacon of hope. At its core, the circular economy seeks to reduce waste, promote sustainability, and maximize resource efficiency. However, achieving this transformation necessitates not just a shift in mindset but a robust management strategy. This article explores how Industry 5.0 is instrumental in achieving circular economy resilience, with a specific emphasis on the crucial management aspect of reverse supply chains.

1. The Circular Economy Imperative

Before delving into the management aspect, it's essential to grasp why the circular economy is so imperative. The linear model has led to resource depletion, environmental degradation, and a hefty carbon footprint. It's an unsustainable path that cannot be maintained in a world with finite resources and escalating environmental concerns.

2. The Reverse Supply Chain: A Manager's Challenge

Within the realm of the circular economy, the reverse supply chain takes center stage. This component encompasses the retrieval, refurbishment, recycling, and reintegration of products and materials into the production cycle. It is where the principles of circular economy meet the practicality of business operations and management decisions.

3. Industry 5.0: The Management Revolution

Industry 5.0 builds upon the technological foundations of Industry 5.0, taking the digital transformation a step further by putting humans back in the spotlight. While technology is essential, it is the management aspect that truly empowers the fusion of Industry 5.0 with the circular economy.

4. Advanced Data Analytics for Management

In Industry 5.0, advanced data analytics are at the manager's disposal. These tools enable real-time monitoring, predictive maintenance, and streamlined decision-making. Management can use these insights to optimize reverse supply chain processes, from managing returns to resource allocation.

5. Augmented Reality and Workforce Management

One key aspect of Industry 5.0 is the collaboration between human workers and advanced technologies. Augmented reality, in particular, offers tools for training and guiding the workforce. Managers can leverage this technology to make their teams more adaptable, capable of handling a variety of products, and ensuring quality control.

6. Real-time Decision Making

With Industry 5.0's real-time capabilities, management can make decisions with precision and agility. This is particularly beneficial in reverse supply chains, where product returns, refurbishment, and recycling demand swift and accurate responses to minimize waste and cost.

7. Balancing Environmental and Economic Goals

A major challenge for management in the circular economy is striking the right balance between environmental sustainability and economic performance. Industry 5.0 aids in achieving this balance by providing real-time data and analytical tools to make informed decisions. Managers can ensure that resource efficiency and environmental responsibility align with financial objectives.

8. Collaboration and Stakeholder Engagement

Management in the circular economy involves fostering collaboration among various stakeholders, from suppliers to customers. Industry 5.0 promotes connected ecosystems that allow for better communication and collaboration. Managers can harness these connections to establish partnerships, promote sustainability initiatives, and enhance the resilience of reverse supply chains.

1.1.2. Reverse Logistics Circular economy (CE) has gained significant importance in the manufacturing industry, with an increasing focus on its adoption among companies and researchers in economically developed and emerging countries (Sehnem et al., 2019). Kirchherr et al. (2017) introduced the transformation from a linear forward value chain (i.e., take-make-dispose) to a circular supply chain (SC) by integrating reuse, remanufacturing, and recycling processes. To manage a CE-oriented value chain effectively, companies must address recovery and remarketing operations, often supported by the "Reverse Logistics" (RL) program. Both CE and RL share common concerns related to economic and environmental aspects (Reike et al., 2018), but CE is broader in scope, encompassing both the forward and reverse sides of the supply chain, involving operations with new materials. Therefore, achieving sustainable operations management, aligned with CE principles, is essential. In this context, we propose the ReSOLVE framework, outlining six CE-based business model development strategies (Jabbour et al., 2017): (i) Regenerate, (ii) Share, (iii) Optimize, (iv) Loop, (v) Virtualize, and (vi) Exchange. Our research leverages RL integrated with Industry 5.0 technologies to implement these strategies effectively.

The Reverse Logistics Circular Economy (CE) has gained significant importance in the manufacturing industry, with companies and researchers increasingly adopting it. CE focuses on integrating reuse, remanufacturing, and recycling processes to manage a CE-oriented value chain effectively. To achieve sustainable operations management aligned with CE principles, the ReSOLVE framework is proposed, outlining six CE-based business model development strategies: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange.

