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Sustainable reverse logistics network design using simulation: Insights from the fashion industry

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A B S T R A C T

While direct logistics optimization is a common practice, reverse logistics management is frequently neglected. This study explores how reverse logistics configurations affect the environmental sustainability of global supply chains in the fashion industry. The paper addresses the gap in the literature regarding carbon footprint of hybrid configurations for return flows. A case study is conducted in an Italian luxury fashion company with global operations, and we use supply chain simulation to assess sustainability-focused network design alternatives. The findings reveal that decentralizing specific operations significantly reduces carbon footprint without compromising service levels or lead time, both critical aspects in such segment. This research emphasizes the importance of considering reverse logistics in the overall sustainability strategy of supply chains, offering practical insights for businesses seeking to balance environmental impact with operational efficiency in the fashion industry.

1. Introduction

Logistics is covering a key role in the supply chain to measure businesses' service le. Besides the optimization of direct logistics is a well known practice, reverse logistics (RL) is too often overlooked (Kamal et al., 2022), despite its increased relevance. Traditional supply chains focus on delivering products to customers and usually do not efficiently accommodate RL (Barker & Zabinsky, 2008). This oversight in traditional systems presents a significant gap, particularly in high-return industries like fashion, where RL can dramatically impact both sustainability and consumer satisfaction. Nowadays, especially considering online purchases, any businesses have to deal with products returned by customers for non-compliances or even because they could simply change their mind and no longer want the product they ordered (Ambilkar et al., 2022). Looking at the numbers, the most frequently returned online product categories are clothing and shoes (56 %), electronics (42 %) and accessories and jewellery (30 %) (Meghani, 2020). Thus, if we combine clothing, shoes, jewellery and accessories, 76 % of online returns belong to the fashion industry.

The increased attention to sustainability issues, especially considering the shift from linear to circular approaches, even pushes companies to manage the return flows focusing on tradeoffs in logistics services (Gatenholm et al., 2021). The RL that directly impact supply chains the most are the return of products from the end consumer back to the manufacturer (Münch et al., 2023). On the one hand, returning flows became necessary to guarantee the required service level to the final customer, especially in luxury industries. On the negative side, RL can increase greenhouse gas emissions and pollution (Ullah, 2023). For instance, optimizing the returns management process in the global scenario presents challenges to face in terms of localization of supply chain nodes, from green field or as improvement of existing networks.

Evaluating centralization and decentralization strategies is crucial. Additionally, defining hybrid configurations for RL that combine centralized and decentralized approaches depending on the item is essential. Thus, network design can support green and sustainable goals since these choices impact the environmental footprint of global supply chains. This integration of RL into sustainability strategies is where our research brings novel insights, particularly through the use of simulation to assess and optimize network designs. Given the substantial environmental and operational challenges posed by RL in the fashion industry, which sees a high volume of returns, our first research question (RQ1) becomes crucial. The first research question (RQ1) of our research can be therefore formalized as follows:

"*How does network design play a role for suistanability for RL?*"

This question aims to reveal the strategic implications of network

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design choices on sustainability, examining how optimized design can notably reduce environmental impacts and enhance efficiency. By delving into this inquiry, we aim to provide actionable insights that could influence both policy and operational practices within the industry, addressing an urgent need for sustainable development.

Sustainable goals cannot be considered the only target to achieve in RL. Businesses have to manage return processes quickly and cost-effectively (de Araújo et al., 2018). Moreover, some industries prioritize time or cost, depending on their critical success factors. For instance, mass-market sectors will be more oriented on efficient return network, while luxury industries more on lead time, to be reduced even with extra-costs.

While green logistics practices mostly go parallely with efficient solutions, such as reducing transportations to decrease both the emissions and logistics costs, shortening lead time goes in the opposite direction (Rosano et al., 2022). To bridge this gap, we propose employing simulation modeling as a tool to explore the trade-offs between environmental impact and service efficiency, providing a clearer pathway from problem identification to solution implementation. The way businesses handle returns could directly affect how customers feel about the company. By offering options to customers who wish to return items that make it easier for them or, most of all, quicker, it can boost customer satisfaction. To address consumers' needs, companies can move to the air freights instead of the less impacting shipments by sea, road or rail. Besides, delivery frequency can be increased to reduce lead time, even if shipments become smaller and more transportations are therefore needed to fulfill the same requests (Marino et al., 2018).

To manage the trade-off between lead time and environmental impact represents a relevant issue to address. Decision support tools enable managers to make informed choices in RL management, balancing sustainability and customer satisfaction (Allaoui et al., 2019). For instance, simulation modelling can be used to perform what-if analyses, even in challenging industries like the fashion luxury one (Nunziatini et al., 2022). Through simulation, different supply chain networks can be compared by a set of key performance indicators (KPIs), giving managers the information needed to make conscious decisions (Chiadamrong and Piyathanavong, 2017). As industries continue to struggle with balancing operational efficiency against environmental considerations, the second research question (RQ2) of our research can be formalized as follows:

"*How could trade-off between lead time and carbon footprint be managed?*"

This inquiry is designed to highlight the urgency of finding solutions that do not compromise service quality for environmental gains. With rising consumer expectations and stricter environmental regulations, addressing this trade-off is increasingly critical. Our research intends to shed light on strategic decisions that can help firms better manage these conflicting demands, offering a blueprint for sustainable yet competitive business practices.

