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Remanufacturing Strategies for Second-Hand Systems

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Research work to apply for the degree Industrial Engineering

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Resumen

La remanufactura es el proceso de restauración de productos usados que busca entregarlos como nuevos mediante el desmontaje, la limpieza, la reparación, el reemplazo de piezas y el montaje final. Económicamente, la remanufactura puede ser rentable, pero la industria, el tipo de producto y el nivel de incertidumbre tanto en la cantidad de productos devueltos como en la calidad de las devoluciones lo condicionan en gran medida. La condición y el estado de degradación de los productos devueltos afectan la confiabilidad y las tasas de rendimiento de los componentes recuperados por el desmontaje de estos productos. El uso de piezas recuperadas en el proceso de remanufactura también requiere actualización y reacondicionamiento, lo que puede aumentar el costo de los productos de segunda mano remanufacturados. Además, las compañías tienden a ofrecer una generosa cobertura de garantía para atraer a los consumidores. Las implicaciones ambientales y económicas de todas estas decisiones de logística, producción, ventas y soporte son altas. Este proyecto pretende extender un modelo matemático para apoyar la toma de decisiones en el diseño de la cadena de suministro de productos remanufacturados de segunda mano.

Palabras clave: remanufactura, cadena de abastecimiento de circuito cerrado, logística inversa, modelo multiperíodo.

Abstract

Remanufacturing is the process of restoring used products to like-new condition by disassembly, cleaning, repairing, and replacing parts, and reassembly. Economically, remanufacturing can be profitable, but the industry, product type, and on the level of uncertainty in both the number of returned products and the quality of the returns heavily condition this. The condition and state of degradation of returned products affect the reliability and yield rates of the components recovered by disassembly from these products. Using recovered parts in the remanufacturing process also requires upgrading and reconditioning which can increase the cost of the remanufactured second-hand products. Moreover, remanufacturers tend to offer generous warranty coverage to attract consumers. The environmental and economic implications of all these planning, production, sales, and support decisions are high. This project aims to extend a mathematical model to support decision-making in the supply chain design for second-hand remanufactured products.

Keywords: remanufacturing, closed-loop supply chain, inverse logistic, multiperiod model.

Introduction

Environmental problems related to the excessive consumption of products worldwide have been evidenced, which indicates that it is necessary to generate a more efficient use of them to reduce emissions in their production phase and the volume of waste generated. Two of the mechanisms proposed to deal with these environmental impacts are: i.) improving the design of the goods thinking about its subsequent recycling, and ii.) prolonging the useful life of the products to reduce their consumption. The later involves, design for durability, maintenance, repair service, reuse of parts, remanufacturing, as well as leasing or rental in which the Product Service System (PSS) strategy is established (Besch, 2005).

First, it is necessary to understand the problem, characterize the actors that interact, and understand their relationships. In this sense, the tool used is the closed supply chain (CLSC), which is characterized by being a combination of supply chains. direct and reverse. For its part, the reverse supply chain begins with the acquisition of products that have already reached their useful stage and have the characteristics of being analyzed and classified, to determine if they can be remanufactured (Guide et al., 2003). When the products are already remanufactured, they are distributed and sold in a market that is interested in this type of product. Many companies see this type of economy of scale as a fantastic opportunity, since the advantages among many are, the expansion of the market, support for the environment, and expansion of the labor market, among others. However, the analysis of the entire supply chain and the implications and risks taken are factors that must be studied to make the best decisions (Ven katadri, Diallo, and Ghayebloo, 2017).

In this way, the need arises to know and clearly trace the supply chain of the production process of remanufactured products; and thus, optimize it with the help of an engineering model. For this reason, the objective of this project is to propose a model that supports decision-making in the supply chain design for second-hand remanufactured products, which integrates multi-periodicity. The model proposed extends the work of (Venkatadri et al., 2017), who use a similar setting.

To fulfill the objective of this project a three-phase methodology is followed. First, the supply chain for remanufactured products is described in detail based on a literature review. Second, a model is structured that reflects the said process and that can contribute to the determination of the optimal configuration of the supply chain. And finally, the model is validated, either in a real scenario or in a simulation case.

The remainder of this document is organized as follows, then the first section is the literature review, to give clarity and context to fundamental issues in a conceptual way. Then the formulation of the model is described, where there is a description of the problem to be studied, the base model on which this document is based is described, and finally the extension of this model, which is the contribution that is executed. In the third section are the results of the four experiments that validate the dynamics of the model. Below is the due analysis of each of these experiments. And finally, there are the conclusions and future work.

1 Literature review

1.1 Supply Chain

In the last century, the definition of the supply chain (SC) has had a constant evolution, for example (Van der Vorst, 2000) begins to associate it with a set of activities by material and information flows, which seek to satisfy the needs of the client and at the same time of the interested parties (stakeholder). A year later (Mentzer et al., 2011) propose a broader definition, stating that SC "Is defined as the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole".