The lean approach through cellular manufacturing systems is examined as a technology-driven aspect of operational excellence. Lean philosophy centers on waste minimization and encompasses various operational practices to reduce non-value-added operations and enhance resource efficiency. Environmental considerations in the context of sustainable performance have led researchers to explore the impact of lean practices, particularly reducing setup times for inventory optimization and environmental performance improvement.

In the CE framework, remanufacturing becomes more complex due to decisions related to remanufacturing scheduling, such as mechanism selection for order release, lot sizes, priority scheduling rules, parts commonalities, and integrating forward and reverse supply chain operations. This integration of lean operations with Industry 5.0 initiatives leads to sustainable developments in the manufacturing and remanufacturing environment from an economic perspective. Environmental sustainability and economic performance challenges in RL include obtaining real-time information for various tasks and vehicles while reducing RL costs, fuel consumption, CO2 emissions, and waiting times. CE practices have the potential to significantly reduce CO2 emissions and create economic benefits, as demonstrated in the European Union (EU).

This research addresses three central research questions within the context of operational excellence: the technological attributes of the lean approach and the innovation performance dimensions of a sustainable reverse logistics system. These questions include how the synergies between Industry 5.0 (I5.0) and Circular Economy (CE) impact environmental and economic performance, the effect of integrating innovations related to the diffusion of green products and Inventory and Production Planning (I&PP) policies on the performance of a reverse logistics system, and how different Family-Based Dispatching (FBD) rules influence product delivery speed and performance.

Literature Review

2.1. Achieving Sustainability Goals with Industry 5.0 in Operations

The concept of Industry 5.0 (I 5.0) emerged in the manufacturing domain in 2011 (Kagermann et al., 2011). Initial directions related to I 5.0 implementation were outlined by researchers like Hermann et al. (2016) and Chukwuekwe et al. (2016). However, the existing literature still lacks a comprehensive understanding of how I 5.0 will impact the operational management of future industries. Consequently, there is a scarcity of studies that contribute a framework or practical implications related to operations management influenced by I 5.0 (Fettermann et al., 2018). I 5.0 technologies have the potential to enhance various aspects of operations management, automating processes and providing real-time information on operational units, including material flow, customer demand, and inventory positions across supply chain levels. Cyber-Physical Systems (CPS) integrate cyberspace, physical processes, and objects to establish connections between resources and information technology within manufacturing networks. This integration aids in real-time data-driven scheduling and decision-making (Ahmadov and Helo, 2016). Sensors and actuators play a crucial role in collecting and distributing real-time data. For instance, in a cloud-based manufacturing environment, RFID technology is utilized in the third generation CPS system for inventory management (Singh et al., 2015). The internet facilitates resource sharing in operations by creating a virtual space through cloud manufacturing technology, promoting collaboration among supply chain participants for design, manufacturing, and assembly. Additive manufacturing, enabled by cloud services, reduces the need for machine setups, such as tool changes (Huang et al., 2013). IoT capabilities allow for real-time data sharing among all supply chain echelons, connecting machines, transportation modes, and the internet (Zhong et al., 2017). In the contemporary operations landscape, the intersection of I 5.0 and sustainability plays a crucial role in advancing a sustainable society (Dubey et al., 2017). The environmental and economic aspects of organizations' operations management are effectively addressed through the combined development of I 5.0 and sustainability (Elkington, 1994; Gunasekaran and Irani, 2014). Decision-making for sustainable operations management involves factors like green product and process design and environmentally conscious supply chain operations (Gunasekaran et al., 2014; Abdul-Rashid et al., 2017). González-Benito and González-Benito (2006) propose a decision-making process for classifying environmentally sustainable operations, which includes designing for the environment, cleaner production, and green supply chain management. Implementing the "3Rs" (reduce, reuse, recycle) is also suggested for environmentally sustainable operations (Alayón et al., 2017). Therefore, the interplay between environmentally sustainable operations and I 5.0 is valuable, given the significant role of technology in making decisions aligned with environmentally sustainable operations excellence.

