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Minimization of the Environmental Emissions of Closed-Loop Supply Chains: A Case Study of Returnable Transport Assets Management

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Abstract: This study investigates the issue of minimizing the environmental burden of a real closed-loop supply chain (CLSC), consisting of a pallet provider, a manufacturer and several retailers. A simulation model is developed under Microsoft Excel™ (Microsoft Corporation, Washington, US) to reproduce the flow of returnable transport items (RTIs) in the CLSC and to compute the corresponding environmental impact. Multi-objective optimization, including some relevant environmental key performance indicators (KPIs), is then carried out exploiting the commercial software ModeFRONTIER™ (ESTECO S.p.A., Trieste, Italy), to determine the settings that minimize emissions of the CLSC. In addition, economic and strategic metrics are taken into account in the optimization, to make the analysis more comprehensive. Three scenarios are considered (one “base” scenario and two scenarios examined in a sensitivity analysis) with different relative importance assigned to the metrics subject to optimization. Results show that the asset retrieving operations contribute to the environmental impact of the system to the greatest extent, mainly because of the quite relevant distance between Company A and its customers. Conversely, emissions due to the purchase of new assets contribute to the total environmental impact of the system to a very limited extent. Because the analysis is grounded on a real CLSC, the results are expected to provide practical indications to logistics and supply chain managers, to minimize the environmental performance of the system.

Keywords: closed-loop supply chain (CLSC); returnable transport items (RTIs); environmental impact; sustainability; simulation; multi-objective optimization; case study

1. Introduction

A closed-loop supply chain (CLSC) is a system where the forward and reverse flows of items occur and should be managed simultaneously [1,2]. It therefore embodies various reverse logistics practices, i.e., the collection of returned items from the end-users and the management of their end-of-life through different decisions, including recycling, remanufacturing, repairing or final disposal [3]. The proper management of a CLSC requires the design, control and operation of the system to maximize value creation over the entire life cycle of a product, with dynamic recovery of value from different types and volumes of returned items.

Returns of items in a CLSC can occur for a number of reasons [4]. Production- and distribution-related returns [5,6], which are the focus of this paper, reflect the situation where products are returned by consumers to the vendor within some days after the purchase [7], or where products and/or components are first remanufactured or recovered, then returned to like-new quality standards [8], respectively. This paper deals, in particular, with the case of returnable transport items (RTIs), which are used for internal transport of materials, components, semi-finished products and for the distribution

of finished products. RTIs are “*means to assemble goods for transportation, storage, handling and product protection in the supply chain which are returned for further usage*” [9]. Among RTIs, pallets as well as all forms of reusable crates, totes, trays, boxes, roll pallets, roll cages, barrels, trolleys, pallet collars, racks, lids and refillable liquid or gas containers can be mentioned [10]. In a CLSC, RTIs can be handled either by direct/deferred exchange or by asset pooling [11]. In the latter situation, a pool operator owns the RTIs and manages their deliveries and returns, while in the former, supply chain players own some RTIs, which are exchanged among the actors of the chain. The exchange is “direct” if assets are returned immediately and in the same quantity as that shipped, or “deferred” if the return is completed later. The direct/deferred exchange is widely adopted by companies, because of its simplicity and ease of implementation. Moreover, exchanged RTIs can be reused and do not add to the amount of items to be recycled or destroyed, which is relevant to ensure sustainability of logistics activities [12] and is crucial to CLSCs [9,13].

In recent years, there has been increasing concern about the environmental impact of supply chain processes and of CLSCs in particular [12]; this is why CLSCs are becoming more and more important areas of research [14,15]. Compared to the traditional forward supply chain, CLSCs tend to save energy, consume less material and be more environmentally friendly [16]. Moreover, they are attracting attention both in developed countries, because of legislation and social pressures, and in developing ones, where the adoption of reverse logistics practices may become a leverage of competitive advantage [17]. Recovering value from returned products and assets is an important activity of CLSCs from a sustainability perspective [3], since one of the ways to “green” a supply chain is to involve the players in downstream activities like product or asset recovery [18,19]. In addition, as asset returns are common in CLSC, these systems should also embody an appropriate asset recovery strategy [20]. Despite the relevance of these concepts, however, most of the research relating to supply chain sustainability has been focused on analyzing and greening the forward flows of products, while it is significantly less frequent that reverse flows of returned items are included in the analysis [21–24]. The aim of this paper is to contribute to the literature by evaluating and minimizing the environmental impact of an existing CLSC. A simulation model, which takes inspiration from a previous study [25], is used to support the analysis and specifically to quantify the environmental impact caused by the key activities of the asset management process. Starting from the previous study, which focused on evaluating the economic performance of the CLSC, this paper goes ahead by minimizing the environmental impact of the asset management process in the same system. This paper represents the second part of a research project whose general aim is to model and optimize the sustainability of supply chains.

The paper proceeds as follows. Section 2 reviews the literature relevant to this research. Section 3 provides some information about the case study under examination. Section 4 describes the simulation model developed to evaluate the environmental impact of the targeted CLSC. In Section 5, we describe the logic used to carry out the simulation and multi-objective optimization. In Section 6, we report the results of the simulated scenarios, of the optimization procedure and of the solutions ranking. Section 7 concludes by summarizing the key findings of the study, highlighting the main limitations and suggesting future research directions.

2. Literature Analysis

The scientific literature on CLSCs offers numerous topics of interest to logistics and production managers, including the development of methods for vendor selection in reverse logistics [26], the relationships between CLSCs and third party logistics service providers [27], the product eco-redesign process and its impact on the performance of a CLSC [28] and the development of taxonomies for CLSC activities [29]. In line with the aim of this study, the review of the literature was focused on those papers that developed quantitative models to analyze the sustainability of CLSCs. Georgiadis and Besiou [30] proposed one of the first examples of these studies. By means of a system dynamics model, the authors have evaluated the importance of the environmental sustainability strategies

and the operational features of a CLSC, their interactions and the corresponding impact on the environmental and economical sustainability of the system, in the context of waste of electric and electronic equipment. Gao and Ryan [31] have examined a CLSC design problem that takes into account the impact of carbon emission regulations. The authors considered three regulatory policy settings, namely: (a) firms are subject to mandatory carbon caps on the amount of carbon they emit; (b) firms are taxed on the amount of emissions; (c) firms can participate in a carbon cap and trade system. Shi and Min [32] investigated two critical environmental factors of the product weight and the collection rate, as well as their environmental consequence on the landfill quantity, in the context of CLSCs. They modelled three closely related CLSCs, consisting of a manufacturer, who also recycles the used products, and a collector of used products. Alfonso-Lizarazo et al. [12] showed how the potential for managing reverse logistics flows could be implemented in the agro-industrial sector. To this end, they developed a mathematical model that considers simultaneously the forward and reverse flows in a CLSC of agri-food products and evaluated different scenarios of interactions between forward and reverse flows. The authors found that taking into account the direct and reverse flows simultaneously has a positive impact on the economic profits of the CLSC considered. Hasanov et al. [33] have developed a CLSC model that considers the economic value and energy content of products. Lot-sizing problems were also investigated thanks to the model. Chen et al. [34] have examined an integrated CLSC network design problem with sustainable concerns in the solar energy industry. The authors developed a deterministic multi-objective mixed-integer programming model which considers the trade-offs between the total cost and the CO₂ emissions of the system, with the aim of capturing both the economic and environmental facets of the problem. Chen et al. [35] proposed a comprehensive CLSC model, composed of eight players, all operating in the existing cartridge recycling scenario of Hong Kong. They developed an integer-programming model to study both the delivery routes of cartridges and the corresponding quantity, and solved it by means of a two-stage genetic algorithm. A similar analysis was carried out by Garg et al. [36]. These authors dealt with the environmental issues to be faced in the design of a CLSC network and to this end modelled a nine-echelon network (four echelons in the forward chain and five echelons in the backward chain). To assess the environmental impact of the resulting network, they formulated a bi-objective integer nonlinear programming problem that was solved by means of an interactive multi-objective programming approach algorithm. Alimorandi et al. [37] modelled a CLSC with recovery options for treating returned products. The recovery system consists in collection centers, remanufacturing plants and disposal centers. In a similar study, Govindan et al. [38] have developed a multi-objective mixed integer mathematical problem for a generic CLSC, to evaluate how a product recovery system helps improve manufacturing sustainability. The network modelled includes a hybrid manufacturing facility, a warehouse, some distribution and collection centers and a hybrid recovery facility. Bottani et al. [25] developed a simulation model to reproduce the reorder process of RTIs in a CLSC and to optimize the cost of the asset management process. With the purpose of enhancing the return rate of used products in CLSCs, Dutta et al. [39] developed a recovery framework that makes use of buy-back offer at retailer level. The proposed recovery framework was integrated with an optimization model for a multi-period problem under demand and capacity uncertainty.

