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Assessing the Circular Transformation of Warehouse Operations through Simulation

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Abstract

Companies across industries increasingly prioritise environmental responsibility, driving initiatives to minimise environmental impact. The logistics industry generates substantial material waste, with cardboard being the primary packaging material. Applying Circular Economy (CE) principles to control usage is crucial for enhancing sustainability. However, there is a significant lack of studies on transforming warehouses into more sustainable operations. This paper focuses on studying the ability to transform the linear supply chain of distribution warehouses into a circular supply chain by applying lean manufacturing principles to eliminate cardboard waste. A framework outlining the project's methodology is presented to illustrate the steps taken to apply the concept of CE. The paper also tests the capability to simulate warehouse operations with engineering software using limited available data to generate multiple scenarios. A comparative evaluation is shown to demonstrate the effectiveness of each alternative and determine the optimum solution. Results indicate that models that do not consider handling the recycling process inside the warehouse demonstrate increased flexibility and improved efficiency. Furthermore, suggestions for future improvements are presented, assisting that on-site actions are grounded in a simulation that reflects reality.

Keywords: Circular Supply Chain (CSC), Circular Economy (CE), LEAN manufacturing, WITNESS, engineering simulation.

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1. Introduction

In a rapidly changing world, transport and logistics companies must focus on decarbonisation and explore the feasibility of implementing greener concepts in their warehouses. By transforming warehouse operations into a closed-

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loop system, this study offers practical solutions to minimise waste and enhance sustainability, thereby contributing to the broader goal of a circular economy.

This project investigates the application of circular economy principles using discrete event simulation (DES) in the warehouse. The simulation model, developed with WITNESS software by Lanner, will be based on company-provided data. Various scenarios will be analysed to determine the most optimal design for achieving their sustainability goals. Lean manufacturing principles are applied. VSM and 6R concepts are also considered while developing the model. Achieving a fully closed loop involves numerous factors across different industries, including stakeholders, warehouses, recycling companies, and even uncontrollable factors like customer behaviour. This paper will focus on a specific part of the process rather than the entire supply chain framework. Four primary wastes were identified after observing the warehouse operations: cardboard, tape, wrapping stretch foil, and labels. Due to the interdependencies among these materials and constraints on time and resources, the focus will primarily be reducing cardboard waste.

This study aims to understand the warehouse's current situation and generate an idea of transforming it into a fully circular supply chain. It will also consider how other wasted materials and factors must change or improve to adopt this new concept. This project must be accomplished through some objectives: finding solutions to eliminate the identified types of waste, knowing the involved industries to achieve the CE transition, developing strategies to ensure the sustainability of the closed-loop supply chain model in the long term, and suggesting improvements for the future.

This paper is structured as follows: Section 1 provides an overview of the paper's objectives and scope. Section 2 is the background and literature review, clarifying the basic concepts and identifying the research field gaps. Section 3 details the methodology for transforming the linear supply chain into a circular. Section 4 describes the simulation model, outlining all scenarios and presenting the experimental results. Section 5 offers a detailed discussion and analysis of the results. Finally, Section 6 concludes the paper.

2. Background and literature review

2.1. Overview of the environmental impact of logistics operations

Logistics operations affect environmental sustainability directly and indirectly through pollution and resource depletion [1]. That is the biggest motivation for logistics companies to adopt change [2]. Transforming into more green operations in logistics has a massive impact on improving the supply chains towards sustainable functions [3]. As a result, the more green the operation becomes, the more environmental harm is reduced, so logistics companies must consider the concept of environmental sustainability in their operations [4]. To achieve this purpose, A change initiative must be outlined, involving the collaboration of various stakeholders from the private and public sectors [5].

2.2. Circular economy concept and its importance in enhancing warehouse operations.

According to [6], organisational concern about environmental management is increasing. In this context, companies are entitled to demonstrate to their stakeholders the sustainability values they should stand for and the possible solutions to maintain them. As per [7], a circular economy could be a fitting solution, especially for sectors pursuing more sustainable growth [8]. This new circular economy model is designed to eliminate waste and pollution by recycling, reusing, refurbishing, and repairing existing environmentally insufficient systems [9].