In later years (Ballou, 2004) he interpreted it as all the activities related to the flow and transformation of products and information that start from the disposal of the raw material to the final consumer, clarifying that the products and information can go from behind to forward and vice versa. With this the same idea (Chopra S. & Meindl, 2008) says that: "An SC is made up of all those parties that are directly or indirectly involved in satisfying customer needs. The supply chain includes the manufacturer, supplier, carrier, warehouse worker, retailer, and even customers.” And on the other hand (Chase R. & Jacobs, 2009) affirms that the SC is a representation, like a map on which companies rely to understand their link and interaction, depending on the point from which they want to analyze, if from a link of the chain or from the company itself. At present, in a more specific way in the strategic decisions of the SC, it is necessary to determine, firstly, the type of product that is going to be manufactured, and secondly, the type of manufacturing activities that the company does to produce the product. type of product and thirdly, the services necessary to satisfy the demand of the final consumer, the above according to (Stevenson, 2012).

The process of recognition, analysis, and construction of the SC is important since it is where the actors, the relationships between them, and their roles within the chain are identified. The configuration of the chain involves mainly strategic decisions but influences activities at the tactical/operational level that remain over time with long-term effects (Shen, 2007). This design implies large capital investments, due to the changes that can be generated in favor of its continuous improvement, since these decisions are key and require studies that allow analyzing its behavior given certain changes and, in the end, being able to choose the best one. Among its benefits is the generation of economic, environmental, and consumer value, which encourages governments and directs entrepreneurs. Therefore, it is of great interest for the academic and research community to study these initiatives that directly contribute to opportunities for improvement in all directions, resulting in scientific contributions, such as articles and publications (Diallo, Venkatadri, Khatab, & Bhakthavatchalam, 2017; Govindan et al., 2017).

To give a general example, Supply Chain Direct Flow (SCND) network design problems deal with issues such as determining the number, locations, and capacities of production/manufacturing/ distribution, intermediate inventories at each facility, and the amount of flow between them (Fleischmann et al., 1997). There are specific cases such as networks in the opposite direction and closed circuit (where the backward network is integrated with the forward network) that require other facilities such as inspection, recovery, and collection centers, since designing the direct flow and reverse separately is not optimal for supply chain objectives, direct flow design, and RLs (Baumgarten et al., 2003; Schultmann et al., 2006). And more recently, (Samuel et al., 2021) highlights the existence of value-added concepts such as partnerships and collaborations, IT solutions, and supply chain processes, together with the design characteristics of products and services, contribute to the economy (income generation, cost reduction), environmental, informative and customer value benefits. Additionally, closed-loop supply chain networks with economies of scale result in higher profits compared to models without economies of scale, which helps to think about studying other types of systems.

1.2 Circular Economy

The circular economy (CE) was born as a paradigm of sustainability that has spread in recent years, displaying different definitions. For its part (Kirchherr et al., 2017) defines it as "an economic system that replaces the concept of "end of useful life" by the reduction, reuse, recycling, and recovery of materials in production/distribution processes and consumption. It operates at the micro level (products, companies, consumers), at the meso level (eco-industrial parks), and at the macro level (city, region, nation, and more), to achieve sustainable development, while creating environmental and economic quality." According to (Macarthur, 2013), CE is characterized by being restorative and regenerative, seeking to maintain the value of products, materials, and components throughout its process to fulfill its objective of decoupling economic growth from the exploitation and consumption of finite resources. Along these same lines, the British Standard Institute adds that by maintaining the materials and components, the technical and biological cycles are distinguished (The British Standard Institution, 2017). Even though the concept has become relevant in recent years, its theoretical bases already existed, encompassing concepts of industrial ecology, biomimicry, and Cradle-to-Cradle (Ceschin F. & Gaziulusoy, 2016).

When implementing CE strategies, a great impact has been evidenced by preventing the negative effects caused by the traditional way of transforming and consuming goods, among which is the accelerated decrease in finite natural resources, the high consumption of raw materials and generation waste, environmental damage from water, air, and soil pollution (Ellen MacArthur Foundation, 2015, 2019; Yang et al., 2018). CE is considered a potential solution that helps protect the environment without becoming an obstacle to economic growth (Lieder M. & Rashid, 2016;

Stahel, 2016). One of its main axes is based on the 3R principle: resource reduction, reuse, and recycling, which seeks to establish a closed system in the flow of materials (Geng Y. & Doberstein, 2008), minimizing virgin materials and energy resources that are inputs to production systems and reducing the amount of waste generated (Lieder M. & Rashid, 2016).

1.3 Remanufacturing

The behavior and availability of the supply is crucial for companies since their increase can improve the size of their market in an innovative and competitive field of business. When articles with extended life use are produced with the help of activities such as remanufacturing, they can help companies increase flexibility and volume of supply, and in parallel meet the increased demand for sustainable products (Diaz R. & Marsillac, 2017). One of the strategies promoted by CE is remanufacturing, which, thanks to its essence, achieves positive results inside and outside the supply chain. The principle of cascading use aims, like the circular economy, to retain the value of materials and resources within the system as much as possible. For this, the materials and resources undergo different uses sequentially and probably with other purposes. During cascade use, the quality of the materials is reduced, and energy consumption is generated (Macarthur, 2013).

Conceptually, remanufacturing is defined as the process of disassembling and recovering the product in the closed or reverse supply chain, this process requires the repair or replacement of parts of the product that are not in good condition or total loss. Remanufacturing contributes to satisfying the demand for some products at a lower price, this is a sustainable option for companies since it helps to extend the useful life of the product through technical updates (Guide et al., 1997). Importantly, remanufacturing is recognized as a recoverable manufacturing system, with an emphasis on value-added recovery, rather than material recovery only (Diaz R. & Marsillac, 2017). In recent years, this process has been recognized not only in the literature but also in practice, obtaining support from the interested and benefited sectors, which in some way demand that companies be encouraged to offer organic products (Guide V. & Van Wassenhove, 2009). For example, Xerox, Hewlett-Packard, Electrolux USA, Black & Decker, Bosch, and Apple are companies recognized for actively participating with remanufactured products, highlighting that in this way they prevent contamination with usable waste (Atasu et al., 2010).