Table 1. Closed-loop supply chain (CLSC) models reviewed in this study and contribution of the present study.

Paper	Field	Sustainability Perspective		Methodology	Main Results
		Environmental	Economic		
Georgiadis and Besiou [30]	Waste of electric and electronic equipment in CLSC	x	x	Extension of a system dynamics-based model	The production of recycled materials of high quality improves the economical sustainability and the availability of natural resources
Gao and Ryan [31]	Document-office company operating in the Iberian market	x	x	Network design	Suggestions to balance the trade-offs between usual costs and the impact of carbon emission regulations
Shi and Min [32]	Supply chain centralization/decentralization	x		Modelling framework	Evaluation of the impact of supply chain centralization or decentralization strategies and of the relationships between government subsidy and fee on these strategies
Alfonso-Lizarazo et al. [12]	Palm oil CLSC		x	Mathematical model	Impact of the simultaneous analysis of direct and reverse flows on the net economic profit of the CLSC
Hasanov et al. [33]	Economic value and energy content of products		x	Novel modelling framework	Suggestions for a SC model that takes into account energy, transportation and disposal costs
Chen et al. [34]	Crystalline solar energy industry	x	x	Deterministic multi-objective mixed integer programming model	Suggestions for capacity expansion, technology selection, supply chain design, factory location options and capacity allocation
Chen et al. [35]	Ink-and-toner cartridge delivering and recycling in Hong Kong		x	Mix integer linear programming model	Suggestion for integration of forward and reverse flows
Garg et al. [36]	Geyser manufacturer CLSC		x	Interactive multi-objective programming approach algorithm	The inflow of returns with better recovery options substantially influences the economic benefit for business by increasing the demand for new products in first customer markets
Alimorandi et al. [37]	CLSC	x		A fuzzy mixed integer linear programming model	Suggestions for a new design of supply chain network in which waste of materials is minimized and the new raw materials are necessary only when the used products may not be recovered
Govindan et al. [38]	Case study from an electrical manufacturing industry	x	x	Multi-objective mixed integer mathematical problem	Suggestions to enhance manufacturing sustainability
Bottani et al. [25]	Manufacturer of fast moving consumer goods operating in the North of Italy		x	Mathematical model reproduced on a Microsoft Excel™ simulator	Suggestions for asset management strategies that minimize the total cost of the CLSC
Dutta et al. [39]	CLSC of electronics products category		x	Recovery framework	Considerations about the profitability of the system as a function of the probability of product acceptance.
Present study	Manufacturer of fast moving consumer goods operating in the North of Italy	x	x	Mathematical model reproduced on a Microsoft Excel™ simulator	Suggestions to minimize the environmental impact of the reverse logistics activities of RTI in a CLSC

Table 1 summarizes the main studies about CLSC networks, along with their aim and characteristics. All the papers listed in Table 1 proposed quantitative models for CLSCs, which highlights the interest toward a quantitative analysis of these systems. However, some gaps exist. More specifically, most of the studies reviewed addressed mainly the economic perspective of sustainability, while only few of them (e.g., [34,36]) tried to model the environmental impact of CLSCs. However, evaluating also the environmental burden of logistics activities is an increasingly important topic, as these activities are likely to generate undesired by-products, such as inefficient (or excessive) use of fossil fuels and their CO₂ emissions [12,24,40]. Secondly, the case of RTIs management is not much explored in literature, despite the fact that RTIs are always subject to forward and reverse flows (as they are expected to be returned after usage) and therefore represent typical items to be managed in a CLSC. This paper contributes to the literature by addressing these gaps, in that it proposes a detailed evaluation of the environmental impact of a CLSC, targeting a real case of RTIs management, and suggests ways to minimize it.

3. Case Study

As mentioned, this paper builds upon the study by Bottani et al. [25] and focuses on the same CLSC, which includes a manufacturer, an asset (pallet) provider and seven customers (retail stores). For the sake of clarity, a short description of the CLSC analyzed is provided in the following; for further details, the reader is referred to Bottani et al. [25].

The manufacturer, which will be referred to as “Company A”, is a fast moving consumer goods producer, operating in the north of Italy. Company A is the focus of the analysis, as it owns a stock of proprietary RTIs (pallets), manages their forward and reverse flows in the CLSC and is therefore responsible for the environmental impact of the asset management process. To be more precise, Company A receives orders of finished products from its customers and fulfils them by preparing and shipping stock keeping units (SKUs), which require a corresponding amount of empty pallets. SKUs are then loaded into trucks and shipped to the customers. Shipments are performed by road using 33-pallet lorries. At the delivery point, the palletized SKUs are unloaded and stored in the customer’s warehouse. Company A adopts the “deferred exchange” practice for asset recovery. This means that, in general, customers are unable to immediately return the whole amount of pallets received and typically return only some empty pallets, available at their warehouse when a shipment is received. To retrieve the remaining pallets, Company A needs to organize dedicated trips to its customers. Retrieving activities, however, do not ensure that the whole amount of pallets will be recovered: more precisely, Company A estimates that it loses approximately 2.5% of the pallets shipped per retrieving cycle. A further quota of pallets (1%) should be replenished annually due to damages. In managing the assets flow, Company A should finally avoid the occurrence of out-of-stock situations, because lack of pallets in stock means that the company is not able to ship the finished products to its customers, resulting in a sale loss. To avoid out-of-stock situations, Company A can either recover assets from its customers, purchase new assets from the pallet provider through regular orders or purchase new assets with urgency.

The process described above causes environmental emissions because of transport activities from Company A to its customers (shipments), from the pallet provider to Company A (regular order or urgent order) and from the customers to Company A (retrieving). A further environmental impact of the system modelled is caused by the assets lost or damaged, which can be considered in the same way as for wasted pallets.

4. Modelling Framework

4.1. Computation of the Environmental Emissions

According to Eriksson et al. [41], the environmental impact of transport activities should include CO₂, NO_x and SO_x emissions. The unitary (i.e., kg/km) values of NO_x and SO_x emissions are

significantly lower than that of CO₂ emissions; more precisely, they account for 0.00021 kg/km and 0.00008 kg/km on average for a heavy vehicle, while for the same kind of vehicle, CO₂ emissions account for 0.699 kg/km (≈ 3000 times as much) [42]. Nonetheless, the effect of NO_x and SO_x on the environment is relevant, as these pollutants can cause acidification of surface water and soil, damages to forests and coastal eutrophication [43]. Looking at the effect on the human population, NO_x and SO_x are responsible for respiratory illness, such as asthma and bronchitis [43]. Therefore, in the model we have computed the CO₂, NO_x and SO_x emissions of transport activities.

As far as the lost and damaged pallets are concerned, their environmental impact takes into account the CO₂ emissions only, according to Carraro et al. [44]; in particular, it is estimated by calculating the CO₂ eq. produced in pallet manufacturing, maintenance and end-of-life.