The remainder of the paper is structured as follows. The next section presents the theoretical background, Section 3 describes the research design while Section 4 presents and discusses the results, finally Section 5 highlights the implications, contributions, and final remarks.

2. Theoretical background

2.1. The role of RL in the fashion industry

The fashion industry is distinguished by its rapid pace and constantly changing trends, and it is encountering significant challenges pertaining to environmental sustainability. A In recent years, there has been a growing recognition of the detrimental impact of the linear fashion model, which follows a "take-make-dispose" approach. Within circular economy, the integral role of RL has been emphasized (Fernando et al., 2022). The transition to this model yields value through the implementation of closed-loop systems, RL, eco-design, meticulous product life cycle management, and the adoption of clean production methodologies (Kazancoglu et al., 2021). RL encompasses a series of steps centered around collecting used goods from consumers, aiming to either reuse, repair, remanufacture, recycle, or appropriately dispose of these items (Aryee and Adaku, 2024). Within the fashion supply chain, RL stands as one of the five essential processes, aligning with sourcing, warehousing, manufacturing, and distribution (Bottani et al., 2020). Although RL covers different options such as reuse, repair, recycle, remanufacture, and land-filling, they have different "sustainability" impact. For instance, a study conducted by Levänen et al., (2021) employed Life Cycle Assessment to examine the CO2 emissions associated with a pair of jeans, considering five different scenarios: base, reduce, reuse, recycle, and share. The findings indicate that the share scenario exhibits the highest global warming potential, primarily due to increased transportation related to product return and refurbishment. Conversely, Sohn et al., (2021) emphasize that production is the primary contributor to the environmental impact when it comes to purchased products. RL is closely linked with return activities that is identified as one of the eight essential business processes within supply chain management, as noted by Marchesini and Alcântara, (2016). RL assumes a crucial role by contributing to the reduction of the environmental footprint associated with textile waste (Hinkka et al., 2023). Additionally, RL helps to recover valuable resources (Van Rensburg et al., 2020), and fosters an environment of customer loyalty and satisfaction (Rasool et al., 2023). Currently, consumers are demanding more accountability and transparency from fashion brands with respect to their environmental and social impacts. At the same time, consumers are also more responsive to participate in RL activities, such as returning, exchanging, repairing, donating, or reselling their used clothing, if they are provided with convenient and rewarding options (Friedrich, 2021).

Despite its importance, RL in the fashion supply chain comes with various challenges and complexities. These challenges encompass enhanced uncertainty (Plaza-Úbeda et al., 2021), issues stemming from the low quality and value of returned products, substantial investment costs (Kazancoglu et al., 2020), a lack of clear and consistent regulations and standards, and a deficit in knowledge and support from top-level management (Moktadir et al., 2020). Consequently, fashion brands must adopt a strategic approach to RL, carefully balancing environmental, economic, and social considerations in their decision-making processes. To address these challenges, simulation emerges as a pivotal tool for exploring trade-offs and optimizing RL operations, enabling better strategic planning and resource allocation (Abid and Mhada, 2021). This integration of sophisticated technologies not only facilitates more robust decision-making but also enhances the sustainability of the logistics processes. In the following section, we discuss how simulation has been effectively utilized in RL to address these multifaceted challenges.

2.2. Simulation use for sustainability aspects in RL

Returned products challenge organisations in predicting demand given the uncertainty of the quantity and quality of returned products while significantly affecting operational activities like scheduling and inventory management (Abid and Mhada, 2021). Therefore, researchers have investigated multiple facets of RL to solve operational issues for increasing sustainability, such as remanufacturing strategies (Lei et al., 2024; Ullah, 2023; Yu, 2022), network design for managing end-of-life (EOL) (Ameli et al., 2019; Govindan and Gholizadeh, 2021; Rentizelas et al., 2022), reuse and recycling (Roudbari et al., 2021; Singh et al., 2023; Yu and Solvang, 2016), and more. Abid and Mhada (2021) present a table summarising dozens of literature reviews covering different aspects of RL.

In such context, simulation has for long been used to investigate such issues regarding RL. More recently, as an attempt to incorporate sustainability-driven decisions, the trade-offs between economic and environmental metrics are considered (Yanikara and Kuhl, 2015). Such models intend, among other things, to deal with alternative configurations for RL networks, respond to demand uncertainty, or even identify how consumer decisions influence logistics networks. The areas of applications vary but are primarily related to discrete manufacturing, such as electric and electronic equipment, the fashion industry, and packaging. Prior studies focus mostly on economic and environmental KPIs, but still limited focus on social ones. Table 1 summarises details of the identified related literature that uses simulation to further explore sustainable aspects in RL.

In practice, these papers use simulation to investigate different trade-offs arising from RL, most with a major cost-related approach. However, there is a notable absence of studies addressing the trade-off between lead time and sustainability. This trade-off, increasingly pertinent due to consumer-driven demands, is particularly prevalent in time-sensitive supply chains, such as the fashion industry. In the next section, we present our research design and detail how we approach such a gap.

