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Agent-Based and Discrete-Event Simulation of Reverse Logistics: A Case Study from the SIIP Project

Raffaele Abbate*, Stefano Sanfilippo, Mario Caterino***, Sergio Lenzi****, Anna Bolognesi**, Pietro De Vito**, Marta Rinaldi*****, Anastasiia Rozhok******, Bianca Vottero*******, Marcello Fera***, Umberto Daniele***

**Enginfo Consulting srl, 80022 Arzano (NA), Italy*
***STAM S.r.l., 16129 Genova, Italy*
**** Department of Engineering, University of Campania Luigi Vanvitelli, 81031 Aversa (CE), Italy*
***** Artigo S.p.A, 17014 Cairo Montenotte (SV), Italy*
****** Department of Industrial Engineering, University of Salerno, Fisciano (SA), Italy*
******* DISPI, University of Genova, 16124 Genova, Italy*
******** Department of Economics, University of Genova, 16126 Genova, Italy*

Abstract: This paper explores the application of a hybrid simulation methodology—integrating agent-based and discrete-event simulation—to enhance reverse logistics (RL) processes. Reverse logistics is increasingly critical in circular economy strategies, enabling the recovery, remanufacturing, and recycling of end-of-life products while minimizing environmental impacts. Within the context of the Sustainable Intelligent Industrial Planning (SIIP) project, financed by the Italian government, this study develops and applies a multi-method simulation framework to model and evaluate RL supply chains using real-world data provided by an industrial partner. The framework supports the analysis of economic and environmental trade-offs across different supply chain configurations, specifically considering direct transportation and transportation to a storage centre before final transportation. Simulation results reveal significant cost-emission trade-offs: while introducing a storage centre reduces CO_2 emissions by optimizing transportation routes, it incurs higher operational costs. The findings emphasize the need for context-specific decision-making to balance sustainability goals with economic efficiency, demonstrating the potential of hybrid simulation tools to inform strategic planning in RL systems.

Keywords: Supply Chain, Reverse Logistics, Multi-Method, Agent-Based Simulation, Discrete-Event Simulation, Digital Model, Economic, Environmental, Real Case Study.

1. INTRODUCTION AND BACKGROUND

In recent years, increasing environmental concerns, resource scarcity, and evolving consumer expectations have driven a paradigm shift away from traditional linear production models—characterized by a "take-make-dispose" approach—toward more sustainable and resource-efficient strategies. This shift aligns with the principles of the circular economy (CE), a framework that seeks to minimize waste, extend product lifecycles, and recover value from materials through innovative processes and business models. CE has gained significant traction across both industrial and policy domains as a solution to pressing global challenges, including climate change, the depletion of natural resources, and growing consumer demand for environmentally conscious products (Geissdoerfer et al., 2017). Key elements of the circular economy, such as remanufacturing (Manco et al., 2023), recycling, and product life extension, play a crucial role in retaining products and components in circulation. These practices reduce the reliance on virgin raw materials, mitigate environmental impacts, and contribute to the reduction of greenhouse gas emissions (Stahel, 2016). For instance, remanufacturing restores used products to "like-new" condition, often requiring less energy and material than manufacturing from scratch, while recycling recovers raw materials for use in new production cycles, thus reducing landfill waste and resource extraction (Caterino et al., 2022).

However, the successful implementation of circular practices relies heavily on the effectiveness of reverse logistics (RL) systems. Reverse logistics, defined as the process of planning, implementing, and controlling the flow of returned goods from the point of consumption to the point of origin for recovery or disposal is pivotal in enabling the collection, sorting, inspection, and transportation of end-of-life products back into the supply chain (Kazemi et al., 2019). Efficient RL systems help firms overcome challenges related to the uncertainty in the quantity, quality, and timing of returns, while ensuring cost-effective and environmentally sustainable recovery processes (Fleischmann et al., 1997). Moreover, reverse logistics serves as a critical enabler of closed-loop supply chains (CLSCs), a core aspect of the circular economy that integrates forward and reverse flows within a single system. CLSCs help companies capture economic value from returned products through reuse, remanufacturing, or recycling while meeting stringent regulatory requirements and aligning with corporate sustainability goals (Govindan et al., 2015).