The relevant equations for the computation of the environmental emissions were added to the model developed by Bottani et al. [25] to describe the flow of assets in a CLSC, using the notation in Table 2. Such flow is controlled by two variables, denoted as OP and MPQ. OP is the reorder point of the traditional economic order quantity (EOQ) policy [45] and triggers the decision of replenishing the stock of assets; MPQ, instead, reflects the minimum amount of pallets that should be available at a customer's site to trigger the retrieving process. For the sake of brevity, the description below is limited to the equations that were added to the original model with the purpose of computing the CO₂ eq. emissions of the CLSC.

Table 2. Nomenclature (partially taken from Bottani et al. [25], with permission from Elsevier).

Symbol	Description	Unit of Measurement
Indexes		
i	delivery point ($i = 1, \dots, 7$)	-
n	truck ($n = 1, \dots, n_{truck}$)	-
t	simulation day ($t = 0, \dots, N_{days}$)	-
e	type of environmental emission ($e = 1$ for CO ₂ ; $e = 2$ for NO _x ; $e = 3$ for SO _x)	-
Subscripts		
L, D	lost or damaged pallets	-
r, s, p_{-u}, p_{-r}	recovery, shipment, urgent purchase, regular purchase	-
Tot	Total	-
DP	delivery point	-
A	Company A	-
$Prov$	pallet provider	-
Superscripts		
P	"physical"	-
T	"theoretical"	-
Simulation parameters		
N_{days}	simulation duration	(days)
Delivery point parameters		
$O_{DP,i}(t)$	order issued	(pallets)
$R_{DP,i*}(t)$	amount of assets retrieved	(pallets)
$\%L, \%D$	percentage of assets lost and damaged	(%)
$d_{A,i}$	distance between delivery point i and Company A	(km)
Company A parameters		
$N_{days/year}$	working days per year	(days)
$S_{A,i}(t)$	amount of assets shipped to delivery point i	(pallets)
$I_A^P(t), I_A^T(t)$	physical and theoretical stock of assets	(pallets)
$O_A(t), UO_A(t)$	amount of assets purchased through a regular or urgent order	(pallets)
$P_A(t)$	amount of proprietary assets	(pallets)
$d_{A,prov}$	distance from Company A to the pallet provider	(km)
OP	order point	(pallets)
MPQ	minimum picked quantity (minimum amount of assets to be collected through retrieving operations)	(pallets)
Environmental parameters		(kg CO ₂ eq./pallet)
I_{pallet}	CO ₂ emissions of a lost/damaged pallet	(kg CO ₂ eq./pallet)
LF	load factor of a truck	(%)
$IFLT_e$	emissions type e of a full load truck	(kg/km)
Other parameters		
$n_{(pallets/truck),s}$	amount of palletized SKUs that can be loaded on a truck during shipment	(pallets/truck)
$n_{(pallets/truck),r}$	and retrieving	

Start of the process. At time t , Company A receives orders from its customers and checks whether the amount of orders received can be fulfilled exploiting the “physical” stock of assets. If the stock is sufficient (i.e., $I_A^P(t-1) \geq \sum_{i=1}^7 O_{DP,i}(t)$), Company A will follow the order fulfilment process (*Branch 1*); otherwise, it will incur an out-of-stock situation (*Branch 2*).

Branch 1—order fulfilment. To fulfil the request, Company A will prepare the order, load the trucks and ship the pallets to its customers. This causes emissions in the environment, which depend on the type of truck used and on its saturation level. Indeed, it can always happen that the 33-pallet lorry used for shipping is not fully saturated ($LF < 100\%$). Infras [46] estimates that the fuel consumption and therefore the emissions of an empty ($LF = 0\%$) truck of gross weight 24–40 tons account for approx. 61% of those of a full load ($LF = 100\%$) truck. For intermediate values of LF , the impact of a truck can be estimated using Equation (1):

$$LF \times IFLT_e + (1 - LF) \times 0.61 \times IFLT_e, \quad (1)$$

where $IFLT_e$ indicates the amount of emissions type e of a full load truck [47]. To calculate the saturation and the emissions of the trucks used to ship the SKUs to the delivery points, the number of vehicles required for shipment at customer i , $n_{trucks,i}$ should be first estimated; the following equation can be used:

$$n_{trucks,i} = \left\lceil S_{A,i}(t) / n_{(pallets/truck),s} \right\rceil, \quad (2)$$

where $n_{(pallets/truck),s}$ is a fixed quantity describing the amount of palletised SKUs that can be loaded on a 33-pallet truck during shipping. Obviously, the result of Equation (2) should be rounded up to the next whole number; for example, a result of 1.76 means that 2 trucks are required for the shipment. The average saturation of the trucks used for shipment at customer i at time t , $\%S_{A,i}(t)$, is computed starting from the total amount of pallets loaded on a truck of given capacity and from the number of pallets shipped, as follows:

$$\%S_{A,i}(t) = \frac{S_{A,i}(t) / n_{(pallets/truck),s}}{n_{trucks,i}}, \quad (\%) \quad (3)$$

The unitary emission type e of truck n during shipping at customer i , $IS_{A,n,i,e}(t)$ can be computed as follows:

$$IS_{A,n,i,e}(t) = \%S_{A,i}(t) \times IFLT_e + (1 - \%S_{A,i}(t)) \times 0.61 \times IFLT_e, \quad (\text{kg}/(\text{km} \cdot \text{day})) \quad (4)$$

The overall emissions type e of a shipment at time t is finally obtained by adding up the contribution of each truck and taking into account the transport distance, as follows:

$$IS_{A,e}(t) = \sum_{i=1}^7 \left[\sum_{n=1}^{n_{trucks,i}} (IS_{A,n,i,e}(t) \times d_{A,i}) \right], \quad (\text{kg}/\text{day}) \quad (5)$$

Further emissions relating to the shipment activities are due to the quota of assets lost and damaged, which, as mentioned, can be considered in the same way as wasted pallets. At day t , their environmental impacts, in terms of CO₂ emissions, can be calculated as follows:

$$I_L(t) = \%L \times I_{pallet} \times \sum_{i=1}^7 S_{A,i}(t), \quad (\text{kg CO}_2 \text{ eq.}/\text{day}) \quad (6)$$

$$I_D(t) = \frac{\%D \times I_{pallet} \times \sum_{i=1}^7 S_{A,i}(t)}{N_{\text{days/year}}}, \quad (\text{kg CO}_2 \text{ eq.}/\text{day}) \quad (7)$$

Product shipment causes the update of the assets inventory at Company A, which will then check whether the stock is lower than OP. If $I_A^T(t) > OP$, Company A will not need to replenish its stock of assets (*Branch 1.1*); otherwise, it will follow the replenishment procedure (*Branch 1.2*).

Branch 1.1—no replenishment. If the stock of pallets is not replenished, there are no transport activities and therefore the emissions associated with this branch score zero.

Branch 1.2—asset replenishment. If Company A needs to replenish its stock of pallets, transport activities are required, because of either retrieving operations or regular orders. To be more precise, in the case that one (or more) customers own more than MPQ assets in its stock, the Company will start the retrieving process (*Branch 1.2.1*); otherwise, it will order new assets (*Branch 1.2.2*).