Since logistics impacts the environment, especially in the transportation of goods, all related fields are collaborating to keep greenhouse emissions under control [4]. Logistic functionality within management decisions has become more essential. Based on the principles of the circular economy model, it appears to be a practical solution for developing a company sustainably. Many stakeholders require more explanation of the circular economy application to their business model since it affects them [10].

Warehouse operation is essential for supply chain logistics strategies because it impacts productivity, operational costs, and performance [11]. To meet the necessary changes in sustainable performance, adaptation to economic trends is critical for warehouse planning and strategies [12]. Applying these essential changes is a further strategic decision of how environmentally and economically valuable each change would be to the company [13].

2.3. Lean manufacturing tools and their importance in improving the sustainability of warehouse operations.

One of the concepts used in this paper is the LEAN manufacturing processes, which use value stream mapping (VSM) to identify waste. A value stream map collects all value-added and nonvalue-added activities, starting from raw materials and extending to end retailers or customers, to identify and eliminate waste activities from the process [14]. The integration of VSMs and related concepts has been carried out to enhance their capabilities. For example, VSM emerged with supply chain product development methodologies and agent-based systems. Integrated 6R into the VSM makes activities with the potential to reduce, redesign, reuse, recycle, recover, and remanufacture more easily identified. Companies are integrating lean and 6R concepts to analyse waste and reduce resources in a circular economy [15]. Training and education are essential in achieving the sustainability of value creation and social well-being. The CE's approach is powerful because it aims to reduce cost and waste while increasing resource efficiency by reusing, reducing, recycling, recovering, redesigning, and reprocessing (6R) [16]. It is worth mentioning that the 6R method is being tried but is limited to 3R applications for specific products [17].

On the other hand, there is a significant interaction between Lean and CE concepts, which will benefit the industrial sector. Thus, the combination of them is naturally occurring. The CE model offers an optimum solution to the current shortage of natural resources and environmental degradation while providing a closed-loop economic system [18]. Conversely, Lean methodologies have effectively reduced waste and generated value, improving efficiency and financial gains [15].

2.4. Challenges and gaps in current research on implementing circular supply chains.

The literature still lacks a sustainability-focused perspective within the circular supply chain [5]. Circular economy (CE) enablers are still in a promising stage [3]. Additionally, the literature review revealed a lack of information on warehouse operations related to the circular economy, and no practical data is available for building simulations due to an absence of studies in this area. However, valuable concepts were discovered that can assist in answering the research questions and generating reliable outcomes.

3. Methodology

This section illustrates the methodology for transforming a warehouse operation into a circular supply chain, focusing on cardboard flow. The methodology involves collecting data to understand the warehouse operations, setting parameters, making assumptions regarding the missing data, and finally building the current model. The following section provides a diagram that further clarifies the study's methodology.

3.1. Framework construction

Several steps are required to build the model, as proposed in Figure 1. Initially, understand the current warehouse process to identify the parameters and determine the waste. This understanding will be achieved by implementing the flow map process. Subsequently, review and decide the parameters. Following this, a set of assumptions for missing data, analysis of the current model's results, and enhancement are needed to transition it into a closed-loop process. Finally, propose the final model.

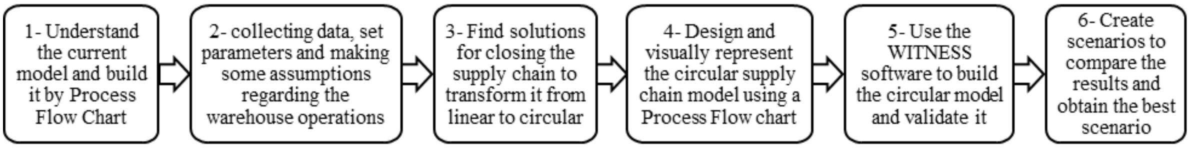

Fig. 1. The proposed framework.