Table 1
Summary of related literature.

References	Objective	Area of application	KPIs analysed	Simulation type
(Yanikara and Kuhl, 2015)	Identify alternative configurations for RL networks considering productivity and sustainability performance measures with weighted-factor comparison for evaluation	Generic product	Costs; inventory; GHG emissions	Discrete-event simulation [Simio]
(Chen et al., 2017)	Identify an alternative solution to the collection of the citywide e-commerce reverse flows	Generic product	Success rate; number of delays; distance ratio	Deterministic Model [Matlab]
(Kim et al., 2018)	Develop a robust closed-loop supply chain model to respond to uncertainty from RL	Fashion industry	Profit	Deterministic Model [ILOG CPLEX Studio]
(Elia et al., 2019)	Compare different alternatives for a WEEE collection service	Electric and electronic equipment	Number of collections; distance travelled; waste collected; time	Hybrid Model (DES, ABM, SD) [AnyLogic]
(Green et al., 2019)	Analyses the influence of take-back decisions on total supply chain cost and carbon footprint	Cycling industry	Costs; carbon emissions	Hybrid Model (DES, ABM) [AnyLogic]
(Beiler et al., 2020)	Analyse the RL system considering the TBL guidelines	Packaging	Storage costs; recycling rate; employment ratio	System Dynamics [Vensim]
(Labelle and Frayret, 2023)	Assessing the impact of consumer decisions on RL material flows and proposing a tool to predict the performance of a RL network	Packaging	Waste collected	Agent-based Simulation [AnyLogic]

3. Methodology

3.1. Case selection and data collection

3.1.1. Company overview

The company chosen for this case study is an esteemed brand within the fashion luxury sector, with its headquarters situated in Italy. Renowned for its excellence in the fashion industry, the company has implemented a centralized returns system. The intricacies of its operations unfold within a well-structured 3-tier fashion supply chain. This includes a central warehouse located in Italy, serving as the epicenter for product distribution. Complementing this central hub are 10 strategically positioned local warehouses and stores, 5 outlets, and a diverse clientele of end customers. It's noteworthy that the local warehouses, stores, and outlets are strategically located in various countries spanning all five continents. The company handles a wide array of products, including appareal, bags, shoes, jewelry, and various accessories, showcasing the breadth of its offerings within the fashion domain. This unique configuration positions the company at the forefront of the international fashion market, allowing for the seamless management and distribution of its varied product portfolio on a global scale.

A theoretical convenience sampling strategy was employed for the case selection (Voss et al., 2002). The case study was selected following a comprehensive investigation based on secondary sources and a comparison with other potential alternatives (Ünal et al., 2019). The rationale for selecting this specific company is twofold. First, its global operational scope and centralized returns system provide a comprehensive framework for analyzing RL in the luxury fashion sector. Second, the company's reputation for excellence and its diverse product portfolio make it representative of the broader luxury fashion industry, thereby enhancing the generalizability of our findings, therefore despite the limited generalizability of a single case study, the authors are confident that their conclusions can be somewhat extrapolated and applied to similar scenarios (Yin, 2014).

3.1.2. Data collection and analysis

While the company also oversees direct logistics, this case study will specifically focus on RL, delving into the analysis of return flows. The initiation of the returns process is consistently handled by the Customer Service Department. When a customer opens a return request, this department is responsible for selecting the type of return, a decision that depends on the specific garment in question. Two main types of returns are identified: markdown and full price. In the case of full-price returns, the products are intended to be resold at the store's original list price, whereas markdowns are products that have lost value. This initial classification reflects the market value of the product and is independent of its condition, whether damaged or not. A further categorisation of return types can be made on the basis of product category, distinguishing between jewellery returns and non-jewellery returns. In addition, the reconditioning type is determined, which specifies the type of inspection the product must undergo when it arrives at the central warehouse for requalification.

Considering the requalification process in return flows is essential, as it significantly influences the final destination of returned products, impacting both the lead time and environmental sustainability of the return flows. Requalification ensures that returned items are accurately categorized and directed to the appropriate channels (e.g., stores, outlets, family sales, or destruction), thereby enhancing the efficiency and reducing the carbon footprint of RL operations. By understanding and optimizing this process, a company can improve its overall sustainability and operational performance. The return process, including the shipment of products, can initiate from either a store or a local warehouse. Subsequently, the products are transported to the central warehouse, the exclusive location for the requalification process. Requalification is not conducted in stores or local warehouses but exclusively at the Central warehouse. Within the central warehouse, the outcomes of the requalification process are determined, with each item assigned a specific outcome. Consequently, each product follows its unique route until it reaches its ultimate destination. Following the requalification process, the ultimate destinations for items include stores, outlets, a choice between stores or outlets, family sales, or destruction. Fig. 1 summed up current return flows.

The dataset used in the case study implementation specifically concerns the returns management system. This comprehensive dataset includes critical variables, including the sender classification (local warehouse or store), the sender designation as a store, the return type (full price or discount), and the return categorization (jewelry or non-jewelry). Furthermore, the key parameters are the return quantity, the date of creation of the return authorization, the collection date (which indicates the departure of the courier to collect the goods), the check-in date (which marks the arrival of the goods returned to the central warehouse), the closing date of the case, the type of reconditioning and the final outcome.