Branch 1.2.1—retrieving process. Once the customer i^* from which empty assets should be retrieved has been chosen, Company A should estimate the number of vehicles needed for retrieving ($n_{trucks,r}$), their LF and their emissions. The former is computed applying the following expression:

$$n_{trucks,r} = \left\lceil R_{DP,i^*} / n_{(pallets/truck),r} \right\rceil \quad (8)$$

where $n_{(pallets/truck),r}$ is a fixed quantity describing the amount of empty pallets that can be loaded on a 33-pallet lorry (i.e., 500 pallets). Again, the result of Equation (8) should be rounded up to the next whole number. The average saturation of the trucks used in the retrieving process $\%S_r(t)$ can be derived starting from the amount of pallets loaded on each truck and the amount of pallets recovered, as follows:

$$\%S_r(t) = \left(R_{DP,i^*} / n_{(pallets/truck),r} \right) / n_{trucks,r} \quad (\%) \quad (9)$$

The unitary emission type e of truck n during retrieving operations $IR_{n,e}(t)$ can be finally computed as follows:

$$IR_{n,e}(t) = \%S_r(t) \times IFLT_e + (1 - \%S_r(t)) \times 0.61 \times IFLT_e \quad (\text{kg}/(\text{km} \cdot \text{day})) \quad (10)$$

The emission type e of all the trucks used to retrieve the pallets from customer i^* at time t is finally obtained by adding up the contribution of each truck and taking into account the transport distance, as follows:

$$IR_e(t) = \left(\sum_{n=1}^{n_{trucks,r}} IR_{n,e}(t) \right) \times d_{A,i^*} \quad (\text{kg}/\text{day}) \quad (11)$$

Branch 1.2.2—reorder process. In line with the EOQ policy, the amount of new pallets purchased by means of a regular order is fixed and accounts for $O_A(t) = O_A = 500$, which reflect the maximum number of empty pallets that can be loaded on a 33-pallet lorry. Therefore, $\%S_{p,r}(t)$ always score 100% and $n_{trucks,p,r}$ always score 1 in this process. The amount of emissions of type e generated by a regular order at time t thus accounts for

$$IP_{r,e}(t) = [\%S_{p,r}(t) \times IFLT_e + (1 - \%S_{p,r}(t)) \times 0.61 \times IFLT_e] \times d_{A,prov} \quad (\text{kg}/\text{day}) \quad (12)$$

Branch 2—out-of-stock. In the case $I_A^P(t-1) < \sum_{i=1}^7 O_{DP,i}(t)$, Company A will incur an out-of-stock situation and will place a urgent order to the pallet provider. In line with the aim of minimizing the environmental impact of the CLSC, in the model it is assumed that $UO_A(t) = UO_A = 500$, meaning that whenever an urgent order is required, the transport will be a full truck load. This is expected to decrease the number of transports required and consequently their environmental impact. Hence, as per *branch 1.2.2*, in this process $\%S_{p,u}(t)$ and $n_{trucks,p,u}$ always score 100% and 1 respectively. The amount of emissions of type e caused by an urgent order at time t thus accounts for:

$$IP_{u,e}(t) = [\%S_{p,u}(t) \times IFLT_e + (1 - \%S_{p,u}(t)) \times 0.61 \times IFLT_e] \times d_{A,prov} \quad (\text{kg}/\text{day}) \quad (13)$$

Figure 1 summarizes the environmental impacts generated in each branch of the decision process.

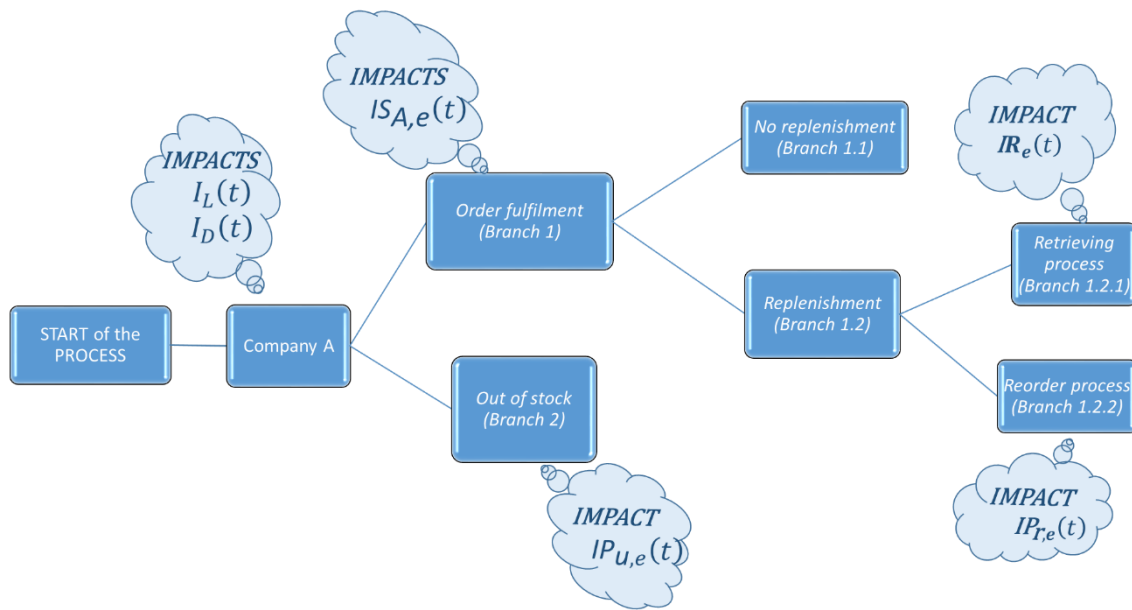


Figure 1. Sketch of the model and environmental emissions (adapted from [25]).

4.2. Environmental Key Performance Indicators

The following key performance indicators (KPIs), averaged on N_{days} , are used to assess the environmental performance of the CLSC.

- (1) Total impact of retrieving for emissions of type e ($IR_{TOT,e}$):

$$IR_{TOT,e} = \frac{\sum_{t=0}^{N_{\text{days}}} IR_e(t)}{N_{\text{days}}} \quad (\text{kg/day}) \quad (14)$$

- (2) Total impact of shipments for emissions of type e ($IS_{TOT,e}$):

$$IS_{TOT,e} = \frac{\sum_{t=0}^{N_{\text{days}}} IS_{A,e}(t)}{N_{\text{days}}} \quad (\text{kg/day}) \quad (15)$$

- (3) Total impact of purchase for emissions of type e ($IP_{TOT,e}$):

$$IP_{TOT,e} = \frac{\sum_{t=0}^{N_{\text{days}}} IP_{r,e}(t) + IP_{u,e}(t)}{N_{\text{days}}} \quad (\text{kg/day}) \quad (16)$$

- (4) Total impact of lost and damaged pallets ($Ipallet_{TOT}$):

$$Ipallet_{TOT} = \frac{\sum_{t=0}^{N_{\text{days}}} I_L(t) + I_D(t)}{N_{\text{days}}} \quad (\text{kg CO}_2 \text{ eq./day}) \quad (17)$$

- (5) Total environmental impact of the CLSC for emissions of type e ($I_{TOT,e}$), computed by adding up the contributions listed above, as follows:

$$I_{TOT,e} = \begin{cases} IR_{TOT,e} + IS_{TOT,e} + IP_{TOT,e} + Ipallet_{TOT} & \text{for } e = 1 \text{ (kg CO}_2 \text{ eq./day)} \\ IR_{TOT,e} + IS_{TOT,e} + IP_{TOT,e} & \text{for } e = 2, 3 \text{ (kg/day)} \end{cases} \quad (18)$$

4.3. Strategic and Economic Performance

Besides the environmental performance, some further economic and strategic KPIs were to assess the efficiency of the asset management process of Company A. Such KPIs reflect those already detailed in Bottani et al. [25]; hence, in the following paragraphs we simply define them, without proposing a detailed computational procedure, which can be found in the previous paper.

The main economic performance of the CLSC is the total cost (C_{tot}) Company A incurs in managing the flow of assets. For the CLSC considered, C_{tot} takes into account the cost of retrieving assets from the delivery points, the cost of purchasing new assets (by means of regular or urgent orders), the cost of holding the stock of assets and the opportunity cost. Although the economic performance is not the main focus of this study, from a strategic point of view computing C_{tot} allows the observation of how the cost of the CLSC varies when trying to optimize its environmental impact.