3.2. Detailed explanation of the current warehouse operations.

- **Collecting data**

Data is required to visualise the overall picture of warehouse operations to construct the essential model. A meeting with a logistics company was arranged to gain insights into the current activities and processes within the warehouse. The company expert provided the needed numerical data. Additionally, research was conducted online to find similar warehouse layouts for comparable work. After the warehouse operation process was illustrated, approximate figures were proposed to the company, and the experts approved them.

- **Parameters**

parameters are determined by referencing various sources, primarily by examining similar studies in the field. While there are limited papers specifically on circular economy within warehousing or logistics companies, several published articles on related topics are identified. Once the parameter matrix is set, an understanding of the potentially required parameters is attained. By examining this matrix alongside the current process flow chart, the key parameters are number of arrival cardboard (Part/hour), time between arrivals (Hours), time to prepare packages (Hours), time to package (Hours), Storage capacity (Parts), and Number of dispatched packages (Part/hour).

- **Assumptions**

After thoroughly understanding all preceding aspects of the process, some variables remain unknown or undetermined. Therefore, some assumptions had to be made before constructing the simulation model. These assumptions are detailed below.

  - All cardboard specifications conform to a standard size of 30×30×30 cm.
  - ten daily trucks for delivery. Each truck transports a maximum of 15 pallets containing 80 boxes.
  - Parcel information barcodes are directly printed onto the boxes.
  - Packaging tasks are conducted within the warehouse.
  - Warehouse operations extend for 12 hours per day.
  - Maintenance and idle times of machinery are not taken into consideration.

- **Process Flow Map of the Current Model**

The process flow map provided in this section is designed to illustrate the primary processes of cardboard. However, it is essential to note that no exact similar work was found when conducting the literature review. Therefore, the flow map was created based on related work [19] and observations of warehouse operations. The current module, illustrating the operations of cardboard from arrival at the warehouse to dispatch, is shown in Figure 2.

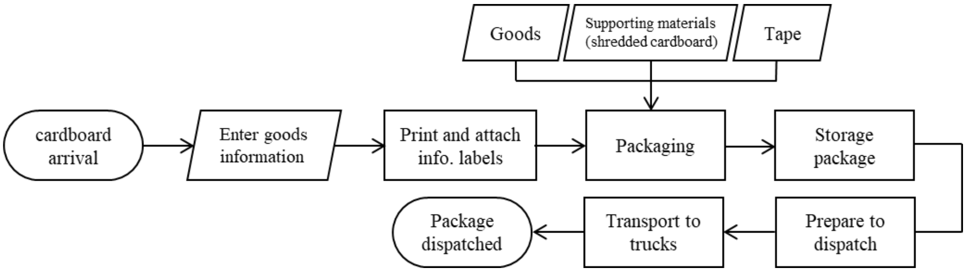

Fig. 2. The current model of the warehouse operations.

3.3. Technical approach

Establishing a fully circular supply chain in the initial phases is unrealistic. To achieve circularity, cardboard, previously considered waste in the current model, must be reintroduced into the system. Various factors contribute to this challenge, including cardboard waste generated by customers (individuals and businesses) whose behaviour cannot be controlled or forced to align with the company's objectives. Some returned cardboard may not be recyclable and must be discarded as scrap. Several suggestions are made to streamline this process and encourage customer cooperation.

The first proposed solution targets business customers who are more receptive to collaboration. The company can establish contracts encouraging clients to return cardboard packaging in exchange for expedited deliveries and exclusive pricing, promoting sustainability and strengthening partnerships. Additionally, the company can implement a loyalty program, offering benefits to influence behaviour and align with sustainability goals. Supported by previous studies [20], this cost-effective solution can raise awareness about environmental conservation. Customers earn points for returning cardboard, redeemable for discounts, partner vouchers, or exclusive promotions, fostering community engagement and highlighting sustainability's personal and social rewards.