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Many studies have been conducted about RL, primarily to understand how to improve decisions to make the entire RL process more efficient (Ferguson and Souza, 2010; Fleischmann et al., 1997). Later, with the development and easier access to technologies, simulation became an important tool to evaluate RL. Kara et al., (2007) simulated RL in the Sidney metropolitan area to assess the costs. The simulation was able to adapt to "what-if" scenario and provided good results. Suyabatmaz et al. (2014) explored RL in case of uncertainty in the quality of returned products by using a hybrid simulation approach based on a problem specific method and a generic method, finding that it was able to balance the trade-offs between cost minimization and performance measures. Generally, the review by Abid and Mhada (2021) highlighted that Monte Carlo simulation and Discrete Event Simulation are the most widely used techniques for addressing RL problems such as uncertainty, inventory control, and network design, while hybrid simulations are increasingly popular for handling complex RL systems and provide the best results. One of the research gaps related to RL is the lack of models reproducing real contexts, in which data are provided by the companies interested in a good RL (Pereira et al., 2023). Addressing this gap, this paper presents a methodology for generating hybrid RL simulations to provide information to decision-makers about the efficiency of RL. The method is applied to a real case study, by integrating agent-based simulation and discrete event simulation. The methodology is an excerpt of the SIIP project (Sustainable Intelligent Industrial Planning), financed by the Italian MIMIT (Ministero delle Imprese e del Made in Italy). Within the context of this project, one of the partner companies provided real data about their current process of RL. The data have been used to simulate the case study reported in this paper, where 2 different supply chains are compared. The remainder of the paper is as follows: Section 2 presents the methodology of this paper, while Section 3 details the application of the methodology. Section 4 presents the results and discussion of the case study, while Section 5 concludes the paper.

2. METHODOLOGY

In the context of the SIIP project, a framework was developed to support companies in evaluating the economic and environmental impacts of reverse logistics within circular strategies. The operational flow of the framework, outlined in the green area of Figure 1, enables users to follow a structured process for assessing their reverse logistics supply chain. This is achieved through three application modules that allow users to: i) digitize the reverse logistics supply chain to model its structure and operations; ii) simulate its behaviour to analyse performance under different scenarios; and iii) visualise Key Performance Indicators (KPIs) that provide actionable insights for decision-making.

The application modules were developed using a four-step methodology depicted in the blue area of Figure 1. The first step focuses on modelling the reverse logistics supply chain by identifying its key elements, defining the relationships between them, and establishing their operational principles. Building on this, the second step involves the creation of a digital model of the supply chain. This digital model is based on clearly defined assumptions, mathematical relationships, and simulation logic, providing a dynamic representation of the system. In the third step, a user-friendly Graphical User Interface (GUI) is developed to facilitate the input of data required for the model. This interface ensures that users can easily configure the parameters of their specific supply chain. Finally, the fourth step deals with the design of a results dashboard, where users can visualize the outputs, including Key Performance Indicators, to support data-driven decision-making and optimize performance.

It is worth noting that throughout Steps 1 to 3, the most appropriate tools for implementing the framework were identified. This choice was guided by the project's goal of creating a scalable tool easily adaptable to various industrial contexts.