Further strategic KPIs considered are:

- (1) The amount of proprietary assets (P_A), which reflects the average number of pallets owned by Company A and is expressed in (pallets);
- (2) Asset rotation (AR), i.e., the number of times per year that the pallet stock rotates. It is expressed in (year^{-1});
- (3) Pallet utilization rate ($U\%$), computed as the ratio between the time (days) of real usage of the asset in the CLSC, either at the delivery point or in transportation activities, and its cycle time (days), which measures the time required for an asset to complete a cycle in the CLSC considered (i.e., from Company A to the customer and back to Company A);
- (4) Out of stock (OOS), which provides a quantitative measure of those critical situations where Company A does not have pallets available to ship products to its customer (days/year).

4.4. Input Data

To apply the model described in the previous sub-sections, several input data were collected, by means of the direct examination of Company A and from other available sources. The full list of input data is provided in Table 3.

Table 3. Input data (partially taken from Bottani et al. [25], with permission from Elsevier).

Parameter	Numerical Value	Measurement Unit	Source
$N_{\text{days/year}}$	260	(days)	Company A
$O_A = UO_A$	500	(pallets)	Company A
$\%L$	2.5%	-	Company A
$\%D$	1%	-	Company A
$d_{A,i}$	362 ($i = 1$); 358 ($i = 2$); 606 ($i = 3$); 352 ($i = 4$); 232 ($i = 5$); 934 ($i = 6$); 632 ($i = 7$)	(km)	Company A
$d_{A,prov}$	38	(km)	Company A
$n_{(\text{pallets/truck}),r}$	500	(pallets/truck)	Company A
$n_{(\text{pallets/truck}),s}$	33	(pallets/truck)	Company A
I_{pallet}	7.16	(kg CO ₂ eq./pallet)	[44]
$IFLT_1$	0.699	(kg CO ₂ /km)	[42]
$IFLT_2$	0.21×10^{-3}	(kg NO _x /km)	[42]
$IFLT_3$	0.08×10^{-3}	(kg SO _x /km)	[42]

4.5. Software Implementation

The set of equations described in Sections 4.1–4.3 was implemented in a Microsoft ExcelTM simulation model, which consists of two spreadsheets. The first one is the complete database of the inbound/outbound flows of assets recorded by Company A in 2016, including the forward shipments to the customers and the reverse flows of the assets returned. In this spreadsheet, the environmental impacts of the retrieving process are also computed (Equations (8)–(11)). The second spreadsheet reproduces the flow of assets in the CLSC and computes the environmental impacts of

shipments, purchases and losses/damages of assets (Equations (1)–(7), (12) and (13)). In the same spreadsheet, the KPIs related to the environmental performance of Company A (Equations (14)–(18)) and the economic/strategic KPIs are also calculated. As far as the OP and MPQ parameters are concerned, simulation was used to vary them in a range of suitable values (from 50 to 1200, step 5) to determine the setting that optimizes the overall performance of the CLSC.

5. Optimization and Ranking Procedures

5.1. Optimization Procedure

As already mentioned, the system under examination generates emissions because of transport activities from Company A to its customers (shipments), from the pallet provider to Company A (regular order or urgent order) and from the customers to Company A (retrieving); a further environmental burden is caused by the amount of assets lost or damaged. A multi-objective optimization procedure was set up using the commercial software ModeFRONTIER™ release 4.6.2 (Esteco S.p.A.), to:

- minimize the emissions of the system;
- minimize the occurrence of out-of-stock situations;
- maximize the use of assets;
- maximize the number of rotations of assets.

As far as the emissions are concerned, the CO₂ emissions (i.e., $I_{TOT,1}$) are set as the KPI to be minimized, for simplicity; therefore, the results reported in section 6.1 refer to this specific KPI. Nonetheless, minimizing the CO₂ emissions is expected to lead to the minimization of the whole environmental impact of the system (i.e., of NO_x and SO_x emissions too), as the computational procedure is the same for the three types of emissions. Therefore, NO_x and SO_x emissions are likely to exhibit the same trend as the CO₂ emissions.

ModeFRONTIER™ was integrated with the Microsoft Excel™ simulation model, by setting the input data in Table 3 and defining the range for the OP and MPQ variables. A constraint on the maximum number of proprietary pallets ($P_A < 3000$) was introduced in the simulation, to take into account the fixed storage capacity of Company A. The solutions returned by ModeFRONTIER™ are marked as “feasible” (green dots in Figures 2–5) if they satisfy this constraint and “unfeasible” (yellow dots) otherwise. Finally, only integer values were allowed for P_A , OP and MPQ.

According to the list proposed above, the main outputs returned by the simulation are $I_{TOT,1}$, OOS, AR and $U\%$. Further outcomes provided are $IS_{TOT,1}$, $Ipallet_{TOT}$ and $IP_{TOT,1}$; however, these KPIs are not taken into account in the optimization procedure, because the Company has a limited control over them. In fact, $IS_{TOT,1}$ depends only on the demand for finished products and therefore cannot be modified by Company A; similarly, $Ipallet_{TOT}$ depends on the percentage of assets lost or damaged by the customers, over which Company A has no control. $IP_{TOT,1}$, instead, is not taken into account in the optimization procedure because it has a very low value compared to the remaining environmental KPIs (as it will be shown later in the paper); minimizing this component would not lead to significant savings in the environmental emissions of the system.

A two-stage optimization procedure was implemented on ModeFRONTIER™; that procedure consists in the preliminary application of the Design of Experiments (DOE) technique and then in the use of a genetic algorithm. To be more precise, in the DOE stage only the boundary values and the intermediate value of OP and MPQ (i.e., 50, 625 and 1200) were considered, resulting in a 3² full factorial design. Outcomes of the DOE provided some preliminary insights about the solution space and were used to guide the non-dominated sorting genetic algorithm (NSGA-II) towards the optimal solution in the second stage of the optimization. The NSGA-II was selected after a preliminary testing of two additional algorithms, i.e., the multi-objective genetic algorithm (MOGA) and real-coded multi-objective genetic algorithm (ARMOGA). The preliminary testing showed that the NSGA-II was

more effective than the remaining algorithms with respect to the computational time, as it explored a lower number of solutions (261 vs. more than 900), without a significant difference in the results returned. This is consonant with the better performance of the NSGA-II in converging near the true Pareto-optimal front compared to other evolutionary algorithms [48]. Overall, the number of configurations simulated is 270 per scenario, which is significantly less than the number of simulations required if the model was simply run under Microsoft Excel™ by varying the OP and MPQ in their range of values (i.e., $231 \times 231 = 53,361$ simulations).

The optimization procedure was run on an Intel® Xeon®E3, 16 GB RAM desktop equipped with Windows 7 Professional. Simulating each scenario (with $N_{\text{days}} = 20,000$) required approximately 1 h and 2 min.

5.2. Ranking Procedure

As a last step, the multi-criteria decision making (MCDM) tool of ModeFRONTIER™ was exploited to rank the feasible configurations on the basis of their score against the objectives set in the optimization, to enable an effective final choice of the dyad MPQ-OP which returned the best solutions in terms of all the relevant KPIs. A linear MCMD model was chosen to rank the configurations, as it is the simplest approach to ranking. This approach computes a sort of weighted sum of the scores of each KPI subject to optimization, after the user has set a relative importance (weight) for the KPIs. In the “base” configuration, the highest relative importance was assigned to the total CO₂ emissions (0.40), in line with the focus of the study, and to the OOS(0.40), because configurations that avoid the occurrence of out-of-stock situations should be preferred for a practical implementation at Company A. The lowest weights (0.10) were assigned to AR and U%.

However, because determining the relative importance of the KPIs is a subjective process, two additional scenarios were analyzed in a sensitivity analysis, with different weights assigned to the KPIs. The weights set in these scenarios are:

- 0.25 for all the KPIs. This scenario should capture the situation where Company A attributes the same importance to all KPIs considered in the optimization;
- 0.40 for AR and U% and 0.10 for the total environmental impact and for the OOS. This scenario should capture the situation where Company A attributes the highest importance to the strategic KPIs, while the environmental impact is perceived as less important.