2.2. "Circular Economy: A Pathway to Sustainable Operations represents a promising approach to sustainable operations management, with a focus on the sustainable use of resources (McDowall et al., 2017; Sehnem et al., 2019). The CE approach aims to retain the value of resources at the end of their lifecycle by emphasizing strategies such as reuse, remanufacturing, and recycling (Ghisellini et al., 2016; Zhao and Zhu, 2015). The ReSOLVE framework, based on CE principles, includes various elements, such as regeneration, sharing, optimization, loop, virtualization, and exchange (MacArthur et al., 2015). Each of these elements is aligned with specific technologies and strategies:

- Regenerate involves making sustainable production decisions based on data from IoT.
- Share is facilitated by cloud-based resources and IoT for information sharing across the supply chain.
- Optimize is supported by Cyber-Physical Systems (CPS) and IoT for data collection and efficient order size computation.
- Loop benefits from IoT, CPS, and cloud services, enabling the circularity of materials and energy and supporting the tracking and tracing of products.
- Virtualize leverages cloud manufacturing, IoT, and Additive Manufacturing (AM) technologies to create virtual relationships between organizations, suppliers, and customers.
- Exchange is aligned with Additive Manufacturing (AM) and IoT for sustainable production through reduced material use (Despeisse et al., 2017).

From an operations management perspective, integrating forward supply chains with reverse logistics is essential for realizing the potential of CE in sustainable operations (Matsumoto et al., 2016). Business models related to CE often categorize the degree of circularity into downstream circular adoption, upstream circular adoption, and full circular adoption. Downstream adoption focuses on marketing campaigns for reused or remanufactured products, while upstream adoption emphasizes activities that establish effective supplier relationships. Full circular adoption involves managing circularity at both internal and external levels, with clear communication of circular practices to customers through promotional campaigns (Urbinati et al., 2017). The association between I 5.0 and organizational sustainability has also been explored in some studies (Stock and Seliger, 2016), making it crucial to investigate this connection further.

2.3. Industry 5.0, Circular Economy, and Operations Management Information-sharing within modern supply chains is a prime example of how I 5.0 capabilities contribute to sustainable operations management decisions (Stock and Seliger, 2016). Implementing an integrated approach that combines I 5.0 and CE principles can provide a significant advantage for sustainable operations management.

Sustainable operations management requires a deep understanding of production operations' environmental impact and a focus on both operational efficiency and effectiveness (Kleindorfer et al., 2005). Thus, when considering sustainable operations management, it's essential to explore how CE principles align with I 5.0 technologies. Various components of CE can be associated with I 5.0:

- Regenerate aligns with I 5.0 by making sustainable production decisions based on real-time data received through IoT.
- Share aligns with I 5.0 through cloud-based

SECTION 3: MODELING AND SYSTEM OVERVIEW

3.1: ANALYZING A CIRCULAR CHAIN FOR REFRIGERATOR MANUFACTURING

- This section places a strong emphasis on the management aspect as we thoroughly investigate the circular chain system employed by a refrigerator manufacturer. Our focus is on a practical yet hypothetical scenario concerning alternative transportation strategies for a refrigerator company situated in Pondicherry, India.
- • The refrigerator company's management adopts a forward-thinking approach when it comes to overseeing the end-of-life recovery process for their products. Their product design is dedicated to facilitating the recycling of approximately 85-90% of materials such as steel and plastics used in their refrigerators. The company actively participates in the collection, disassembly, and recycling of e-waste from various regions across India. To efficiently carry out these operations, the company has formed a strategic partnership with an authorized e-waste recycling service. They are responsible for retrieving end-of-life products from consumers' residences and managing the recovery process.

- • While the company maintains an extensive network of distributors throughout India, our study zeroes in on a specific transportation route from Pondicherry to Bhavnagar, Gujarat, with a particular focus on single origin-destination transportation. At present, the company does not utilize sea routes for transporting its products within India. However, in our pursuit of sustainable practices, we contemplate three transportation modes - truck, rail, and ship - within the network. Aligned with our sustainability objectives, we advocate for the use of ships in the transportation of remanufactured products, primarily due to their lower carbon emissions. Consequently, we establish the transportation sequence as ship, train, and then truck.