Furthermore, the company should track cardboard as part of its operations before it leaves the warehouse rather than treating it as waste. As shown in Figure 3, the tracking process monitors dispatched and returned cardboard, identifying cooperative businesses or customers. This allows the company to track the percentage of returned cardboard and offer discounts or promotions to customers who meet the targets, encouraging sustainability practices.

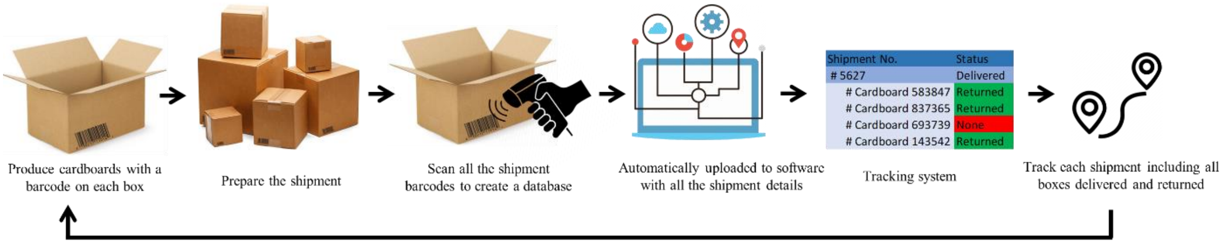

Fig. 3. The process of tracking the cardboard.

The final proposed solution is to refurbish or recycle the cardboard based on the condition of each piece. Returned cardboard undergoes a quality inspection to assess its condition. If the cardboard has minor issues, such as small tears or scratches, recycling may not be the most efficient or cost-effective solution; refurbishing it would be preferable. However, if the cardboard's condition is poor, it will be recycled. Recycling is crucial for establishing a circular economy, especially in this project, as it converts waste into new raw materials and extends its lifetime.

- **Process Flow Map of the Circular Model**

To reduce waste and enhance resource efficiency, the linear supply chain is transformed into a more sustainable and circular one. All the solutions proposed in the previous parts are introduced to improve the circular model. This new model was created using the flow map technique to visually describe the entire process, as illustrated in Figure 4.

This structured method improves sustainability and increases efficient supply chain operation, reducing waste and optimising the use of material in the system. This transition marks a notable advancement in the company's dedication to environmental responsibility and the circular economy.

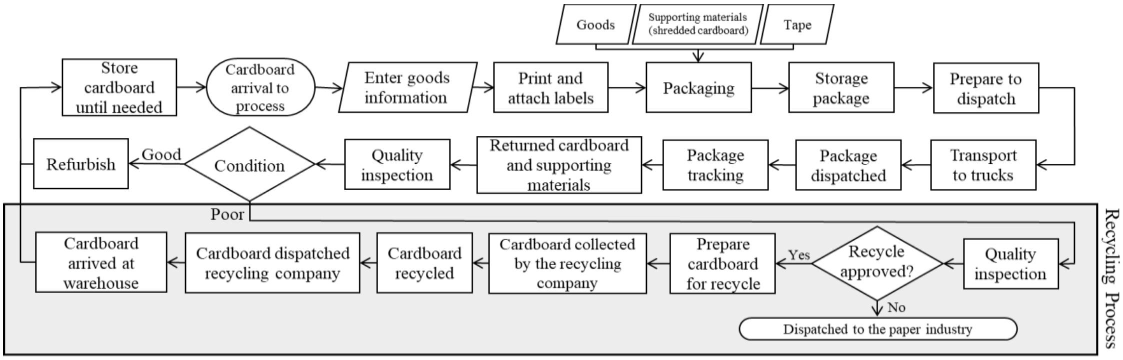

Fig. 4. The process flow map of the circular supply chain.