6. Results

6.1. Simulation Results

The main results of the simulation runs are reported in the form of trend of the KPIs chosen for the optimization as a function of two problem variables, i.e., OP and MPQ. Such representation is effective in highlighting the impact of these parameters on the environmental performance of the system. A correlation analysis on the simulation outcomes was also performed to help identify relationships among the variables and the KPIs.

The trends of U%, AR, OOS and $I_{TOT,1}$ as a function of OP and MPQ are proposed in Figures 2–5.

Starting from the environmental KPI, from Figure 2a it can be seen that $I_{TOT,1}$ varies approximately from 75 to 150 kg CO₂ eq./day, while solutions with $I_{TOT,1} < 75$ kg CO₂ eq./day are all unfeasible. The design space includes (feasible) solutions with the same $I_{TOT,1}$ (e.g., 75 kg CO₂ eq./day), which stem from very different values of OP (from 150 up to 1200 pallets). Similarly, the same value of OP (e.g., 150 or 450 pallets) generates very different $I_{TOT,1}$. Therefore, the relationships between these parameters are not immediately easy to identify. The correlation analysis confirms this consideration: indeed, the correlation between OP and $I_{TOT,1}$ is very weak (0.09). Figure 2b shows, instead, a clear relationship between $I_{TOT,1}$ and MPQ. More precisely, the increase in MPQ involves a corresponding decrease in $I_{TOT,1}$, which is confirmed by the quite strong negative correlation (−0.68) between these

variables. When MPQ is higher, Company A will use recovery operations less frequently, resulting in lower CO₂ emissions of the retrieving activities and in a better environmental performance.

With respect to the strategic KPIs, Figure 3a shows that the highest AR (>200 rotations/year) is obtained with OP \approx 150–200 pallets. Solutions with OP < 100 pallets are almost all unfeasible. In general, it is reasonable to expect that the increase in OP involves a corresponding increase in the number of P_A . This, in turn, increases the cycle time of assets, worsening the AR. This is confirmed by the negative correlation between these variables (−0.66). The relationship between AR and MPQ (Figure 3b) is very similar (−0.49). When the MPQ is higher, Company A will reduce the recovery operations and will probably increase the number of orders, resulting in a higher P_A and thus decreasing the usage of each asset.

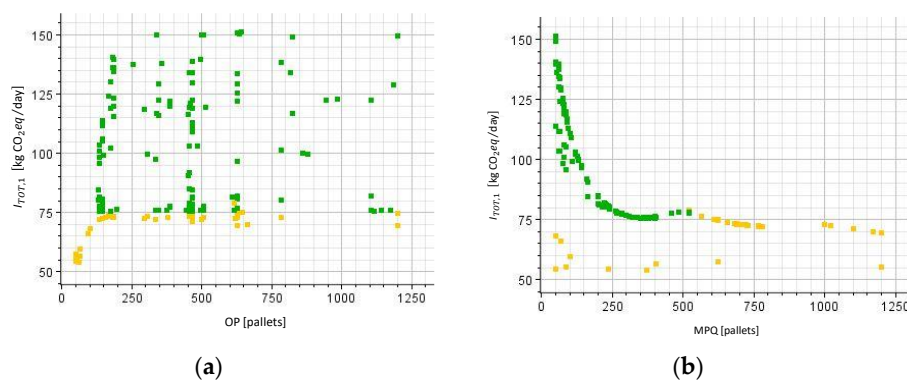


Figure 2. Trend of $I_{TOT,1}$ [kg CO₂ eq./day] as function of OP (a) and MPQ (b).

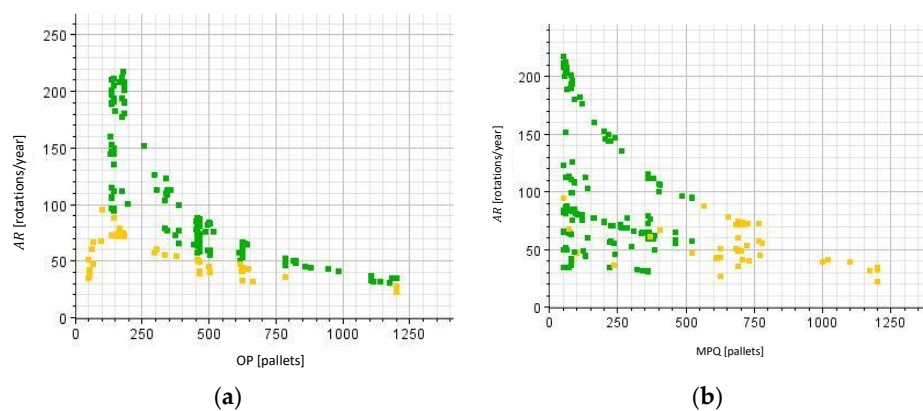


Figure 3. Trend of AR [rotations/year] as function of OP (a) and MPQ (b).

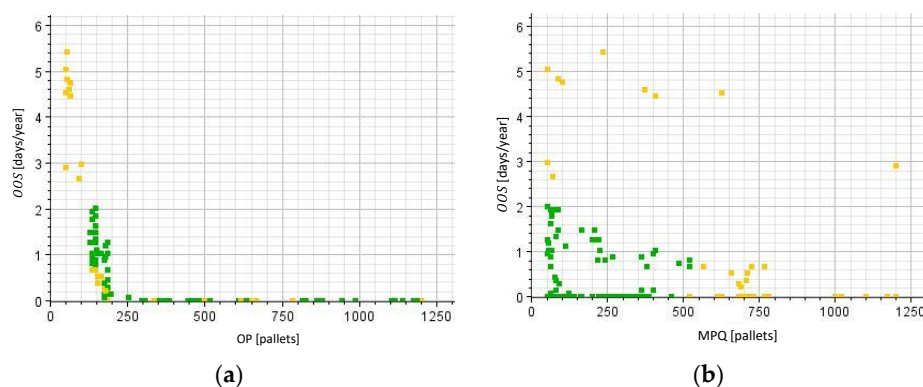


Figure 4. Trend of OOS [days/year] as function of OP (a) and MPQ (b).

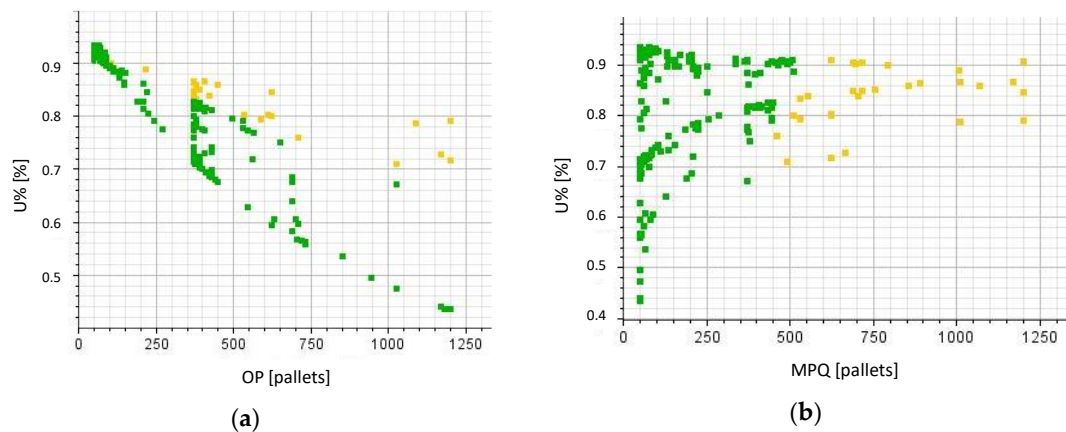


Figure 5. Trend of $U\%$ [%] as function of OP (a) and MPQ (b).