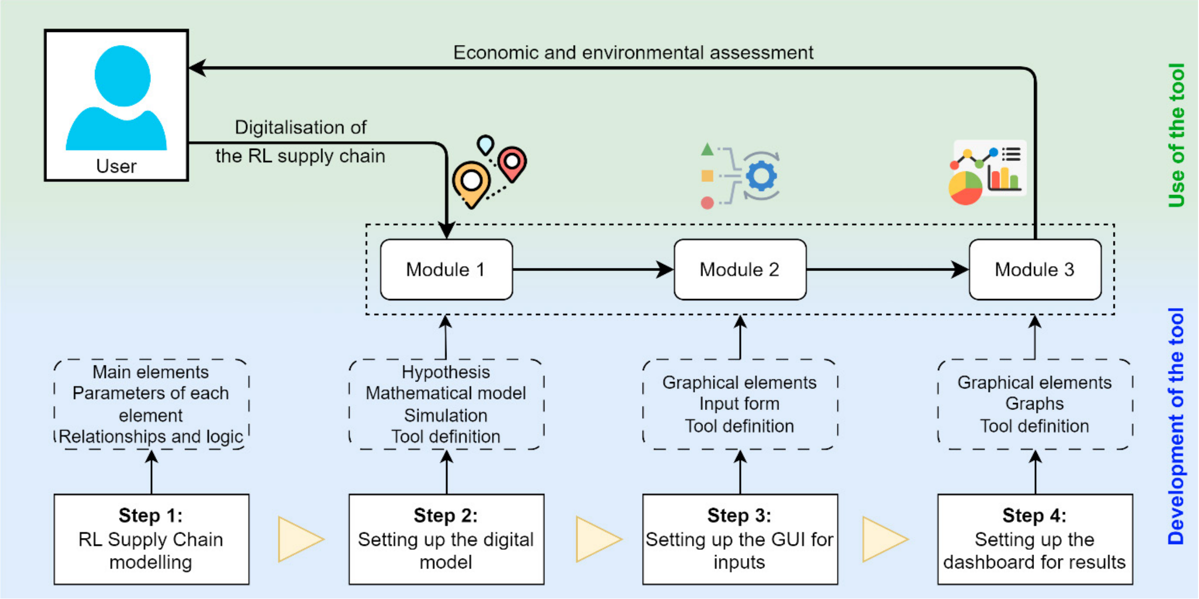

Figure 1 - Methodology used for developing the framework for reverse logistics assessment.

3. APPLICATION

This section provides a detailed explanation of the four steps of the methodology, as applied in the SIIP project case study.

Step 1: RL supply chain modelling

The reverse logistics supply chain was modelled with three key nodes as shown in Figure 2. These nodes cover the whole process of recovering an end-of-life product from the user to the receiving centre where it is remanufactured or recycled:

- **EOL Location**: the node represents the location of the product to be remanufactured/recycled.
- **Warehouse/Pre-Process Centre (CS)**: the node represents a possible storage warehouse or pre-processing centre.
- **Remanufacturing/Recycling Centre (CR)**: the node denotes the facility where the EOL product is remanufactured or recycled.

Each movement between these nodes is modelled as a transportation activity. The model identifies two specific transportation routes: (i) from the EOL Location to the CS, and (ii) from the CS to the CR. These routes capture the flow of materials and associated logistics activities within the reverse logistics network.

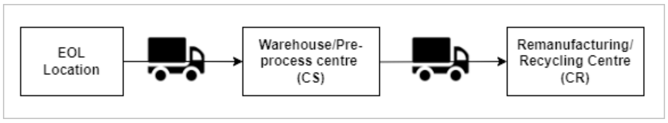

Figure 2 - RL supply chain key elements

The main parameters characterizing each element in Figure 2 were identified based on interviews with industry personnel, ensuring the model's applicability in an industrial context.

Five parameters were defined for the EOL Location node to characterise the (i) geographical location (*Name*, *Location*); (ii) type of EOL product (*Product Type*) and (iii) generated quantity (*Quantity unit measure* [um], *Unit generated quantity* [um/t]). Moreover, two logics were defined to recover the EOL product, i.e., (1) Retrieval from Customer (RDC) where the remanufacturing/recycle centre organizes the transport to collect the product from the EOL Location node; (2) Customer Pickup (CPR) where the user delivers the product to the warehouse/pre-process centre.