This large dataset serves as the foundational framework for our simulation model. Its richness facilitates the exploration of complex configurations and the evaluation of their implications on the efficiency and effectiveness of the company's return process. This meticulous analysis is aimed at obtaining insights that contribute to the improvement and optimization of the overall returns management system from a sustainable perspective.

The focus of our investigation will center on managed and authorized return requests. Given the global operational scope of the entity, the demand originates from diverse countries. Analyzing the demand distribution across the three global regions reveals the following breakdown:

- Europe, the Middle East, and Africa (EMEA) contribute 78.59 %
- The Asia-Pacific (APAC) region accounts for 18.22 %
- The Americas (AMER) make up 3.19 %. It is evident that the majority of requests originate from the EMEA region.

This aligns with the company's headquarters being in Italy and the Central Warehouse also located in Italy, justifying the concentration of operations in this region. Furthermore, the second most significant market is the Asian region, which, despite its importance, is managed similarly to the EMEA region. In both cases, returns are sent from stores to the Central Warehouse in Italy for the requalification process, and subsequently, after requalification, they are shipped to a specific destination. This centralized system could be optimized through the implementation of a more sustainable network design.

3.2. Simulation modelling

Simulation has been used as a highly effective approach for analysing complex supply chain networks and recently has been used to identify network design strategies for increasing the overall supply chain sustainability (Ivanov, 2023; Mafia et al., 2022). The simulation software AnyLogistix Studio Edition 3.1.0 was used to model the network design and run the proposed experiments. The software has been used in several studies for analysing intertwined supply chains (Andoh and Yu, 2023; Liu and Nishi, 2023; Stewart and Ivanov, 2022; Vimal et al., 2022).

For the model, we used real data from the return flow of a 3-tier fashion supply chain consisting of 1 central warehouse, 10 local warehouses and stores, 5 outlets, and customers. The central warehouse is located in Italy, while the local warehouses, stores, and outlets are located in different countries covering all five continents. Fig. 2 provides an overview of the current network design, including locations. Note that the simulation considers the exact site locations for calculations, and the modelling shown below also includes the four ports used when goods are transported by ferries.

Since we are analysing the return flow, the demand comprises all return authorisations. The simulation uses the data from 18 months, ranging from January 2022 to June 2023, divided by location, as shown in Table 2.

The return process is always initiated by the customer service department. In the central warehouse, the returned items are requalified considering two main parameters: (i) jewellerys or not jewellery, which defines the product category, and (ii) full price or markdown, depending on the defects found in the returned items that define if the item can be

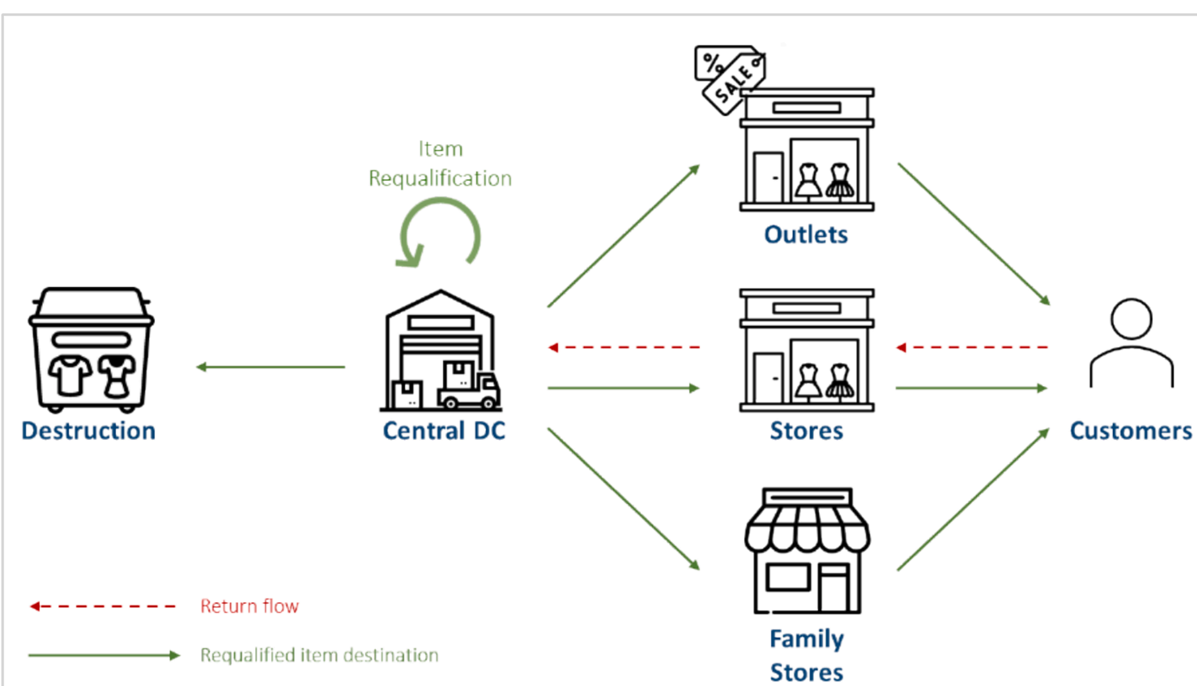

Fig. 1. Current return flows.