The relationship between OOS and OP is evident from Figure 4a and quite easy to explain. Higher OP generates higher inventory available when orders are placed and therefore, out-of-stock situations are less likely to occur. Accordingly, these variables exhibit a negative correlation (-0.59). From Figure 4a it can also be seen that configurations with $OP > 250$ pallets always generate null (or almost null) OOS, which is an important evidence for Company A. Conversely, with values of OP from 100 to 200 pallets OOS situations are particularly likely to occur, although the resulting configurations are unfeasible. The relationship between OOS and MPQ is slightly less evident (Figure 4b). In general, lower MPQ seems to generate higher OOS, probably because higher MPQ involves a higher P_A , thus making OOS situations less likely to occur. Nonetheless, it should also be noted that, in feasible configurations, stock-out situations are very unlikely to occur, as their maximum value is 2 days/year. The low correlation coefficient (-0.14) confirms a weak relationship between these variables.

Figure 5a shows that $U\%$ tends to decrease with the increase in OP. Increasing OP causes a corresponding increase in the number of P_A and, consequently, a higher cycle time of assets. Since $U\%$ is inversely proportional to the cycle time, it decreases accordingly. The two variables thus exhibit a strong negative correlation (-0.81). Conversely, the relationship between $U\%$ and MPQ (Figure 5b) seems to be opposite, i.e., the increase in MPQ involves a corresponding increase in $U\%$. However, this relationship is weaker than the previous one (0.31).

6.2. Multi-Criteria Ranking

The solutions described in the previous paragraph were subject to multi-criteria ranking using the linear MCDM tool of ModeFRONTIER™. We start by considering the “base” scenario, in which the highest importance (0.4) is assigned to the environmental KPI and the OOS, while the importance of the remaining KPIs is set at 0.1. Table 4 shows an extract of the top-5 simulation runs after ranking.

From Table 4 it is easy to see that the top-5 configurations are similar in terms of all environmental emissions ($I_{TOT,1}$, $I_{TOT,2}$ and $I_{TOT,3}$), which confirms that these KPIs follow the same trend. $I_{TOT,1}$, which was subject to minimization, turns out to be in the range 75.50 to 76.43 kg CO₂ eq./day. It is also easy to see that, as already recalled, $I_{palletTOT}$ does not vary as a function of OP and MPQ, as it depends only on the amount of pallets lost and damaged. Such contribution accounts for approximately 38.28% of the total CO₂ emission of Company A. $I_{STOT,e}$ does not vary either, as shipments are triggered by the customers’ demand and as such do not depend on OP and MPQ.

In all the top-5 configurations, $I_{TOT,e}$ is almost constant; $I_{TOT,1}$ for instance, always accounts for 0.23 kg CO₂/day, corresponding to approximately 0.30% of the total CO₂ emissions of the system. $I_{TOT,2}$ and $I_{TOT,3}$ account, instead, for approximately 0.50% of $I_{TOT,2}$ and $I_{TOT,3}$, respectively. Therefore, purchasing activities have very limited impact on the environmental performance of the CLSC. The last environmental KPIs, i.e., $I_{RTOT,e}$, turns out to be the most important quota of the

environmental emissions of the CLSC. To be more precise, $IR_{TOT,1}$ ranges from 42.76 to 43.69 kg CO₂ eq./day, corresponding to 56–57% of $I_{TOT,1}$; the contribution of $IR_{TOT,2}$ and $IR_{TOT,3}$ to $I_{TOT,2}$ and $I_{TOT,3}$ is even higher (ca. 91%). This suggests that minimizing $I_{TOT,e}$ basically corresponds to minimizing $IR_{TOT,e}$ for the system considered.

With respect to the strategic KPIs, the top-5 configurations do not exhibit a significant difference in terms of OOS, which accounts for 0.15 days/year in the first two configurations and is null in the remaining ones. Despite an OOS greater than 0, the first ranked configuration, obtained setting OP = 175 and MPQ = 360 pallets, shows a very high AR and a good U%. Configurations 196, 237 and 170 are instead interesting because of the null OOS, which could be of practical interest to Company A; however, AR and U% are slightly worse compared to the first two ranked configuration.

6.3. Sensitivity Analysis

We now consider the case of a change in the relative importance of the KPIs subject to optimization, to highlight possible modifications in the asset management strategy of Company A as a function of the weights assigned to these KPIs.

We begin by analyzing the situation in which the same relative importance (i.e., 0.25) is assigned to all the KPIs subject to optimization; with these weights, the top-5 configurations resulting after ranking are proposed in Table 5. As Table 5 shows, in the case all the KPIs are given the same importance, the results are quite variable in terms of the total environmental emissions ($IP_{TOT,1}$, $I_{TOT,2}$ and $I_{TOT,3}$), OOS and AR. Moreover, the top-5 configurations all exhibit a non-null OOS, meaning that if Company A is interested in enhancing also AR and U%, the occurrence of stock-out situations cannot be avoided. Looking, for instance, at the CO₂ emissions ($I_{TOT,1}$), it can be noticed that they are significantly higher in this scenario than in the “base” scenario, with a peak of 102.6 kg CO₂ eq./day in the third ranked configuration. Once again, this is due to the relevant contribution of $IR_{TOT,1}$. AR and U% improve significantly compared to the “base” scenario, reaching ca. 150 rotations/year and 88.3% respectively in the first ranked configuration.

It is interesting to note that configuration 154 ranked fourth in this scenario and first in the “base” scenario; this suggests that this configuration returns performance values that are quite robust with respect to the weights assigned to the KPIs.

A further interesting point is that, apart from configuration 154, all the remaining configurations are obtained setting a quite low MPQ (from 120 to 265 pallets). Because of the low MPQ, from a practical point of view it could be hypothesized that Company A would be able to carry out retrieving operations using low capacity vehicles. These vehicles produce less CO₂ compared to 33-pallet lorries (whose use has been hypothesized in this study); therefore, the real environmental impact could be lower than that estimated by our model.

Table 6 shows the results obtained in the case the highest importance (0.4) is assigned to AR and U%, while less importance (0.1) is assigned to $I_{TOT,1}$ and OOS. As it is reasonable to expect, the top-5 configurations all exhibit a very good AR (around 200 rotations/year), which involves a limited amount of proprietary assets (ca. 1000 pallets at maximum). The environmental emissions in this situation are not optimized, because, with fewer pallets, Company A should organize very frequent collections of pallets from the customers’ sites. Nonetheless, as per the previous case, the MPQ of the top ranked configurations is quite low, which suggests that Company A could carry out retrieving operations using low capacity vehicles, resulting in reduced CO₂ emissions compared to those computed using our model. Finally, the results in Table 6 confirm that when maximizing R and U%, out-of-stock situations are more likely to occur.

Table 4. Top-5 configurations of the “base” scenario after ranking.

Decision Variables			Strategic KPIs			CO ₂ eq. (kg/day)					NO _x (g/day)					SO _x (g/day)				
Configuration ID	OP	MPQ	OOS	AR	U%	P _A	IR _{TOT,1}	IP _{TOT,1}	Ipallet _{TOT}	IS _{TOT,1}	I _{TOT,1}	IR _{TOT,2}	IP _{TOT,2}	IS _{TOT,2}	I _{TOT,2}	IR _{TOT,3}	IP _{TOT,3}	IS _{TOT,3}	I _{TOT,3}	C _{tot}
154	175	360	0.15	111.63	87.15	2047	42.76	0.23	28.90	3.61	75.50	12.80	0.07	1.08	14.00	4.80	0.03	0.14	5.33	179.28
262	195	400	0.15	100.80	86.85	2253	43.69	0.23	28.90	3.61	76.43	13.10	0.07	1.08	14.27	5.00	0.03	0.14	5.43	184.07
196	335	360	0.00	79.372	82.78	2205	43.05	0.23	28.90	3.61	75.79	12.90	0.07	1.08	14.08	4.90	0.03	0.14	5.36	184.31
237	345	370	0.00	76.41	82.23	2262	43.07	0.23	28.90	3.61	75.81	12.90	0.07	1.08	14.09	4.90	0.03	0.14	5.36	184.47
170	375	360	0.00	73.19	81.46	2228	43.18	0.23	28.90	3.61	75.92	12.90	0.07	1.08	14.13	4.90	0.03	0.14	5.38	185.28

Table 5. Top-5 configurations after ranking with modified weights—first scenario.