Five parameters were defined for the CS node to characterise the (i) geographical location (*Name*, *Location*); ; (ii) unit cost of the CS considering both variable and fixed costs (*Unit CS cost* [€/um/t], *CS fixed cost* [€/t]) and (iii) unit CO2 emission related to the activities of the CS (*CS CO2 unit emission* [gCO2/um]).

Two parameters were defined for the CR node to characterise its geographical location (*Name*, *Location*). It is worth noting that any other parameter was defined for this node as the remanufacturing/recycling activities carried out within the CR node are outside the scope of the proposed framework.

Finally, five parameters were defined for the Transportation activity to characterise the (i) type of vehicle (*Type*, *Maximum load capacity* [kg]); (ii) travelled distance (*Distance* [km]); (iii) unit transport costs (*Unit transport cost* [€/kg]) and (iv) unit CO2 emission related to the transportation activity (*Transport CO2 unit emission* [gCO2/kg/km]).

Step 2: setting up the Digital Model

The AnyLogic® software was selected for the design and development of the reverse logistics simulator due to its flexibility, adaptability, and capability to support the creation of multi-method models. These features make it an ideal software for capturing the complexity and variability of the reverse logistics process. In addition to its robust modelling features, AnyLogic® is highly regarded for its problem-solving focus, which allows it to address real-world challenges effectively. The modelling approach adopted for the simulator integrates discrete event and agent-based methodologies, providing a dynamic and comprehensive view of the reverse logistics process. Hybrid simulation was chosen to capture both temporal and spatial dynamics. Discrete event modeling manages the system's temporal evolution, ensuring actions occur at each timestep. Agent-based modeling defines the structure of each component of the supply chain, allowing them to share parameters while maintaining distinct attributes and behaviors for greater flexibility. This approach enables the simulation of multiple branches within the same framework, allowing, if necessary, to capture their interactions and dependencies. Each branch incorporates the key elements identified during the analysis phase, such as nodes and transport activities. These elements are tailored using parameters defined in the earlier stages of development, ensuring that the model is accurately calibrated to reflect real-world conditions and variations. The mathematical model, which connects all input parameters with the corresponding KPIs, has been implemented to calculate results for each branch of the supply chain. This includes scenarios where numerous branches are simulated simultaneously, enhancing the simulator's scalability and relevance to complex industrial applications. The model can be adapted to different timestep granularities for the input parameter's *Unit generated quantity* and can accommodate various temporal windows, corresponding to different durations of the simulation, to suit specific needs. This flexibility enables the analysis of both short-term performance and long-term trends, providing valuable insights into the impact of various operational strategies over different timeframes. The simulator has been specifically designed for easy configuration, allowing users to customize it to meet the unique requirements of different industrial reverse logistics branches.

Step 3 - Setting Up the GUI for Inputs

Excel was chosen as the input GUI for the supply chain model due to its widespread use in industrial contexts, ease of use, flexibility, and compatibility with AnyLogic®, allowing for seamless data integration and efficient management. The input sheet was set as a table where the columns include the parameters defined in Step 1 and the rows can be used to digitalise the branches of the RL supply chain, i.e., each row is a specific route between the start and end point of the supply chain; or the same route can be modelled in multiple rows by considering each time different configurations or logics, i.e., rows can be used to conduct a what-if-analysis to find the best configuration for a specific route. Once the Excel input file has been fulfilled, the user can load it into the AnyLogic® simulator to run the simulation according to its data. AnyLogic® will instantiate a number of supply chains equal to the number of rows in the Excel file, allowing the simulation to reflect the different configurations or scenarios represented in the data.