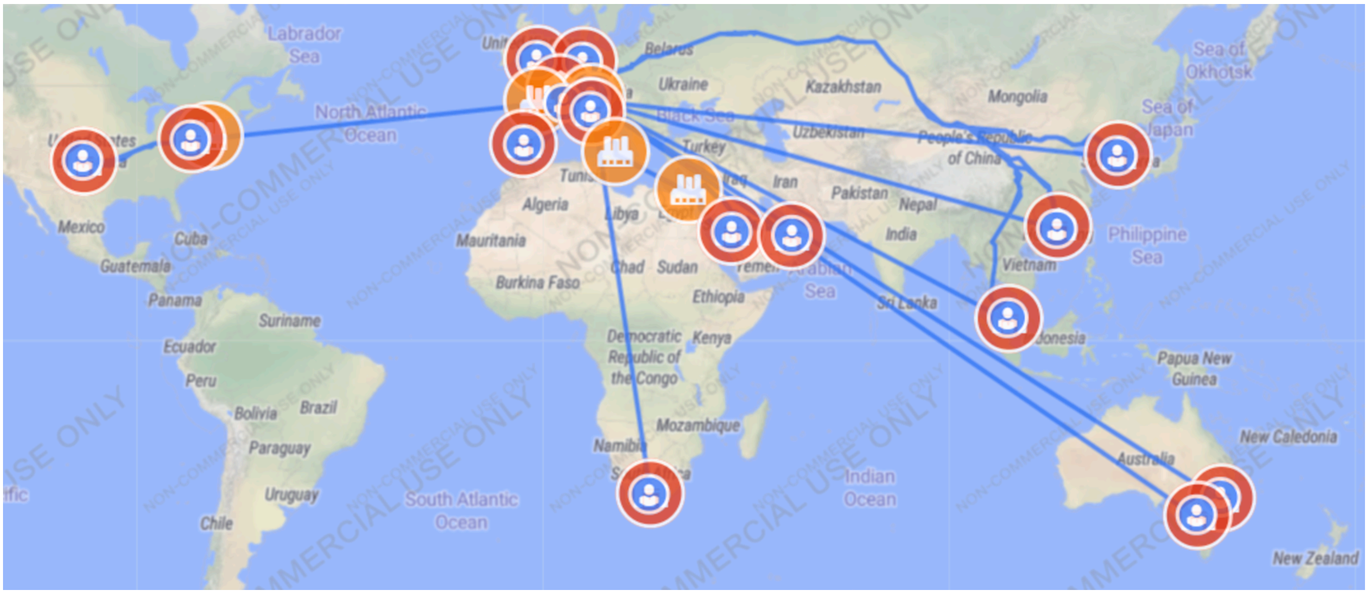

Fig. 2. Current supply chain network for return flows.

Table 2
Number of return authorisations per Area.

Region	Area	% of return authorisations
EMEA	Europe	70.32 %
	Middle East	3.53 %
	Africa	0.74 %
AMER	America	3.19 %
APAC	Pacific Asia	19.09 %
	Australia	3.13 %

resold by the same original price or not. Naturally, this process results in four main categories of requalified items, which the requalification yields can be seen in Table 3.

After the requalification process, the items can have four different destinations: (i) store: when the product can be sellable for the same price as a new one; (ii) outlets: when the item has lost value but is still sellable in outlets for a reduced price; (iii) family sales: when the item presents defects but can still be sellable in family stores near the company; (iv) destruction: when the product has a severe defect that does not allow them to be sold.

Two important points. First, the requalification refers to the item's market value. For instance, garments with no damages but from previous collections can lose value, therefore being sold as markdown. That is one of the reasons that makes lead time very important. Second, a minor part of the production can be allocated either to stores or outlets to compose the demand. The requalification process yields the following percentage within the four categories, as presented in Table 4.

Now that the characteristics of our network design and return process are demonstrated, next we present the assumptions we applied to our simulation modelling.

Table 3
Requalification categories.

Item requalification category	% of Total
Jewellery – Full Price	0.1 %
Jewellery – Markdown	4.3 %
Not Jewellery – Full Price	1.7 %
Not Jewellery – Markdown	93.9 %

Table 4
Percentage of requalified items per destination.