2 Model formulation

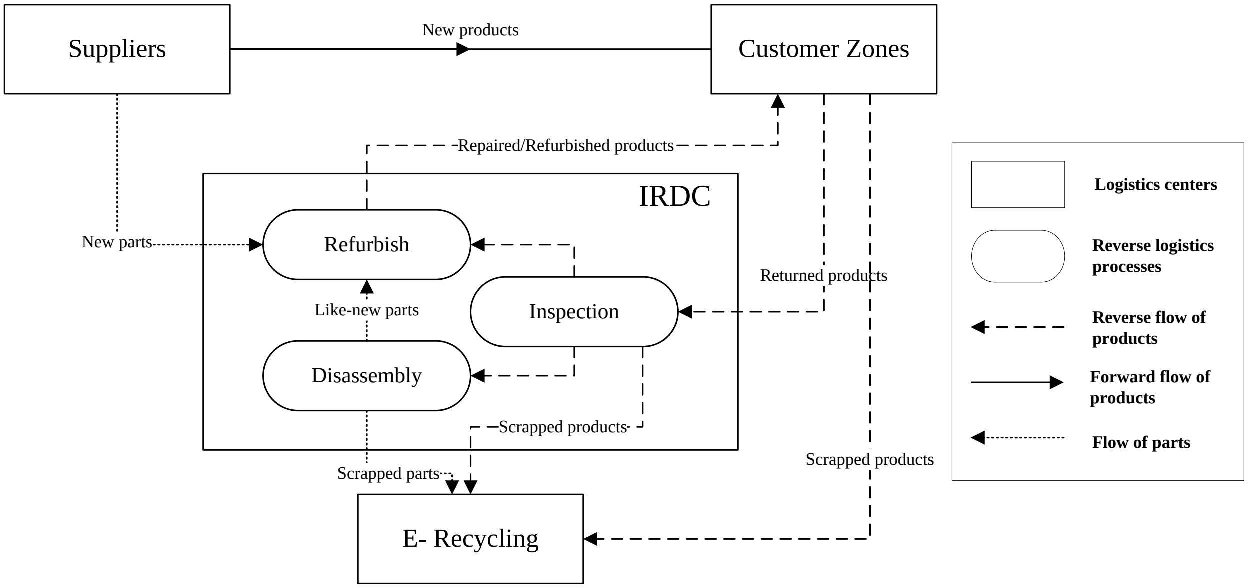
2.1 Problem statement

Currently, companies are betting on policies and measures that help to reduce environmental risks, caused directly or indirectly by their commercial work. These initiatives open the door to a market for reconditioned products, where it is possible to demonstrate success stories that guarantee quality and reliability, with an added value of a more affordable price given its origin and with a competent guarantee. In this process, the products are classified depending on the state of each piece into products to be reconditioned, products to be disassembled to extract spare parts for other products, and products to be recycled. Regarding disassembly, the condition and performance can be affected by the process it had in assembly (Crowther, 1999; Güngör, 2006). It must also be considered that parts with welding processes will be more difficult to recover and have an elevated risk of being damaged. This way, these types of parts with low reliability are available for recycling since they are called non-operational.

We consider a closed-loop supply chain network consisting of suppliers, customer zones (CZ), inspection, repair, and disassembly centers (IRDC), a recycling center, and an inventory center. Each IRDC has three main recovery activities: inspection, repair, and disassembly (Venkatadri et al., 2017). Suppliers' ability to provide new parts, inventory center capacity, and inspection and disassembly capacity of IRDCs are supposed to be limited.

Figure 1

Representation of the closed-loop network with IRDC nodes and recycling



Nota. Fuente (Venkatadri et al., 2017).

The process described in (**Figure 1**), begins with the demand for new products that are satisfied by the corresponding suppliers. After a certain time of use, which depends on the client, the product or parts of it is returned to the collection centers/depots. From the collection centers, products are sent to the IRDC, for inventory (depending on capacity) or recycling (depending on their status). Some of the inspected products are reconditioned to satisfy the demand for reconditioned products. There is an option of installing a disassembly line in each IRDC. In this disassembly line, the disassembled products produce two types of parts: parts in good condition that are used for restoration and parts that are discarded and sent for recycling. When recovered parts are not enough to support refurbishment activities, new parts will be purchased and shipped to IRDCs.

In this proposed chain, there are two types of product markets: new and reconditioned, where reliability is measured by the failure rate of the parts, this means that the higher the failure rate the lower the reliability.

We first describe the model proposed by (Venkatadri et al., 2017) on which we based the proposed extension. In this base model, the design of RL networks considers the reliability of the parts, levels of the greenness of the network, and demand for renewed products. Part reliability is calculated using the fraction of parts requiring replacement at the refurbishment stage in IRDC as an indicator of part reliability. The greenness score is defined as an aggregate score of the reliability of the parts and the greenness of the products.