4. Case study

Digital modelling and simulation can aid decision-making in remaking operations. The discrete event simulation (DES) method uses data-driven analysis to simulate reprocessing systems, though its application in this context is limited [21]. While simulations exist for automotive, electronics, logistics, and construction remanufacturing, more research is needed for robust, data-driven remanufacturing simulations. At this stage, data preparation involves identifying all processes and their durations, setting inter-arrival times for parts, configuring machines based on operation types, determining buffer capacity, and allocating labour based on operation nature. Variables are introduced as counters to monitor the model's performance.

4.1. The experiment

The WITNESS software can simulate a model using various elements, such as parts, machinery, buffers, and workers. A model was built based on the circular model flow map and run using the software. Some bottlenecks appear, and some aspects can be improved. Implementing the VSM concept in the model defined and eliminated the unnecessary elements (such as incorporating two quality check stations into one to serve both processes). The simulation in Figure 5 shows the enhanced model achieved by successfully implementing all proposed enhancements.

After refining the model and ensuring its smooth operation, it is presented to the company for review and verified by its experts. Based on that, various scenarios are studied to improve warehouse performance. These scenarios are outlined in Table 1. Two main models were considered: one with recycling operations and one without (handled by an external company), as shown in Figure 6. Seasonal variations were also examined, with off-peak seasons handling 7,960 packages/shift and peak seasons handling 10,799 packages/shift.

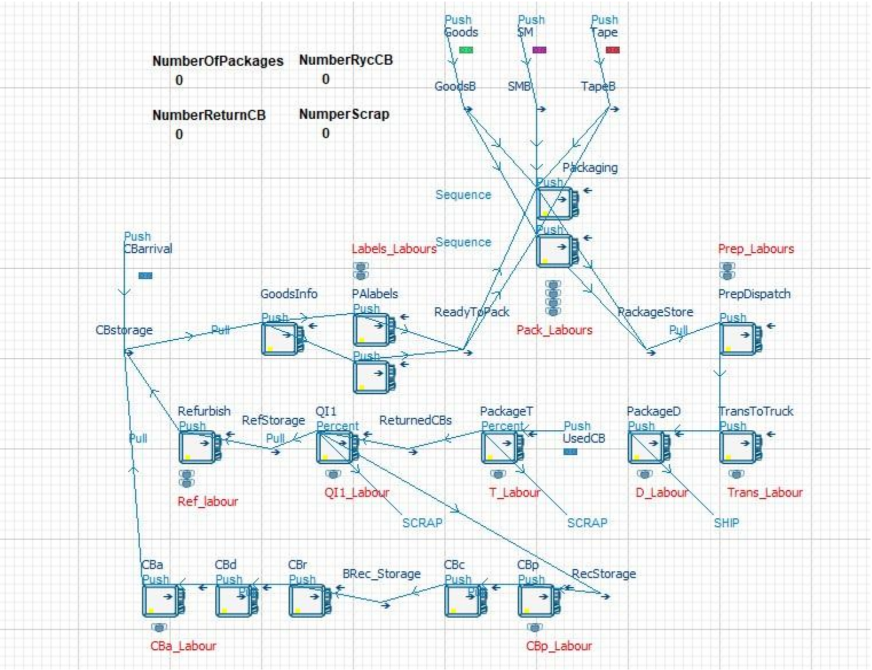

Fig. 5. The simulation model with the recycling process.

Table 1. The model scenarios based on the three levels

Scenario	Level 1	Level 2	Level 3
1	Original Model	off-peak	One shift (12hr)
2	Original Model	off-peak	One week

3	Original Model	off-peak	One month
4	Original Model	Peak	One shift (12hr)
5	Original Model	Peak	One week
6	Original Model	Peak	One month
7	No Recycling Model	off-peak	One shift (12hr)
8	No Recycling Model	off-peak	One week
9	No Recycling Model	off-peak	One month
10	No Recycling Model	Peak	One shift (12hr)
11	No Recycling Model	Peak	One week
12	No Recycling Model	Peak	One month