Item destination	% of Total
Stores	85 %
Outlets	6.0 %
Either stores or outlets	3.5 %
Family sales	0.5 %
Destruction	5.0 %

3.3. Model assumptions and limitations

The baseline scenario in our simulation uses the day as a time-unit, both to set average demand from stores and replenishment frequency. The following data have been used, and assumptions have been made:

- **Vehicle type**: following the current strategy used by the company, we use three types of transportation modes: truck, ferry, and aeroplane. Their usage depends on the value-added of the product and follows a strict minimum order size per modal.
- **Carbon policies**: in line with common industry practices, carbon emissions are calculated per piece per kilometre rather than per shipment. The average emissions per transportation modal were extracted from ISPRA, 2022. Note that using average t-km emissions has small limitations since it might vary depending on the product type or operation conditions. Besides, we consider only transportation emissions, while emissions from loading/unloading operations are not included.
- **Replenishment**: the trigger for replenishment is either a minimum number of pieces to be shipped at the end of the day following a restriction per transportation modal or three days, which comes first. The lead time is set per hour to better support decision-making since the lead time is one of the most critical KPIs for the company.
- **Distribution networks**: the type of vehicle chosen depends on the route and type of product but must be in line with the maximum lead time accepted by the company from a strategic point of view given their time-sensitive business. Returns from Europe use trucks regardless of the product category. Second, products from stores in Australia travel by air regardless; from the United States and the Middle East via truck and ferry regardless; those from Pacific Asia travel by air for full-price items and by truck for markdowns; those from Africa, full-price items travel by air and markdowns by ferry.

For shipments of products to or from the Italian store, the capacity check is instead carried out every two hours due to the high volumes for that store, which would otherwise have increased the lead time considerably.

As proposed by Ivanov (2021), we validated our model in three different ways. First, the results obtained for the baseline scenario resulted in similar numbers obtained by the company system related to both lead time and shipments, demonstrating the simulation appropriately reflects their current process. Second, we checked the dynamics of material flows visually in our simulation. Third, we varied the parameters of our experiments (e.g., replenishment time, carbon emission per modal), which confirmed the model's sensitivity. Next, we present the experiments conducted.

3.4. Design of experiments

Two scenarios are proposed for this case study. Firstly, we analyse how the decentralisation of items' requalification process influences both the lead time and carbon footprint of the reverse flow. Secondly, we analyse how changing the transportation modes in critical routes also impacts the lead time and carbon footprint. Supply chain network and transportation modes per scenario are summed up in Table 5.

3.4.1. Experiment 1

Currently, the requalification process is centralised in the Central warehouse located in Italy and cannot be done in stores. In this scenario, we investigate how decentralising this requalification process, allowing it to take place in selected stores, will impact the lead time, number of shipments, and the carbon footprint of the reverse flow. Looking at the numbers of Table 2, it is evident that Europe exhibits the highest percentage of returns. However, these returns can still be effectively managed within the existing central warehouse, located in Italy. Moving on to other EMEA areas, it is observed that the Middle East accounts for 3.53 % of returns. Although this is noteworthy, the relatively proximity of the Middle East to Italy suggests that establishing a new requalification center may not be justified. Similarly, Africa's 0.74 % return rate deems it not relevant for immediate warehouse expansion considerations. Within the AMER region, the return rate stands at 3.19 %, yet it does not emerge as the most impactful area, and as such, it does not warrant a priority for the establishment of a new warehouse to requalification of items. In contrast, the APAC region represents the second-highest percentage of returns, with Pacific Asia contributing 19.09 % and Australia 3.13 %. Consequently, the strategic placement of a new requalification center in Pacific Asia is proposed. It is acknowledged that total decentralization (i.e., moving requalification activities close to the stores) would be the optimal solution in terms of environmental performance. However, it is deemed unfeasible due to associated costs, required competences, and other practical constraints. Thus, the establishment of a new requalification center in Pacific Asia emerges as a pragmatic compromise that balances logistical considerations with environmental objectives.

Besides, note that after requalification, the item can be sent to any other store depending on the placed orders, regardless of where it was requalified. Therefore, even though an item is requalified in a store, it will not necessarily remain there if an order for such an item is already placed in a different store. The process is set this way to reduce average lead time, which also led to defining FIFO as the prioritisation policy in our simulation. This increases uncertainty on the decentralisation since it does not necessarily guarantee a reduction of shipments, therefore the importance of simulating it.

3.4.2. Experiment 2

Based on Experiment 1, which allows decentralisation of return flows, we also investigate a different distribution strategy as an attempt to decrease lead time. In this scenario, we eliminate water transportation, which is the most time-consuming one. Instead, we investigate the use of road transportation for the return flow for the Site 11 placed near the new requalification center in Pacific Asia, while the others in Pacific Asia, Autralia, Africa, Middle East and America are done by air transportation. Our concerns relate to how it impacts the total carbon footprint and average order fulfilment lead time. Note that since the fleet composition has been changed, the travel distance does not necessarily directly correlate with carbon footprint due to the different emissions per type of transportation mode.

Finally, since the use of planes will increase, we of course expect an increase in carbon emissions, but it is relevant to understand to what extent it influences the lead time and therefore be able to quantitatively analyse this trade-off currently found by the company and commonly found in time-sensitive supply chains.

4. Results and Discussion

The purpose of the simulations carried out is to evaluate the impact of two alternative scenarios compared to the current implementation of the reverse supply chain. A comprehensive analysis of the results obtained in the two experiments is carried out to clarify their positioning in relation to the current operational state.

In the context of Experiment 1, the investigation centers around the decentralization of the requalification process, deviating from the

Table 5
Supply chain network and transportation modes per scenario.