Decision Variables			Strategic KPIs			CO ₂ eq. (kg/day)					NO _x (g/day)					SO _x (g/day)				
Configuration ID	OP	MPQ	OOS	AR	U%	P _A	IR _{TOT,1}	IP _{TOT,1}	Ipallet _{TOT}	IS _{TOT,1}	I _{TOT,1}	IR _{TOT,2}	IP _{TOT,2}	IS _{TOT,2}	I _{TOT,2}	IR _{TOT,3}	IP _{TOT,3}	IS _{TOT,3}	I _{TOT,3}	C _{tot}
209	145	215	0.82	149.79	88.29	1467	48.17	0.23	28.9	3.61	80.91	14.47	0.07	1.08	15.62	5.51	0.03	0.14	5.95	202.03
61	145	240	0.82	147.05	88.21	1500	46.69	0.23	28.9	3.61	79.43	14.02	0.07	1.08	15.18	5.34	0.03	0.14	5.78	195.72
246	175	120	0.07	177.05	84.9	972	69.32	0.23	28.9	3.61	102.06	20.83	0.07	1.08	21.97	7.93	0.03	0.14	8.37	288.01
154	175	360	0.15	111.63	87.15	2047	42.76	0.23	28.9	3.61	75.5	12.80	0.07	1.08	14.00	4.80	0.03	0.14	5.33	179.23
91	145	265	0.89	135.51	88.19	1714	44.99	0.23	28.9	3.61	77.73	13.52	0.07	1.08	14.67	0.14	0.03	0.14	5.59	188.56

Table 6. Top-5 configurations after ranking with modified weights—second scenario.

Decision Variables			Strategic KPIs			CO ₂ eq. (kg/day)					NO _x (g/day)					SO _x (g/day)				
Configuration ID	OP	MPQ	OOS	AR	U%	P _A	IR _{TOT,1}	IP _{TOT,1}	Ipallet _{TOT}	IS _{TOT,1}	I _{TOT,1}	IR _{TOT,2}	IP _{TOT,2}	IS _{TOT,2}	I _{TOT,2}	IR _{TOT,3}	IP _{TOT,3}	IS _{TOT,3}	I _{TOT,3}	C _{tot}
130	135	60	1.93	210.9	89.28	967	70.64	0.23	28.9	3.61	103.38	21.22	0.07	1.08	22.38	8.09	0.03	0.14	8.52	299.89
62	145	60	1.63	211.25	87.83	919	79.03	0.23	28.9	3.61	111.77	23.74	0.07	1.08	24.90	9.05	0.03	0.14	9.48	335.18
78	135	85	1.93	196.68	90.39	1051	63.12	0.23	28.9	3.61	95.86	18.96	0.07	1.08	20.12	7.22	0.03	0.14	7.66	268.14
123	135	80	1.93	200.95	88.96	1030	68.1	0.23	28.9	3.61	100.84	20.46	0.07	1.08	21.61	7.79	0.03	0.14	8.23	288.14
191	145	50	2.01	211.93	87.7	886	80.97	0.23	28.9	3.61	113.71	24.33	0.07	1.08	25.48	9.27	0.03	0.14	9.71	344.01

7. Conclusions

This paper has proposed an analysis of the environmental emissions caused by the asset management process of a real CLSC, consisting of a pallet provider, a manufacturer (Company A) and several retailers. The analysis was supported by a Microsoft Excel™ model, which computes the CO₂, NO_x and SO_x emissions of the system on the basis of the flows of asset. This model was integrated with ModeFRONTIER™ in a multi-objective optimization procedure, which took into account these emissions and some strategic KPIs of Company A. The multi-objective optimization targeted, in particular, the minimization of the CO₂ emissions, coupled with the minimization of stock-out occurrence and the maximization of assets usage and rotation. As a result, the setting of the asset management process, in terms of OP and MPQ, which performed best against the objectives set was derived as a function of the relative importance assigned to each KPI.

When assigning the highest relative importance to the minimization of CO₂ emissions and OOS occurrence (“base” scenario), the best performance of the system is achieved setting OP = 175 and MPQ = 360 pallets. With this setting, the total CO₂ emission of the CLSC accounts for 75.50 kg CO₂ eq./day approximately. The different components of the environmental impact contribute to this KPI in different ways and to a different extent. Asset retrieving activities contribute to the total impact to the greatest extent (approx. 42.76 kg CO₂/day), while the CO₂ emissions caused by the purchasing of new assets and the replenishment of lost and damaged assets are significantly less relevant. The CO₂ emissions due to the shipping activities, although not irrelevant, cannot be minimized by Company A, as shipments depend on the final customers’ demand only. This implicitly means that to minimize the total emissions of the system, Company A should actually minimize the environmental burdens caused by asset retrieving operations. In turn, the high environmental impact of retrieving activities is due to the quite relevant distance between Company A and its customers (delivery points), which is always higher than 250 km (approximately 496 km on average) in the system considered. This distance also prevents the possibility of visiting more than one customer in a single shipment. Moreover, as retrieving activities are ad hoc transports, they are rarely optimized in terms of truck load. Therefore, if using lorries with a capacity of 33 pallets, an effective strategy to decrease the environmental impact of retrieving operations is to set the MPQ at a quite high value, close to a full truck load shipment—this is why the top-5 ranked configurations of the “base” scenario all exhibit MPQ > 360 pallets.

Besides the “base” scenario, we carried out a sensitivity analysis to evaluate two additional situations, in which different weights were set for the KPIs subject to optimization. In the first situation, the same relative importance was assigned to all KPIs considered in the optimization process. In this case, the most effective performance is obtained when setting OP = 145 and MPQ = 215 pallets and exhibits a very good AR and U%. However, the environmental impact of the CLSC is not optimized in this scenario and stock-out situations are more likely to occur. In the case where the highest importance is assigned to AR and U%, the top ranked configurations obviously show excellent scores against these KPIs, while the environmental performance and the OOS worsen significantly compared to the base scenario. Nonetheless, it is interesting to note that the MPQ of the top-ranked configurations examined in the sensitivity analysis is always lower than that of the base scenario and, in particular, it is lower than the number of assets that can be retrieved with a full-truck load shipment. From a practical perspective, this means that retrieving activities will be more frequent, but that Company A could carry out these activities using low capacity vehicles (instead of 33-pallet lorries, as hypothesized in our model); therefore, there is room for reducing the resulting environmental impact.

A further consideration that can be derived from the analysis of the top-5 ranked configurations of all scenarios is that the total environmental performance and the total cost of the CLSC, although not strictly proportional, seem to go at the same pace. The lowest total environmental impact and total cost were indeed obtained in the first scenario (i.e., when the minimization of the environmental KPI is given the highest relative importance), while, with the increase in the total impact, the total cost of the system increases too.

To sum up, the results of this study provide Company A with an overview of its current performance in terms of environmental emissions and can help the company improve the environmental impact of its asset management process.

From a theoretical perspective, the model developed in this paper includes a set of formulae that were added to an original (economic) model for the computation of the environmental emissions of the system. From a practical perspective, this paper is structured as a case study, as it focuses on the specific context of Company A. Nonetheless, a similar evaluation can be easily extended to different companies or CLSCs. When analyzing different systems, it could be interesting to evaluate whether lower distances between the focal company and its customers could modify the environmental balance of the system or change the strategy to be adopted for assets management. Similarly, the multi-objective optimization procedure could be applied with different relative importance of the KPIs or setting different objectives, with the aim to evaluate the impact of different assets management strategies on the environmental performance of the system. Therefore, the model itself represents an interesting addition to the literature about CLSCs.

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