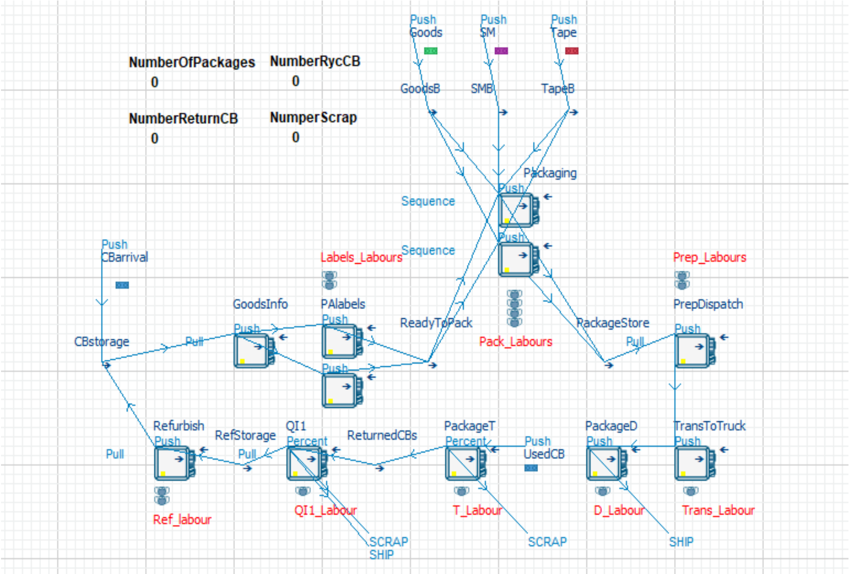

Fig. 6. The simulation model without the recycling process.

4.2. Results

A thorough analysis of the results arising from each scenario will be provided, offering insights into their performance and outcomes. The outcomes will be compared to identify the most effective alternatives for the warehouse to adopt. The results will represent the statistical outputs generated from simulating each scenario. These visuals will provide a clear and insightful summary of the performance and outcomes linked with each scenario.

- **The original model, peak Season**

The model was run for a day (one shift), and it did not take long to see its validation. It was run for one week to evaluate the model's resilience over an extended duration. Notably, some blockages have begun to emerge, primarily attributed to the extended processing time required by recycling machines. The blockage levels increase after running the model for a month (see Figure 7(a)).

- **The original model, off-peak Season**

During off-peak seasons, there is reduced demand, and adjustments were made to the parts input commands to accommodate package arrivals at the warehouse better. After a week of operation, the first two processes show an operational efficiency of less than 50%. The simulation's packaging process efficiency decreases over time, indicating that not all four operators must be active continuously. Additionally, blockages, primarily from recycling operations, remain a critical issue that needs addressing to ensure smooth processes. Moreover, running the model for a month (see Figure 7(b)) revealed a repeated pattern of increasing machine idleness as the simulation progressed. This highlights the need for resource optimisation to enhance efficiency, ensuring that processes are not overburdened and can operate at peak performance.

- **The model with no recycling, Peak Season**

As indicated by the simulation runs, it is commonly noted that blockages occur due to the long queue before the recycling processes. The recycling procedures, which extend over several weeks, require substantial storage capacity. Given that recycling is handled by an external company, the recycling process in the simulation is substituted with a shipping command. After running the model, the results are promising. There are only minor blockages in refurbishing and an average operational efficiency of 95% for the rest of the processes. Over seven shifts, process utilisation rates exceed 90%, though blockages appear in dispatch preparation during demand surges. However, extending the simulation to a month later (see Figure 8(a)) revealed a noticeable blockage increase. Additionally, increasing storage capacity is essential to accommodate high demands during extended periods.

- **The model with no recycling, off-peak Season**

In response to shifts in demand during off-peak seasons, input parameters were adjusted by reducing inter-arrival times and lot sizes to match real-time volumes. No blockages are observed when the model runs for a shift, although some processes experience high idle times. After a week, most processes maintain stable performance, but blockages emerge in the tracking process, negatively impacting efficiency. This bottleneck highlights the need for optimisation to ensure smooth and consistent outputs. In a month-long simulation, results are similar to the one-week run, with stable performance across most processes (see Figure 8(b)). However, blockages in the tracking process persist and worsen, emphasising the importance of optimising this area to align its performance with overall system efficiency.