In this model, the levels of greenness are defined based on the level of DFD technology, since there is no standard for its measurement in the industry, several authors propose indexes or scores (Deif, 2011; Hui et al., 2002), in this case, the greenness score is defined based on the parameters that affect the reliability of the part and the greenness of the product. This score affects four values, since as the greenness level increases, product price (πm) and stripping performance (θp) increase, while restoration costs (Rml) and stripping costs (Dml) decrease.

2.2 Model Formulation

The main base model is described below. The assumptions used in the creation RL model are:

- The cost of restoring salvaged parts to like-new condition is negligible compared to the cost of disassembly; therefore, it is not considered a cost.
- The suppliers are known, and the location of the CZs and the recycling center are fixed and predefined.
- The cost of disposal is included in the cost of shipping to the recycling center.
- The satisfaction of the demand for refurbished products is not mandatory.
- The following notation is used in the formulation of the closed-loop supply chain network model.

Sets

P	Parts
M	Products
K	Costumers CZs
L	Centers IRDC

Parameters

F_l	Fixed cost of opening IRDC l
F_l^D	Fixed cost of installing disassembly line at IRDC l
π_m	Unit purchasing price of product m
C_{mk}	Shipping cost of new product m delivered to CZ k
C_{mlk}	Shipping cost of refurbished product m delivered from IRDC l to CZ k
a_{pl}	Freight on board (FOB) destination cost of part p delivered to IRDC l
C_{mkl}	Unit shipping cost of product m from CZ k to IRDC l
C_{ml}	Unit shipping cost of product m from IRDC l to recycling
C_{mk}^e	Unit shipping cost of product m from CZ k to recycling center
C_{pl}	Unit shipping cost of scrapped part p from IRDC l to recycling center
I_{ml}	Unit inspection cost of product m at IRDC l
R_{ml}	Unit refurbishing cost of product m at IRDC l
D_{ml}	Unit disassembly cost of product m at IRDC l
C_p	Supply capacity for new part p
C_l	Inspection capacity of IRDC l
C_{ml}^D	Disassembly capacity of product m at IRDC l
d_{mk}	Demand for new product m in CZ k
d_{mk}^R	Demand for refurbished product m in CZ k
r_m	Return rate of product m from CZs
γ_p	Fraction of part p requiring replacement at the refurbishment stage at IRDC
σ_{pm}	Binary parameter indicating if part p is present in product m or not
θ_p	Fraction of good parts of type p recovered from disassembly at IRDC
ρ_{mk}	Unit sale price of new product m in CZ k
ρ_{mk}^R	Unit sale price of refurbished product m in CZ k
η_{mk}	Lost sale for unmet demand of refurbished product m in CZ k

Decision variables

f_{mkl}	Quantity of returned products m shipped from CZ k to IRDC l

f^R_{mkl}	Quantity of refurbished products m shipped from IRDC l to CZ k
f_{pl}	Quantity of new part p shipped from suppliers to IRDC l
f^R_{ml}	Quantity of product m refurbished at IRDC l
f^D_{ml}	Quantity of product m disassembled at IRDC l
g_{ml}	Quantity of scrapped product m shipped from IRDC l to recycling
g_{pl}	Quantity of scrapped part p shipped from IRDC l to recycling
$-\Delta_{mk}$	Shortfall of refurbished products m in CZ k
O^e_{mk}	Quantity of returned products m shipped from CZ k to recycling center

$$Y_l \quad \begin{cases} 1 & \text{if IRDC is open at location l at the start} \\ 0 & \text{otherwise} \end{cases}$$

$$Z_l \quad \begin{cases} 1 & \text{if disassembly line is installed at IRDC l} \\ 0 & \text{otherwise} \end{cases}$$

The mathematical formulation for the maximization of total profit in the network is given below.

$$\begin{aligned} \text{Maximize Z} = & \sum_{m\epsilon M}\sum_{k\epsilon K}\rho_{mk}\, f_{mk} + \sum_{m\epsilon M}\sum_{k\epsilon K}\sum_{l\epsilon L}\rho^R_{mk}\, f^R_{mlk} - \sum_{l\epsilon L}F_l\, Y_l - \sum_{l\epsilon L}F^D_l\, Z_l \\ & - \sum_{m\epsilon M}\pi_m\, f_m - \sum_{m\epsilon M}\sum_{k\epsilon K}c_{mk}\, f_{mk} - \sum_{m\epsilon M}\sum_{k\epsilon K}\sum_{l\epsilon L}c_{mkl}\, f_{mkl} \\ & - \sum_{m\epsilon M}\sum_{k\epsilon K}c^e_{mk}\, o^e_{mk} - \sum_{m\epsilon M}\sum_{k\epsilon K}\sum_{l\epsilon L}C^I{}_{ml}\, f_{mkl} - \sum_{m\epsilon M}\sum_{l\epsilon L}R_{ml}\, f^R_{ml} \qquad (1) \\ & - \sum_{m\epsilon M}\sum_{l\epsilon L}D_{ml}\, f^D_{ml} - \sum_{m\epsilon M}\sum_{l\epsilon L}\sum_{k\epsilon K}c_{mlk}\, f^R_{mlk} - \sum_{p\epsilon P}\sum_{l\epsilon L}a_{pl}\, f_{pl} \\ & - \sum_{m\epsilon M}\sum_{l\epsilon L}c_{ml}\, g_{ml} - \sum_{p\epsilon P}\sum_{l\epsilon L}c_{pl}\, g_{pl} - \sum_{m\epsilon M}\sum_{k\epsilon K}\eta_{mk}\, \Delta^-_{mk} \end{aligned}$$