Region	Area	Site	Transportation mode					
			AS IS		Experiment 1		Experiment 2	
EMEA	Europe	1, 2, 3, 4, 5	🚚		🚚		🚚	
EMEA	Middle East	6, 7	🚢		🚢		✈	
EMEA	Africa	8	🚢 Markdown	✈ Full-Price	🚢 Markdown	✈ Full-Price	✈	
APAC	Australia	9, 10	✈		🚢		✈	
APAC	Pacific Asia	11, 12, 13	🚢 Markdown	✈ Full-Price	🚚		🚚 Site 11	✈ Site 12, 13
AMER	USA	14, 15	🚢		🚢		✈	

existing paradigm where this procedural step is confined to the central warehouse situated in Italy. Experiment 1 introduces a novel approach, extending the requalification process to the new requalification center placed in Pacific Asia.

Within the context of Experiment 2, the primary focus is on minimizing lead time by eliminating maritime transportation, known for its extended duration. This experiment builds upon the decentralized framework established in Experiment 1. Unlike Green et al. (2019) and Yanikara and Kuhl (2015), who focus on cost-efficiency, we highlight the trade-off between service level and environmental impact. Complementing Lei et al. (2024) and Sohn et al. (2021), we provide empirical evidence for balancing operational efficiency with sustainability.

Focusing on total CO_2 emissions, we observe a significant variation in the three scenarios shown in Table 5. Experiment 1 demonstrates a clear reduction in overall emissions. This suggests that a more localized distribution of requalification activities can have a positive impact on environmental sustainability leading to a reduction of 43.6 % of CO_2 emissions. On the other hand, examining the results of Experiment 2, we observe a 64.6 % increase in total emissions compared to the current state. This substantial increase, as seen from the emission values broken down by transportation mode in Table 6, is attributed to the decision to eliminate maritime transportation, resulting in an increased reliance on air transport, therefore it has come at a significant environmental impact in terms of carbon emissions.

Evidences are summed up from Table 6. Experiment 1′s reduction in emissions aligns with the sustainability goals of the company, showcasing the potential benefits of localizing requalification processes. Besides, Experiment 2′s increased emissions highlight a trade-off between lead time reduction and environmental impact when delivery time represents the only target.

These findings highlight the crucial need for companies to weigh the benefits of reduced lead times against the environmental impacts of increased carbon emissions. This balance is particularly relevant as industries increasingly prioritize sustainability alongside efficiency to meet both consumer expectations and regulatory standards.

Looking at the customer service level, the average lead time is a key metric in supply chain analysis. Both experiments demonstrate a reduction in the average time compared to the AS IS scenario, as Table 7 reported.

However, while Experiment 1 shows a moderate decrease of 28.78 %, Experiment 2 exhibits a significant reduction in lead time of 82.65 %. This can be attributed to the higher speed of air transportation compared to maritime transport that has been removed in the Experiment 2. However, the increase in CO_2 emissions raises the critical question of how much the reduction in lead time takes precedence over environmental sustainability. This juxtaposition invites further investigation into alternative strategies that might achieve a more favorable balance, potentially through the use of emerging technologies or alternative fuel sources for air transport.

Conducting similar studies in other high-return industries could also provide a broader understanding of how these trade-offs are managed across different sectors, enriching the dialogue within the supply chain management community about sustainable practices.

Table 6
CO_2 emissions within scenarios.

	AS IS [k tons]	Experiment 1 [k tons]	Experiment 2 [k tons]
	62	151	–
	276	147	1279
	481	164	69
TOTAL	**819**	**314 (−43.6 %)**	**1348 (+64.6 %)**

Table 7
Average Lead Time within scenarios.

	AS IS [days]	Experiment 1 [days]	Experiment 2 [days]
Lead Time	**11.991**	**9.539 (−28.78%)**	**2.080 (−82.65 %)**

Analyzing the lead time variations for each site across different scenario (i.e., Fig. 3) provides valuable insights into the effectiveness of the proposed changes in the supply chain.

For EMEA Region, we can identify two group of sites with different behaviours: the European Sites (1, 2, 3, 4, 5) and Middle Eastern and African sites (6, 7, 8). Across multiple European sites, the lead time remains consistent for both experiments as no changes in the transportation mode and neither decentralization are made. According to the existing company strategy, centralized requalification, and truck-based transportation are effective for European locations since the central warehouse is located in Italy. On the other hand, Middle Eastern and African sites experience notable reductions in lead time in Experiment 2. The transition from ferry to air transportation contributes to a faster return flow but at the cost of higher carbon emissions. While in the current state and during Experiment 1, some returns from Africa were already being transported by air, these were predominantly full-price items, constituting only a small portion of the total. The substantial reduction in lead time is achieved by also opting for air transportation for markdown items, as they collectively contribute to the significant enhancement in delivery speed.

In the APAC region, two groups can be identified, the first in Australia (9, 10) and the second in Pacific Asia (11, 12, 13). Experiment 1 demonstrates a notable decrease in lead times comparing to the AS IS only for the Pacific Asia since the new requalification center is placed in this area. In addition, most of items are returned by ferry (i.e., markdown) while only a few percentage (i.e., full price) by plane in the current configuration. On the other hand, despite the decentralization strategy for the APAC Region, the Australian sites show an increased lead time compared to AS IS. This fact is related to the transportation mode and capacity, as air mode from Australia to Italy is replaced with ferry transportation from Australia to Pacific Asia and, due to the few returned items in Australia, longer waiting times are expected to fulfill the ferry capacity.