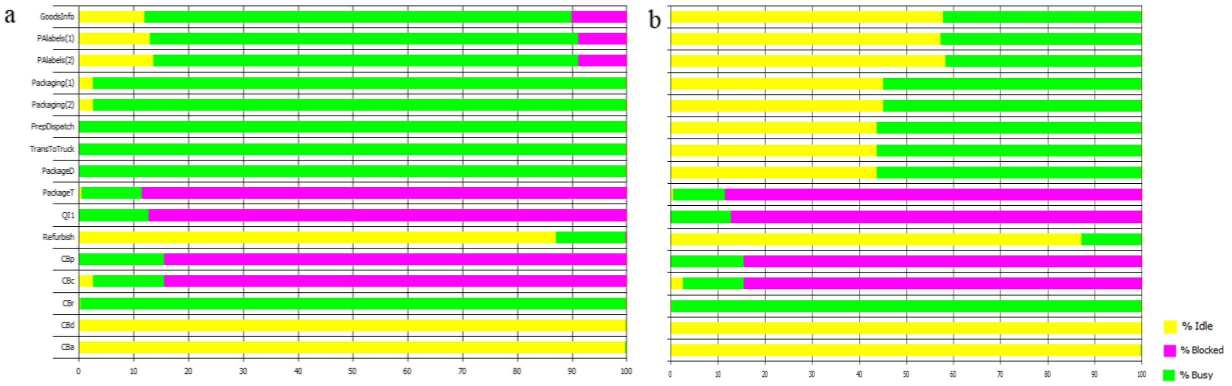

Fig. 7. Running the original model for one-month duration (a) peak season (b) off-peak season.

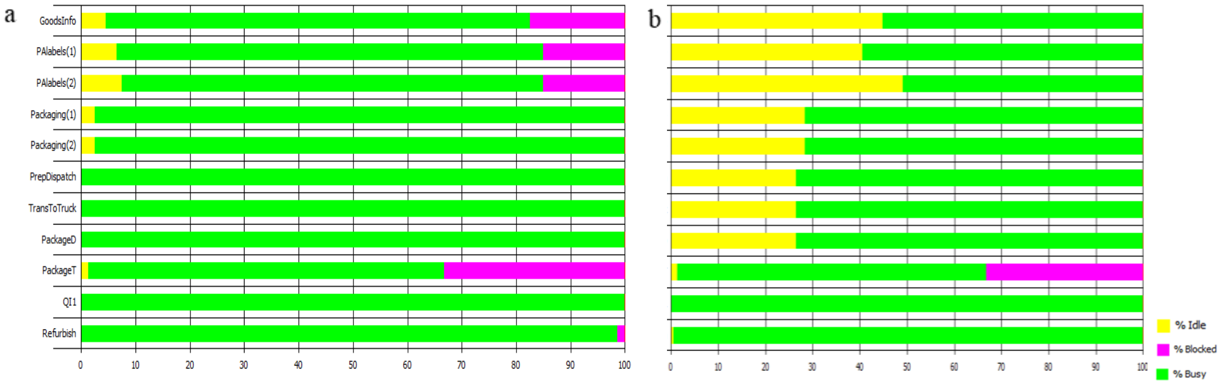

Fig. 8. Running the model with no recycling for one-month duration (a) peak season (b) off-peak season.