Subject to

$$\sum_{k\in K} f_{mkl} = f_{ml} \quad \forall m \in M, \forall l \in L \tag{2}$$

$$\sum_{k\epsilon K} f_{mk} = f_m \quad \forall m \in M \tag{3}$$

$$f_{ml} = f_{ml}^{R} + f_{ml}^{D} + g_{ml} \quad \forall m \in M, \forall l \in L \tag{4}$$

$$f_{ml}^{R} = \sum_{k\epsilon K} f_{mlk}^{R} \quad \forall m \in M, \forall l \in L \tag{5}$$

$$\gamma p \sum_{m\epsilon M} \sigma pm\, f_{ml}^{R} = f_{pl} + \theta_p \sum_{m\epsilon M} \sigma pm\, f_{ml}^{D} \quad \forall p \in P, \forall l \in L \tag{6}$$

$$g_{pl} = (1 - \theta_p) \sum_{m\epsilon M} \sigma pm\, f_{ml}^{D} \quad \forall p \in P, \forall l \in L \tag{7}$$

$$f_{mk} = d_{mk} \quad \forall m \in M, \forall k \in K \tag{8}$$

$$\sum_{l\epsilon L} f_{mlk}^{R} = d_{mk}^{R} - \Delta_{mk}^{-} \quad \forall m \in M, \forall k \in K \tag{9}$$

$$o_{mk}^{e} + \sum_{l\epsilon L} f_{mkl} = r_m\, f_{mk} \quad \forall m \in M, \forall k \in K \tag{10}$$

$$\sum_{k\epsilon K} f_{mk} \le C_m \quad \forall m \in M \tag{11}$$

$$\sum_{l\epsilon L} f_{pl} \le C_p \quad \forall p \in P \tag{12}$$

$$f_{ml}^{D} \le C_{ml}^{D} Z_l \quad \forall m \in M, \forall l \in L \tag{13}$$

$$f_{mkl}, f_{mk}, f_{ml}^{R}, f_{ml}^{D}, g_{ml}, f_{mlk}^{R}, f_{pl}, g_{pl}, f_{mkl}, o_{mk}^{e} \ge 0 \quad \forall m \in M, \forall k \in K, \forall l \in L, \forall p \in P \tag{14}$$

$$Y_l, Z_l = \{0,1\} \tag{15}$$

The objective function (1) is to maximize the total profit, which is determined by the total revenue minus the total cost. Where total revenue is the sum of revenue from the sale of new and refurbished products. And the total cost is the sum of all costs incurred: fixed cost to set up facilities, supply cost to purchase parts and products from suppliers, shipping, inspection, reconditioning, disassembly costs, and lost sales costs (Venkatadri et al., 2017).

Constraints (2) enforce that the demand generated in the CZs is fulfilled through the different IRCDs. Constraints (3) assure the flow balance of products in the IRDCs. The left-hand side of the equation shows the total quantity of products inspected. The right-hand side shows the total quantity of refurbished, disassembled, and scrapped products. Constraints (4) ensure the flow of reconditioned products leaving the IRDC. Constraints (5) requires that compliance in quantities of parts delivered by the supplier be equal to that of the refurbished products. Constraints (6) set the total quantity of scrapped parts going to recycling after disassembly. Constraints (7) ensure that the demands in all CZs for refurbished products are satisfied. The possibility of lost sales is acceptable for refurbished products. Constraints (8) ensure that returned products from all CZs are either sent to IRDC or to the recycling center. Constraints (9) to (11) are capacity limit the supplier capacity for new products, supplier capacity for new parts, IRDC capacity for inspection, and IRDC capacity for disassembly. Finally, Constraints (12) and (13) enforce the non-negativity and binary restrictions on corresponding decision variables. As is conventional practice, the flow variables (f_{mkl}, f_{mk}, f_{ml}^{R}, etc.) are modelled as continuous instead of an integer (Venkatadri et al., 2017).