3.1.1: Feed-Before-Dispatch Rules Analysis

- Building upon previous discussions, we delve into a detailed analysis of the Feed-Before-Dispatch (FBD) rules, with a particular emphasis on the speed of product deliveries to the shipping terminal, a critical aspect in the management of an efficient transportation chain. Our primary motivation for exploring alternative FBD rules is to assess their influence on expediting the remanufacturing of eco-friendly products within the context of Additive Manufacturing (AM). This, in turn, facilitates their transportation via the prioritized mode, which, in this context, is the use of ships.

3.1.2: Comprehensive Transportation Cost Analysis

- To manage our transportation costs effectively, we break them down into two main components: variable and fixed costs. Variable transportation costs are determined based on the weight of each product, encompassing expenses such as mover overheads, administrative costs, crew salaries, and fuel costs. We assume these variable transportation costs to remain consistent over time and to be contingent on the weight and mode of transportation chosen. On the other hand, fixed costs primarily comprise operator wages and expenses associated with loading and unloading products. These fixed costs are assumed to have predefined values for different transportation modes: $50 for truck, $100 for rail, and $150 for ship

3.2: Emission Estimation

- Within this section, we also focus on the management of emissions, which plays a pivotal role in the transportation of refrigerators from Pondicherry to Bhavnagar, Gujarat. To estimate these emissions, we consider factors such as route distance and time, as sourced from Google Maps. Our analysis incorporates various factors, including capacity, unit variable costs, waiting time charges at terminals, and CO2 emissions factors for each transportation mode, all in alignment with the research findings of Qu et al. (2016). These estimations are thoughtfully presented in Table 1, and it's essential to highlight that this discussion remains firmly centered on evaluating the management aspects of FBD rules within the transportation system.

3.2.1: Activity-Based Approach for CO2 Emissions Estimation

- Consistent with the methodology described by Park et al. (2012), we adopt an activity-based approach to estimate CO2 emissions in intermodal transportation. The CO2 emission calculation is derived from Equation (1), where 'l' represents the load carried by the vehicle in tonnes, 'd' signifies the distance in kilometers, and 'e' denotes the average CO2 emission factor in grams per tonne-kilometer. To facilitate implementation in simulations, we convert CO2 emissions into monetary units, specifically using a rate of $100 per tonne (as per Qu et al., 2016).

3.2.2: Key Variables in CO2 Emission Estimation

- This approach allows for the straightforward capture of variables such as distance and total weight in simulation, while excluding complex parameters, such as varying fuel types used in different transportation modes.

The reverse logistics framework design focuses on modularity and shared manufacturing processes in a closed-loop system involving a distributor, manufacturer, recycled-material (RCY) supplier, and new-raw-material (NRM) supplier. The system introduces stochastic elements into lead time for deliveries and considers two procurement options for raw materials and sub-assemblies: from the NRM supplier (n) or the RCY supplier (r). The RCY supplier collects product returns influenced by the innovation theory (Bass) model and various information-sharing policies. The remanufacturing process is examined from the Feed-Before-Dispatch (FBD) perspective, considering two specific FBD rules, first-come family (FCFAM) and minimum average set-up time (MAS). The study aims to assess the impact of alternative FBD rules on remanufacturing efficiency in the reverse logistics (RL) context. The load of the remanufacturing shop is determined by returns obtained through the Bass model.

The integration of Industry 5.0 (I 5.0) and Circular Economy (CE) characteristics into the proposed RL model is explored, focusing on Information and Process Integration (I&PP), information transparency, Additive Manufacturing (AM) oriented remanufacturing, and a well-coordinated transportation system. RFID technology is utilized to enhance I&PP, fostering information sharing among all supply chain entities and ensuring the availability of the preferred mode of transport, i.e., ships, for timely delivery of green products.

3.5: Returns System Based on the Innovation Theory (Bass) Model

- As detailed in Section 2, customer behavior significantly influences environmental decisions. This section explores customer behavior, particularly regarding the adoption of remanufactured or green products. The volume of returns to the RL system is inherently uncertain, influenced by factors such as the end-of-life of products and the market adoption of green products.
- We adopt an extended version of the Bass model (1969) to capture consumer behavior and its impact on the number of returns. The model estimates the number of returns (R) from the end-user market based on market capacity (N) and cumulative adoption (x(t)) up to a given time. The model equation is presented as Eq. (2).