5. Discussion

A comparative analysis is conducted based on the results obtained from the simulation outlined in the results section. This analysis focuses on the utilisation rate of the different outputs, corresponding to the circularity index. A higher performance rate indicates better process efficiency. Another essential parameter considered in the comparative analysis is the level of blockage within each process. The assessment criteria are as follows: if the blockage is below 20%, it is categorised as "low"; if it falls between 20% and 50%, it is considered "moderate"; and if the blockage exceeds 50%, it is labelled as "high". To provide a clear and concise presentation of these comparisons, the findings are briefly summarised in Table 2 below:

Table 2. The scenario utilisation rate and blockage level

	Level 1	Level 2	Level 3	Utilisation rate	Blockage level
1	Original	off-peak	One shift	80%	Very Low
2	Original	off-peak	One week	65%	Moderate
3	Original	off-peak	One month	70%	Very High
4	No Recycling	off-peak	One shift	72%	Very Low
5	No Recycling	off-peak	One week	72%	Low
6	No Recycling	off-peak	One month	72%	Low
7	Original	Peak	One shift	92%	Very Low
8	Original	Peak	One week	89%	Moderate
9	Original	Peak	One month	95%	Very High
10	No Recycling	Peak	One shift	95%	Very Low
11	No Recycling	Peak	One week	96%	Low
12	No Recycling	Peak	One month	97 %	Low

Table 3. The Circularity Index

	Utilisation	Blockage Factor	Circularity Index
1	0.8	5	4
2	0.65	3	1.95
3	0.7	1	0.7
4	0.72	5	3.6
5	0.72	4	2.88
6	0.72	4	2.88
7	0.92	5	4.6
8	0.89	3	2.67
9	0.95	1	0.95
10	0.95	5	4.75
11	0.96	4	3.84
12	0.97	4	3.88

The analysis, structured according to level 2, enables systematic comparison between peak and off-peak scenarios, considering distinct input rules for each. Utilisation rates are generally lower during off-peak seasons than peak seasons, with blockages varying based on fluctuating demands. In the model without recycling processes, utilisation rates remain consistent across all runs, suggesting optimal process flow and potential for enhanced resource efficiency. In contrast, the original model experiences fluctuations in utilisation rates and blockage levels over time, highlighting the system's sensitivity to external factors and changing demand conditions. The model without recycling shows minimal blockages during peak and off-peak periods, indicating more efficient operations. Off-peak adjustments, such as labour allocation or extended shifts, can increase efficiency. A weighing system determines the optimal scenario by categorising blockage levels as very low, low, moderate, high, and very high, corresponding to factors of 5, 4, 3, 2, and 1, respectively. The outcome involves multiplying utilisation by the blockage factor, with a higher resultant number indicating a more efficient simulation result (see Table 3).

After thoroughly comparing all scenarios and calculating the Circularity Factor (original model: 8.22 and 12.47 for the no-recycle model), it is clear that the recycling process is the main bottleneck in the system. The model without recycling achieves a higher score than the original model. Since the warehouse has a contract with an off-site recycling company, on-site recycling is unnecessary. Removing the recycling process ensures a smooth flow, allowing the closed-loop system to operate efficiently without encountering blockages.

6. Conclusion

In an era of increasing focus on sustainability and technological advancement, logistics supply chains are interconnected systems handling significant resources. This complexity provides sufficient opportunity for waste reduction and continuous improvement. As companies prioritise sustainability and adopt innovative technologies, optimising logistics operations becomes essential for environmental responsibility and operational excellence.

This study achieved its overarching goal of understanding the warehouse's operations and identifying opportunities for a circular supply chain. The model is constructed and validated using simulation software, initially using default data and later refining it with lean manufacturing methodologies like Value Stream Mapping. This iterative process ensured the model's accuracy and practicality.

The final model, validated against accurate data, reflects warehouse complexities and offers actionable insights for performance optimisation and embracing circular supply chain principles. Material flow is categorised into peak and off-peak seasons, resulting in twelve distinct scenarios with varying outcomes. Notably, the model without recycling operations demonstrates higher efficiency and adaptability, suggesting that outsourcing recycling activities to external companies is more advantageous. This strategic shift promotes optimal flow within the system and supports circular supply chain objectives by seamlessly reintroducing recycled materials. The suggestions for future work include incorporating additional waste materials into the process, such as supporting materials and stretch wrapping foil. Additionally, it is vital to consider the cost of implementing the circular concept and its impact on making informed decisions.

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