Step 4 - Dashboard for Results

The simulation outputs can be visualized in AnyLogic® as charts, both for each timestep and as aggregated totals. Additionally, detailed output data are exported to a dedicated sheet within an output Excel file, enabling users to easily analyze them using the tools provided by the Excel suite. Specifically, in line with the case study needs, the outputs are provided for each scenario, corresponding to each row of the input sheet, and include: (i) the number of trips for each branch; (ii) CO2 emissions for each branch, both for transport activities and for storage; (iii) quantities generated; (iv) costs for each branch, both for transport activities and for storage; (v) total costs; and (vi) total CO2 emissions.

4. RESULTS AND DISCUSSION

The potential of the proposed framework and the flexibility of the developed solutions were applied using the real-world requirements of the SIIP project case study. The case study involved Artigo, a global industrial plastics manufacturer interested in developing circular strategies. Specifically, the project focused on the manufacturing supply chain of plastic-based flooring materials. The returned product was scrap material generated during the installation of new flooring at construction sites. This scrap can be reintegrated into production process rather than disposed of, through the implementation of an economically viable return policy.

Two reverse logistics supply chains were simulated based on the case studies suggested by Artigo. Supply Chain 1 consists of three EOL locations distributed in Switzerland and one RC node located in Italy. Supply Chain 2 consists of three EOL locations distributed across Europe (Denmark, Belgium and Poland), with the RC centre also located in Italy. For each supply chain, two configurations were simulated: the first considers direct transportation between the EOL Locations and the RC centre, while the second introduces a CS node, where materials are stored before being transported to the RC node. In the first supply chain, the CS node was positioned in Italy, while in the second, it was placed in Germany. The supply chains and configurations are represented in Figure 3, where the red points represent the EOLs, the blue point represents the CS and the orange point represents the RC.

The selected time unit for the simulation has been the week, and the simulation covered a full year (52 weeks). The quantities generated by the EOL Locations were based on Artigo's estimates for large-scale installations. Specifically, 3 levels of total weekly generated quantities across the three EOL Locations were considered: (Q1) 600 kg/week, (Q2) 1200 kg/week and (Q3) 2400 kg/week.

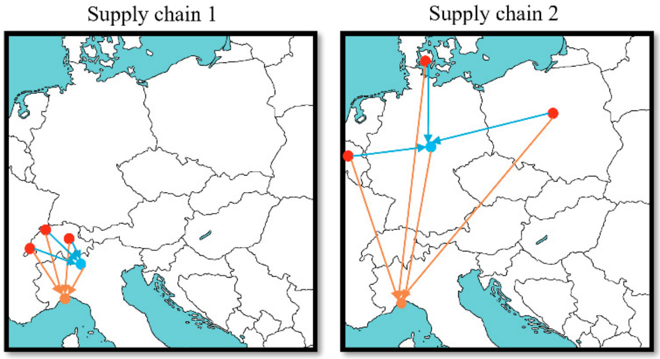

Figure 3 – RL supply chains and configurations.

Each week, these quantities were randomly distributed among the three EOL Locations. A total of 12 scenarios were simulated considering the 3 levels of generated quantities, the two supply chains and the two configurations for each supply chain, as represented in Table 1.

Table 1. Scenarios simulated

EOL Location generated quantity	Supply Chain	Configuration
600 kg/week	Supply chain 1	Yes CS
		No CS
	Supply chain 2	Yes CS
		No CS
1200 kg/week	Supply chain 1	Yes CS
		No CS
	Supply chain 2	Yes CS
		No CS
2400 kg/week	Supply chain 1	Yes CS
		No CS
	Supply chain 2	Yes CS
		No CS

For each scenario, costs and CO2 emissions were calculated under the assumption that transportation from EOL locations occurs whenever any quantity is generated, while transportation from the CS node is triggered only when the accumulated quantity reaches the full capacity of the transport vehicle.

Storage centre (CS) costs included stocking costs, energy costs, natural gas costs and labour costs. Stocking costs were assumed to be 5% of the economic value of the goods. Energy and natural gas costs were based on unit prices in the respective countries and the average daily consumption of Artigo's reference warehouse. Labour costs were estimated based on two operators working 40 hours per week, with hourly wages adjusted for each country.