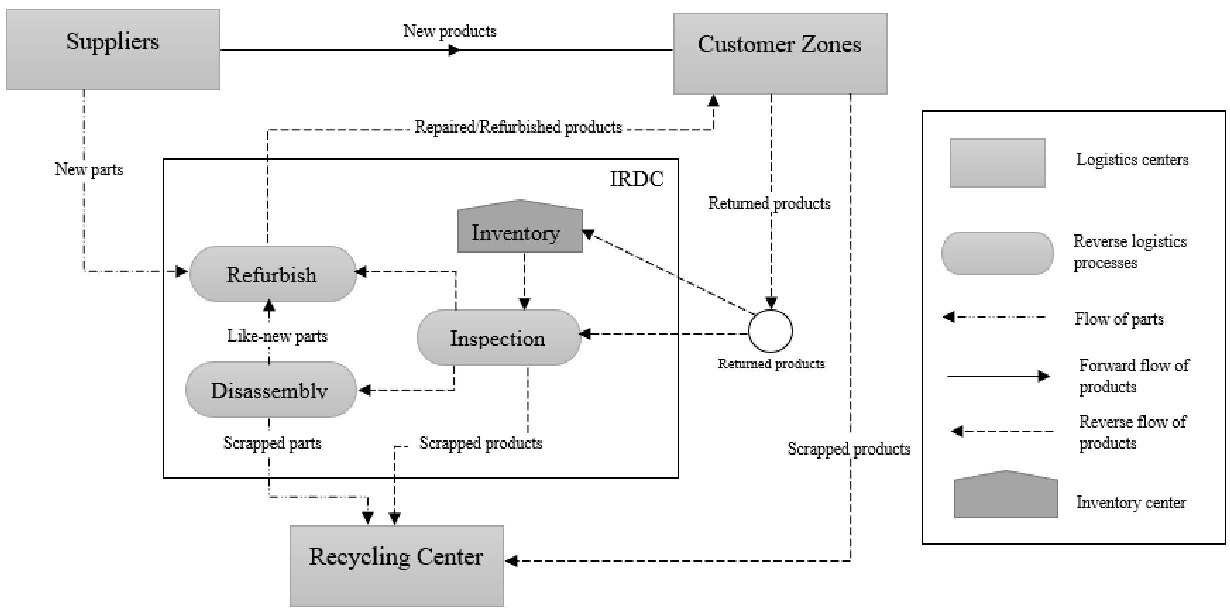
2.3 Model Extension

The purpose of this work is to extend the described model to a multiperiod scenario, which according to (Sarker R. & Newton, 2008) is used when a planning problem considers many periods in the future. In this way, the mathematical model is used to analyze and solve this process in individual periods, to link the planning process from one period to another That it is useful when the parameters of the model (demand, price, etc.) change in each period.

For the extension of the current model, the implementation of multi-period modeling is studied specifically in the IRDC center in the inspection area. In order to do so, an inventory is added to the IRDC center.. This change is represented in **Figure 2**, in which unlike in **Figure 1** the products are not directed directly to the IRDC center, but it has an inventory to create a buffer of products according to the volume of the demand in the market.

Figure 2

Representation of the closed-loop network with IRDC nodes, recycling, and inventory.



Model formulation

The assumptions used in the creation RL model are:

- The suppliers are known, and the location of the CZs and the recycling center are fixed and predefined.
- The cost of disposal is included in the cost of shipping to the recycling center.
- Satisfaction of the demand for refurbished products is not mandatory.
- Demand for new products must be met.
- There is a stability of costs in each year evaluated.
- The decision to open or not a new IRDC center (Yl) will not be considered.
- The following notation is used in the formulation of the closed-loop supply chain network model.

The following notation is used in the formulation of the closed-loop supply chain network model.

Sets

P	Parts
M	Products
K	Costumers CZs
L	Centers IRDC
S	IRDC sizes
T	Time periods

Parameters

F_{ls}^{I}	Fixed cost of opening an inspection station of size s at IRDC l
F_{ls}^{D}	Fixed cost of installing disassembly line at IRDC l of size s
Q_{max}	Maximum warehouse capacity
h_{mlt}	Unit holding cost return product m at IRDC l in period t
$I_{ml,0}$	Initial inventory of returned product m at IRDC l
π_{mt}	Unit purchasing price of product m in period t
C_{mkt}	Shipping cost of new product m delivered to CZ k in period t
C_{mlkt}	Shipping cost of refurbished product m delivered from IRDC l to CZ k in period t
a_{plt}	Freight on board (FOB) destination cost of part p delivered to IRDC l in period t
C_{mklt}	Unit shipping cost of product m from CZ k to IRDC l in period t
C_{mlt}	Unit shipping cost of product m from IRDC l to recycling in period t
C_{mkt}^{e}	Unit shipping cost of product m from CZ k to recycling center in period t
C_{plt}	Unit shipping cost of scrapped part p from IRDC l to recycling center in period t
C_{mlt}^{I}	Unit inspection cost of product m at IRDC l in period t
R_{mlt}	Unit refurbishing cost of product m at IRDC l in period t
D_{mlt}	Unit disassembly cost of product m at IRDC l in period t
C_{pt}	Supply capacity for new part p in period t
C_{ls}	Inspection capacity of IRDC l of size s
C_{mls}^{D}	Disassembly capacity of product m at IRDC l of size s
d_{mkt}	Demand for new product m in CZ k in period t

d^R_{mkt}	Demand for refurbished product m in CZ k in period t
r_{mt}	Return rate of product m from CZs in period t
γ_p	Fraction of part p requiring replacement at the refurbishment stage at IRDC
σ_{pm}	Binary parameter indicating if part p is present in product m or not
θ_p	Fraction of good parts of type p recovered from disassembly at IRDC
ρ_{mkt}	Unit sale price of new product m in CZ k in period t
ρ^R_{mkt}	Unit sale price of refurbished product m in CZ k in period t
η_{mkt}	lost sale for unmet demand of refurbished product m in CZ k in period t