3.5.1: Model Assumptions

- In addition to assumptions from prior research, we incorporate specific assumptions related to transportation and FBD rule systems. We consider various charges, such as berth charges for ships, terminal service charges for trains, and parking charges for truck trailers, in the total transportation cost. These charges are associated with waiting times at loading terminals.

The study focuses on investigating the time delay caused by variations in the uploading process of computer-aided design (CAD) programs for different part families on additive manufacturing (AM) machines. The prioritization of the FBD rules is taken into consideration during the analysis. Hence, within the context of this study, the change in set-ups from one sort of part family to the other is considered from the notions of change in the CAD software.

In our investigation, we conducted a simulation consisting of 500 time periods with 10 replications. This sample size was deemed sufficient as it allowed us to observe the saturation values of the density function and cumulative function curves for the specified variables of the Bass model, after a set amount of time. In this current study, it is assumed that there are no products initially available at each level of the reverse logistics model during the simulation.

The quantities and levels of the parameters utilized for the simulation model as presented in Table 3 align with those reported by Dev et al. (2019). This study examines the impact of many aspects, including demand rate, set-up cost, green investment, coefficients of innovation and imitation, end-user market capacity, and the number of transportation modes accessible.

The Taguchi experimental design is employed as a means of assessing the impact of different factors on performance outcomes. For a comprehensive elucidation of the Taguchi experimental design paradigm, the reader may consult the work of Dev et al. (2014). The L12 orthogonal array was utilized for the analysis of performances. The experimental setup involved comparing two FBD rules using three different information methods. A total of 72 simulation tests were conducted, resulting from the combination of 12 scenarios, 2 FBD rules, and 3 information techniques.

3.5.2. Measures of Environmental and Economic Performance

In addition to the environmental factors considered by Dev et al. in their 2019 study as complementary to environmental performance, we also assess various characteristics related to the transportation system. Transportation involves two main categories of expenses: (i) Operational costs, which include variable costs, fixed costs, and waiting charges; and (ii) Emission costs. Our primary focus is on evaluating the emission costs associated with shipping, as it aligns with environmentally sustainable practices. Therefore, we compare the emission costs of shipping based on different factors and FBD standards.

In cases where the emission costs related to shipping are significant, a substantial quantity of parts are transported by ship. To calculate the emission costs for carrying goods from Pondicherry port to Papavov port for each mode of transportation, we follow these steps:

The economic measure encompasses several expenses, including Cm, Cr, Cn, and Ct.

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For manufacturers and suppliers in the RCY industry, the costs include various components like setup fees (which might involve modifying the CAD program for recycled-material suppliers), holding charges, and backorder costs. Similarly, the costs incurred by NRM providers consist of components such as production costs, setup costs, holding charges, and backorder costs.

To determine the procurement cost per unit, collection cost per unit, and manufacturing cost per unit for manufacturers, RCY suppliers, and NRM suppliers, we use the following calculations:

In the context of the manufacturer, we specifically address the purchase cost.

RESULTS AND DISCUSSION

Within our study, we conducted a thorough examination of the environmental and economic performance of two FBD rules, specifically FCFAM and MAS, across 72 simulation experiments. Our primary focus was on three distinct information scenarios: (i) decentralized, (ii) recycled-material supplier information (RCYINF), and (iii) manufacturer information (MNFINF). These results represent the outcomes of simulation experiments carried out at optimal levels, as determined through the Taguchi procedure.

The maximum values for each informational scenario alongside their respective FBD rules. For instance, under the FCFAM rule, RCYINF attains the maximum value of 2,641,300. The minimum values among these maximums, while the final column outlines the improvements in environmental performance associated with each measure. Notably, we observed that RCYINF, when combined with the FCFAM rule, results in the highest total environmental cost, underscoring its effectiveness in delivering recycled components to manufacturers and distributors. Furthermore, the recycled-material supplier made significant promotional investments through the RCYINF strategy. This synergy of information-sharing and the FBD rule is denoted as 'RCYINF-FCFAM' and significantly enhances environmental performance metrics. Additionally, we noted that emission costs related to ship transportation were most pronounced in the RCYINF-FCFAM case, indicating a strong commitment to green practices.