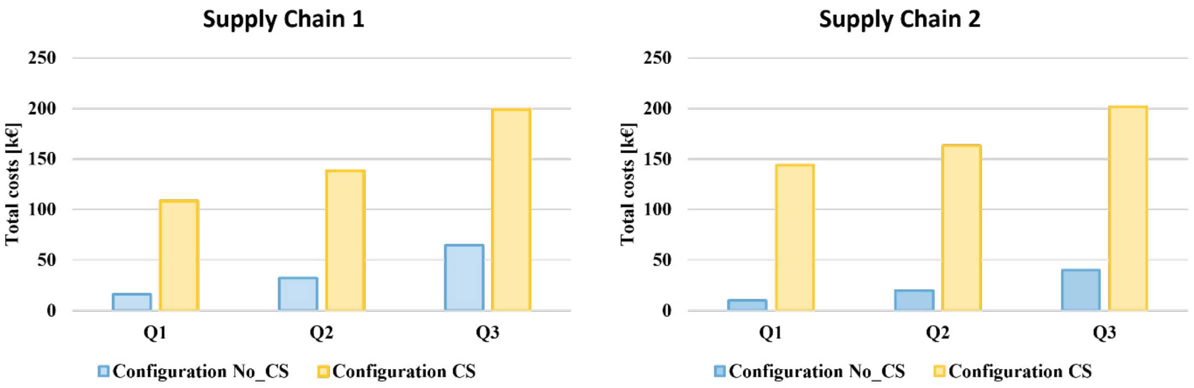

Figure 4 – Total costs for both supply chains and configurations

CO2 emissions for each scenario were calculated taking into account transport and storage activities. Transport emissions were based on an emission factor per unit weight and distance travelled [gCO2/kg/km] derived from SimaPro® LCA data for a EURO5 truck with a capacity of 7.5-16 tonnes. For storage activities, an emission factor per unit of processed product was formulated using LCA data from Artigo's warehouse.

Figure 4 illustrates the results, highlighting the total costs incurred across the two supply chains for each configuration, while accounting for the varying weekly quantities produced. The configuration without a centralized Storage (CS) node (NO_CS) incurs lower costs compared to the configuration with a CS node. This is attributed to the additional costs associated with the CS, such as rent or amortization expenses.

When focusing on the NO_CS configuration, it is observed that total costs are lower for Supply Chain 2 compared to Supply Chain 1, despite the longer transportation distances involved in Supply Chain 2. This counterintuitive result can be explained by the higher transportation costs associated with routes originating in Switzerland (Supply Chain 1) relative to other parts of Europe (Supply Chain 2).