Decision variables

f_{mkt}	Quantity of product m shipped to CZ k in period t
f_{mlt}	Quantity of product m shipped to IRDC l in period t
f_{mklt}	Quantity of returned products m shipped from CZ k to IRDC l in period t
f^R_{mlkt}	Quantity of refurbished products m shipped from IRDC l to CZ k in period t
f_{plt}	Quantity of new part p shipped from suppliers to IRDC l in period t
f^R_{mlt}	Quantity of product m refurbished at IRDC l in period t
f^D_{mlt}	Quantity of product m disassembled at IRDC l in period t
g_{mlt}	Quantity of scrapped product m shipped from IRDC l to recycling in period t
g_{plt}	Quantity of scrapped part p shipped from IRDC l to recycling in period t
$-\Delta_{mkt}$	Shortfall of refurbished products m in CZ k in period t
O^e_{mkt}	Quantity of returned products m shipped from CZ k to recycling center in period t
b_{mlt}	Quantity of uninspected returned products m removed from inventory at IRDC l to be inspected at time t (t=1…, T)
I_{mlt}	Quantity of returned products m sent to inventory in IRDC l without inspection in period t
n_{mlt}	Quantity of returned products m sent directly to inspection at IRDC l in period t

Y_l $\begin{cases} 1 & \text{if IRDC is open at location l at the start} \\ 0 & \text{otherwise} \end{cases}$

Z_{ls} $\begin{cases} 1 & \text{if disassembly line of size s is installed at IRDC l} \\ 0 & \text{otherwise} \end{cases}$

U_{ls} $\begin{cases} 1 & \text{if inspection station of size s is installed at IRDC l} \\ 0 & \text{otherwise} \end{cases}$

The mathematical formulation for the maximization of total profit in the network is given below.

$$\begin{aligned} \text{Maximize Z} = & \sum_{m\epsilon M}\sum_{k\epsilon K}\sum_{t\epsilon T}\rho_{mkt}\, f_{mkt} + \sum_{t\in T}\sum_{m\epsilon M}\sum_{k\epsilon K}\sum_{l\epsilon L}\rho^R_{mkt}\, f^R_{mlkt} \\ & - \sum_{l\epsilon L} F_l\, Y_l - \sum_{l\epsilon L} F^D_l\, Z_l - \sum_{s\in S}\sum_{l\epsilon L} F^I_{ls}\, U_{ls} \\ & - \sum_{t\in T}\sum_{m\epsilon M}\pi_{mt}\, f_{mt} - \sum_{t\in T}\sum_{m\epsilon M}\sum_{k\epsilon K} c_{mkt}\, f_{mkt} \\ & - \sum_{t\in T}\sum_{m\epsilon M}\sum_{l\epsilon L}\sum_{k\epsilon K} c_{mlkt}\, f^R_{mlkt} - \sum_{t\in T}\sum_{m\epsilon M}\sum_{k\epsilon K}\sum_{l\epsilon L} c_{mklt}\, f_{mklt} \\ & - \sum_{t\in T}\sum_{m\epsilon M}\sum_{l\epsilon L} c_{mlt}\, g_{mlt} - \sum_{m\epsilon M}\sum_{k\epsilon K} c^e_{mkt}\, o^e_{mkt} \\ & - \sum_{t\in T}\sum_{m\epsilon M}\sum_{k\epsilon K}\sum_{l\epsilon L} C^I_{mlt}\, f_{mlt} - \sum_{t\in T}\sum_{m\epsilon M}\sum_{l\epsilon L} R_{mlt}\, f^R_{mlt} \\ & - \sum_{t\in T}\sum_{p\epsilon P}\sum_{l\epsilon L} a_{plt}\, f_{plt} - \sum_{t\in T}\sum_{m\epsilon M}\sum_{l\epsilon L} D_{mlt}\, f^D_{mlt} \\ & - \sum_{t\in T}\sum_{p\epsilon P}\sum_{l\epsilon L} c_{plt}\, g_{plt} - \sum_{t\in T}\sum_{m\epsilon M}\sum_{l\epsilon L} h_{mlt}\, I_{mlt} - \sum_{t\in T}\sum_{m\epsilon M}\sum_{k\epsilon K}\eta_{mkt}\, \Delta^-_{mkt} \end{aligned} \tag{16}$$

Subject to

$$\sum_{k \in K} f_{mklt} = f_{mlt} \quad \forall m \in M, \forall l \in L, \forall t \in T \tag{17}$$

$$\sum_{k \epsilon K} f_{mkt} = f_{mt} \quad \forall m \in M, \forall t \in T \tag{18}$$

$$b_{mlt} + n_{mlt} = f_{mlt}^{R} + f_{mlt}^{D} + g_{mlt} \quad \forall m \in M, \forall l \in L, \forall t \in T \tag{19}$$

$$f_{mlt}^{R} = \sum_{k \epsilon K} f_{mlkt}^{R} \quad \forall m \in M, \forall l \in L, \forall t \in T \tag{20}$$

$$\gamma_{p} \sum_{m \epsilon M} \sigma_{pm} f_{mlt}^{R} = f_{plt} + \theta_{p} \sum_{m \epsilon M} \sigma_{pm} f_{mlt}^{D} \quad \forall p \in P, \forall l \in L, \forall t \in T \tag{21}$$

$$g_{plt} = (1 - \theta_{p}) \sum_{m \epsilon M} \sigma_{pm} f_{mlt}^{D} \quad \forall p \in P, \forall l \in L, \forall t \in T \tag{22}$$

$$f_{mkt} = d_{mkt} \quad \forall m \in M, \forall k \in K, \forall t \in T \tag{23}$$

$$\sum_{l \epsilon L} f_{mlkt}^{R} = d_{mkt}^{R} - \Delta_{mkt}^{-} \quad \forall m \in M, \forall k \in K, \forall t \in T \tag{24}$$