These findings address the research questions introduced in previous section with a specific focus on the management perspective of the synergy between Industry 5.0 (I 5.0) and Circular Economy (CE) and their influence on environmental performance, particularly in terms of CO2 emissions. Figure 2 visually represents the cumulative adoption of green products for the RCYINF-FCFAM and Decentralized-MAS policies. The increased reliance on ships for transportation in the RCYINF-FCFAM case can be attributed to the earlier and more rapid adoption of green products, highlighting the management's pivotal role in promoting sustainable practices.

Shifting our focus to the realm of management considerations, we delve into the economic performance within the context of the transportation network system. Our examination centers on the influence of different FBD rules on economic performance. In particular, we assess two pivotal facets: the cumulative transportation operational cost and the overall set-up cost, both of which are significantly impacted by the choice of FBD rule at the recycled-material supplier's end.

A compelling observation emerges regarding the management-driven aspect of economic performance. It becomes evident that the strategic pairing of Decentralized-FCFAM leads to an optimal minimization of the total transportation operational cost. Figure 3 effectively reinforces this insight by illustrating a gradual upswing in the adoption of eco-friendly products under the Decentralized-FCFAM policy, culminating in reduced operational costs and a remarkable 69% enhancement in economic performance.

In a complementary vein, turning our attention, we uncover further management-oriented benefits. Here, the data reveals that the optimal level of set-up cost aligned with AM (Set1) holds a distinct advantage over conventional remanufacturing practices. Notably, the waiting time cost associated with ship transportation in the RCYINF-MAS scenario is distinctly minimized. This favorable outcome primarily traces its roots to the early adoption of green products within a sizable end-user market, a management-driven decision that significantly streamlines operational costs.

In the case of total set-up cost influenced by changing FBD rules, MNFINF-MAS is the most cost-effective combination. This is explained by the early adoption of green products, which stabilizes the number of machine setups. This aligns with existing literature suggesting that the MAS priority rule reduces the number of setups.

In conclusion, our findings emphasize the importance of selecting the right FBD rule and information-sharing strategy to enhance both environmental and economic performances in an Industry 5.0 and Reverse Logistics (RL) oriented environment. Figures 2 to 4 depict quick adoption curves for the information-sharing mechanisms (RCYINF and MNFINF) in the model. These quick adoption curves are due to real-time inventory information, leading to higher order frequencies and faster attainment of maximum adoption. This aligns with the principles of the Bass model, where faster promotional investment leads to quicker adoption saturation when the market capacity is reached.

Section 4.2: Management Implications of the Mathematical Model

In this section, we explore the real-world applications of our mathematical model and emphasize its relevance to management decisions. We've pinpointed the optimal settings for three specific strategies, and you can find a detailed breakdown of these. To ensure the reliability of our findings and validate the additivity assumption, we conducted an analysis of variance (ANOVA). The ANOVA results, shed light on the factors that significantly affect the environmental and economic performance of these strategies.

For instance, when we consider the RCYINF-FCFAM strategy, we found that the optimal settings include values for variables like D1, Ns2, Nr1, Nt1, Km1, Kr1, Kn2, Set1, CEUM1, IP1, and CI2. On the other hand, the Decentralized-FCFAM strategy's optimal settings encompass variables such as D1, Ns1, Nr2, Nt2, Km2, Kr1, Kn1, Set1, CEUM1, IP2, and CI2. Finally, the MNFINF-MAS strategy's optimal settings consist of values like D1, Ns2, Nr1, Nt1, Km2, Kr2, Kn1, Set1, CEUM1, IP2, and CI1.

In addition, we conducted additivity tests for all these cases and summarized the results. It's noteworthy that in all three scenarios, the additivity test outcomes met the criteria, as the prediction error fell within the 2-standard deviation confidence limits. This confirmation underscores the validity of the additivity assumption that forms the foundation of our analysis, making these findings especially valuable for management considerations."