Moving to Experiment 2, the road transportation in the Pacific Asia is replaced by air transportation, excepting for Site 11 since is the one located close to the new requalification center for APAC Region, resulting in a consistent lead time reduction for sites 12 and 13. As expected, significant improvements in lead times result in Australia since the shipping by air instead of maritime transport enables more frequent and faster deliveries.

In the AMER region, the Experiment 1 reflects AS IS scenario, since the requalification process is decentralized for the APAC region, while in the AMER region, where there are only 2 stores, everything is still sent to the central warehouse in Italy. The elimination of maritime transportation in Experiment 2 contributes to a significant reduction in lead time compared to the AS IS scenario. This suggests that, despite the increase in carbon emissions due to more frequent use of airplanes, the company could gain a competitive advantage in terms of faster delivery times, better meeting customer needs.

5. Conclusion, implications and further research

This paper explores how network design impacts RL carbon footprints in global supply chains.

It is well-established that proximity to customers enhances responsiveness and reduces travel distance. However, there is limited evidence

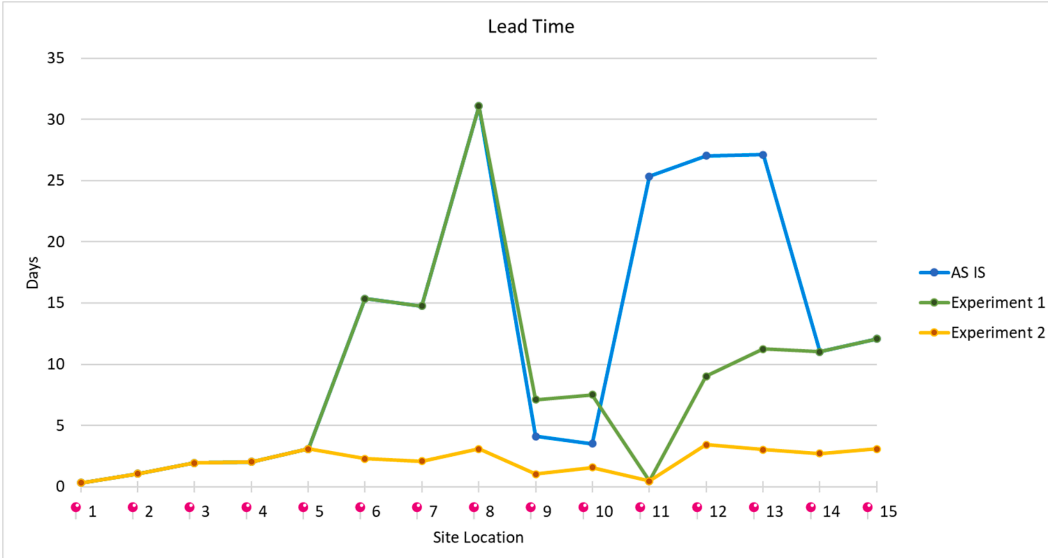

Fig. 3. Lead Time for each Site across scenario.

demonstrating that strategic decentralization can significantly balance the trade-off between lead time and carbon emissions. Our findings indicate that extensive decentralization is not necessarily required to achieve substantial reductions in carbon emissions while maintaining or even improving lead times. This finding is crucial, as it elucidates specific conditions under which decentralization becomes beneficial. By targeting specific sites, both KPIs can be simultaneously improved. Conversely, while changes in transportation modes can enhance lead times, they often increase environmental impact. Therefore, our results suggest that strategic decentralization is a viable approach to balancing lead time and sustainability, whereas modal changes may not always achieve this balance. This strategic approach helps companies optimize network designs by targeting sites with the greatest benefits, offering new practical perspectives and contributing to the literature on sustainable supply chain management.

This study's limitations include a reduced number of experiments due to company strategy, and results that are case-specific, limiting generalizability. Expanding the experimental design to include more variables and aligning simulations with business strategy could provide a more comprehensive understanding and ensure practical feasibility.

Future studies should use a multi-case approach across different fashion industry sectors to enhance the generalizability of findings. Research could investigate the impact of fluctuating return volumes and customer behaviors on RL efficiency, employing predictive analytics to manage unpredictability, especially during peaks. Additionally, exploring RL in varied contexts, such as fast fashion, mid-range segments, and emerging markets, could reveal contextual factors influencing RL effectiveness. Long-term assessments of RL strategies' sustainability impacts are also recommended to deepen understanding and promote sustainable industry practices.

Data Avalaiability Statement

Data available on request from the authors. The data that support the findings of this study are available from the corresponding author, [RB], upon reasonable request.

CRediT authorship contribution statement

Virginia Fani: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Ilaria Bucci:** Writing – original draft, Visualization, Investigation, Data curation, Conceptualization. **Romeo Bandinelli:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Elias Ribeiro da Silva:** Writing – original draft, Software, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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