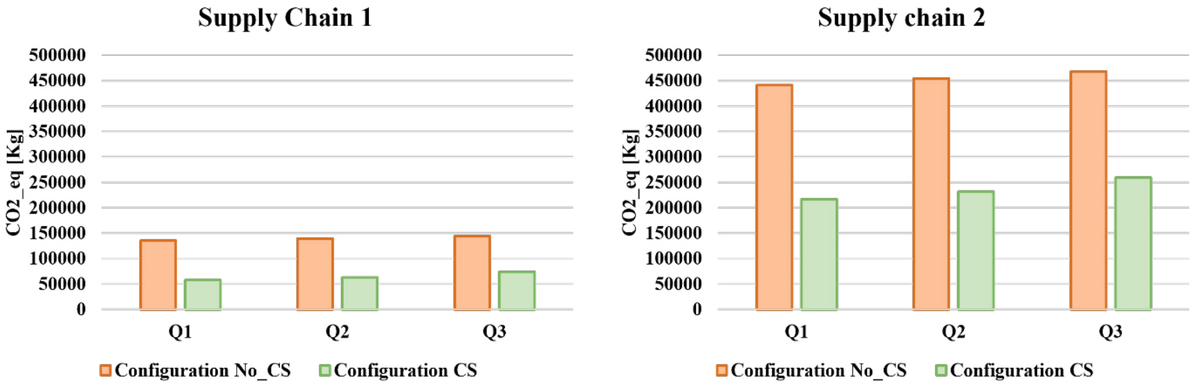

Figure 5 – Total emissions for both supply chains and configurations

In contrast, when analyzing the configuration with a CS node, the situation reverses. The inclusion of the CS node alters the cost structure, as it introduces fixed and variable costs related to storage and pre-processing activities. Additionally, the specific locations of the CS nodes influence cost outcomes. In Supply Chain 1, the CS node is located in Italy, whereas in Supply Chain 2, it is situated in Germany, where operational costs—such as labor and facility expenses—are typically higher. These differences account for the higher overall costs observed in Supply Chain 2 under the CS configuration.

Figure 5 presents the results of CO_2 emissions for the two considered supply chains and configurations. The primary factor influencing the emissions is the total distance travelled. Supply Chain 2 generally results in the highest emissions due to the longer distances required to transport materials to the remanufacturing/recycling centre (CR) in both configurations.

Interestingly, in both Supply Chain 1 and Supply Chain 2, the configuration with a Centralized Storage (CS) node consistently achieves lower emissions, regardless of the amount of scrap material generated. This outcome underscores the environmental benefit of introducing a CS node, as it reduces the total kilometres travelled—a key contributor to emissions in reverse logistics. By accumulating materials at a CS node before transporting them to the CR, the logistics process becomes more efficient in terms of environmental impact.

When comparing costs and emissions, a trade-off becomes evident. While the inclusion of a CS node significantly reduces emissions, it incurs additional costs due to the need for warehouse facilities, which include fixed and operational expenses. Conversely, the direct transportation configuration (NO_CS) minimizes costs but leads to higher emissions due to increased transportation distances.

Ultimately, the decision on which configuration to adopt depends on the company's strategic priorities. If environmental sustainability is a primary goal, incorporating a CS node is advantageous. However, if cost efficiency is paramount, the direct transportation configuration may be preferred. Companies must weigh these factors carefully to align their logistics strategy with their broader objectives.

5. CONCLUSION

This paper presented a hybrid simulation methodology that integrates agent-based and discrete-event simulation to model and evaluate RL. Developed within the framework of the Sustainable Intelligent Industrial Planning (SIIP) project, the proposed methodology emphasizes a structured approach comprising four steps: (1) modelling the RL supply chain, (2) developing a digital representation using the AnyLogic® platform, (3) configuring user-friendly input parameters via an Excel interface, and (4) visualizing performance through dashboards with key performance indicators. The methodology enables a comprehensive analysis of economic and environmental impacts in real-world RL scenarios.

The application of this methodology to the case study involved two distinct supply chain configurations. The results highlighted key trade-offs between costs and environmental impacts. The intermediate storage centre, while effective in reducing CO_2 emissions by minimizing transportation distances, incurs additional costs associated with storage operations. Conversely, direct transportation eliminates these storage costs but results in higher emissions due to increased transportation activity. On the theoretical aspect, the findings underscore the importance of evaluating both configurations in the context of a company's sustainability and financial objectives. Considering managerial implications, the application of the proposed methodology allows for a better assessment of the RL context, which may lead to improved strategic decisions.

This study has some limitations: the first limitation is the reduced number of scenarios simulated. Simulating different products with higher value could completely change the perspectives, since its impact on the total cost would be much higher than the material simulated in this paper. Specifically, higher-value products might lead to an increase in storage costs at the storage centre. Moreover, only 3 material quantities were simulated, while increasing these quantities may generate different result in both configurations, due to the higher storage costs – which would impact especially on the case of direct transportation – and the higher number of travels – which would mainly impact on the number of travels.

The authors will address these aspects in future works.

6. AKNWOLEDGMENT

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