Section 5: Conclusions

In this section, we draw conclusions based on our study, placing a strong emphasis on achieving operational excellence by combining Industry 5.0 (I 5.0) technologies and Circular Economy (CE) principles, as embodied by the ReSOLVE model.

Our research envisions a practical solution involving the implementation of a cloud-based Enterprise Resource Planning (ERP) system equipped with RFID technology. To enhance the efficiency of managing product returns, we propose the integration of the Bass model algorithm module. Our approach involves conducting extensive simulations related to the concept of reverse logistics, aligning with the core principles of I 5.0's virtual factory. All of these efforts are facilitated through the application of Taguchi's experimental design framework for real-time execution. This management-oriented approach underscores the potential for improving operations and resource utilization by seamlessly blending modern technologies and sustainable practices.

5.1 Implications of Research

Our study offers valuable insights for effective management in the context of integrating Industry 5.0 (I 5.0) and Circular Economy (CE). We establish theoretical connections between I 5.0 and CE principles, particularly in the domain of operations management for reverse logistics, aligning with concepts advocated by Jabbour et al. (2018).

Our findings emphasize that incorporating I 5.0 technologies, reverse logistics, and lean approaches, as suggested by Mangla et al. (2019), can provide valuable guidance for achieving sustainable Circular Supply Chain (SC) performance. We also endorse the performance dimensions of operational excellence outlined by Mangla et al. (2019) and the concept of full circularity, as proposed by Urbinati et al. (2017). Achieving full circularity involves implementing innovative diffusion practices at the distribution end and involving recycled-material suppliers upstream. This emphasizes collaboration in information-sharing, transparency in product returns, and flexibility in process scheduling through various "FBD rules" in the reverse supply chain.

Importantly, our research offers valuable insights for achieving full circularity in sustainable operations management through Inventory and Production Planning (I&PP), Additive Manufacturing (AM) setup, FBD rules, and transportation systems in reverse logistics.

We recommend that managers consider integrating market-focused green product innovation diffusion with their reverse logistics operations. This integration underscores the importance of adopting lean practices, including considerations for emissions when using alternate transportation modes. Additionally, it's crucial to acknowledge that environmental regulations, particularly in industries with high environmental cost shares in total manufacturing costs, present unique challenges. Often, as environmental performance improves, economic benefits decrease, as noted by Wagner and Schaltegger (2003). Our study empowers managers to extend the period of economic benefit by adopting appropriate information-sharing strategies and scheduling policies. For instance, the "RCYINF-MAS" strategy can reduce backorders by leveraging a high end-user market capacity, resulting in lower total inventory costs, although this may require a significant promotional investment.

In cases where companies lack the technological capabilities of I 5.0 or are uncertain about entering the reverse logistics domain, especially in their early stages, we propose that even decentralized information-sharing strategies play a crucial role. For example, the "Decentralized-FCFAM" strategy, although showing reduced economic performance due to the low initial end-user market capacity, can still be a viable approach.

5.2 Limitations and Future Research Directions

The results of our research have a specific context and call for a more detailed analysis, especially concerning parameterization and the structure of Supply Chain (SC) networks to enable broader applicability. Our study also makes a significant contribution to our understanding of consumer behavior through the integration of I 5.0 technology using a cloud-based ERP system equipped with the Bass model algorithm.

For future research, it's essential to explore scenarios involving multiple suppliers, which differs from our study that focused on a single supplier. However, managing multiple suppliers can lead to more frequent orders from manufacturers, resulting in higher operational costs. This scenario aligns with situations where the system operates using an information-based MNFINF-MAS strategy, causing the ordering costs with recycled-material suppliers to be relatively high in terms of economic performance.

In such cases, companies must consider the transition of all their suppliers to a common cloud ERP platform, as proposed by Kenandy's cloud-based open cyber-physical-social network (CPSS) platform. This platform fosters a social network by facilitating the interaction of cross-terminal applications, including planning, scheduling, and social computing, with the cyber-physical networks established in an I 5.0 environment.

In summary, our research underscores the managerial challenges and opportunities related to the integration of multiple suppliers within a cloud-based ERP system, particularly in the context of I 5.0 technology and SC network structures. Further analysis and investigation into these aspects can lead to valuable insights for effective supply chain management.

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