$$o_{mkt}^{e} + \sum_{l \epsilon L} f_{mklt} = r_{m} f_{mkt} \quad \forall m \in M, \forall k \in K, , \forall t \in T \tag{25}$$

$$\sum_{k \epsilon K} f_{mkt} \leq C_{mt} \quad \forall m \in M, \forall t \in T \tag{26}$$

$$\sum_{l \epsilon L} f_{plt} \leq C_{pt} \quad \forall p \in P, \forall t \in T \tag{27}$$

$$f_{mlt}^{D} \leq \sum_{s \epsilon S} C_{mls}^{D} Z_{ls} \quad \forall m \in M, \forall l \in L, \forall t \in T \tag{28}$$

$$\sum_{s \epsilon S} U_{ls} = Y_{l} \quad \forall l \in L \tag{29}$$

$$\sum_{m \epsilon M} (b_{mlt} + n_{mlt}) \leq \sum_{s \epsilon S} C_{ls} \; U_{ls} \quad \forall l \in L, \forall t \in T \tag{30}$$

$$b_{mlt} \leq I_{mlt} \quad \forall l \in L, \forall t \in T, \forall m \in M \tag{31}$$

$$f_{mlt} = b_{mlt} + n_{mlt} \quad \forall l \in L, \forall t \in T, \forall m \in M \tag{32}$$

$$I_{mlt} = f_{mlt} - n_{mlt} \quad \forall l \in L, \forall t \in T, \forall m \in M \tag{33}$$

$$\sum_{m \epsilon M} I_{mlt} \leq Q_{max} - \sum_{m \epsilon M} I_{m,l,t-1} + \sum_{m \epsilon M} b_{mlt} \quad \forall l \in L, \forall t \in T \tag{34}$$

$$f_{mlt}, f_{mklt}, f_{mkt}, f^{R}_{mlt}, f^{D}_{mlt}, g_{mlt}, f^{R}_{mlkt}, f_{plt}, g_{plt}, f_{mklt}, o^{e}_{mkt}, b_{mlt}, I_{mlt}, n_{mlt} \geq 0 \quad (35)$$

$$\forall m \in M, \forall k \in K, \forall l \in L, \forall p \in P$$

$$Y_l, Z_l = \{0,1\} \quad (36)$$

The first line in the objective function Eq. (16) represents the revenues obtained by selling new and refurbished products. The second line represents the fixed costs of opening IRDC and installing disassembly and inspection lines within them (only inspection depends on size). In the third line, the first term represents the purchasing costs of products, while the second term represents the unit shipping cost of new products to the CZs. The fourth line accounts for the shipping costs of refurbished products from IRDC to CZs and the shipping costs from CZs to the IRDC, respectively. The fifth line in the objective function represents the shipping costs of scrapped products to the RC, and the shipping cost of returned products from the CZs to the RC, respectively. The sixth line represents the inspection and refurbishing costs. The seventh line represents the freight on board (FOB) destination's costs of delivering parts to the IRDC and the unit disassembly costs of products at the IRDC. The three terms in the eighth line represent the costs of shipping scrapped parts from the IRDCs to the RC, the Unit holding cost of return product at the inventory, and the lost sales cost of refurbished products, respectively.

The changes that were made in a general way, were to add the temporal index in the decision variables, as required, and to add decision variables to model the added section of the inventory. Regarding the restrictions, the changes were aligned with the changes in the temporal index added to the decision variables. Constraint (19) ensures that all returned products that go through inventory are reassembled, disassembled, and scrapped as required. Constraints (28), (29), (30), and (31) are capacity constraints on the supplier capacity for new products and new parts, IRDC capacity for inspection, inventory capacity, and IRDC capacity for disassembly. Constraints (32), (33), and (34) are constraints that guarantee the flow between inventory with the IRDC and returned products.

3 Results

To prove the correct functioning of the model, the design of experiments was guided by four broad questions that manage to answer the central themes of the project, namely, costs, capacity, inventory, and demand. All the models were implemented in Python, using gurobipy to access the solver Gurobi© 7.0.2.

Experiment 1. Effect of the shipping costs

The first experiment seeks to analyze the variation of the objective function due to the increase in the variable costs. This experimental design is univariate, and multifactorial, with the combination of the cross, balanced, and fixed effects levels. The studied factors are Cmkt (Shipping cost of new product m delivered to CZ k in period t) and Cmlkt (Shipping cost of refurbished product m delivered from IRDC l to CZ k in period t) and the response variable is the objective function. **Table 1** presents the levels to be studied, the first row are the base values while second and third rows are the values that are going to be taken to conduct the experiment, which in this case is an increase in the base values.

Table 1
Levels to study of experiment 1

Cmkt	Cmlkt
(2, 3, 5) *	(2, 3, 4) *
(4, 6, 10)	(4, 6, 8)
(6, 9, 15)	(6, 9, 12)

* Values are from the base model.

Regarding the treatments that were used for the analysis of the model, they are detailed in **Table 2**. The first row contains the base values of each factor in each treatment, while the following rows are the type of cross combinations. The column FO shows the result of the Objective Function.

Table 2
Results of experiment 1

Treatments	Cmkt	Cmlkt	FO
BASE	(2, 3, 5) *	(2, 3, 4) *	143.423.600

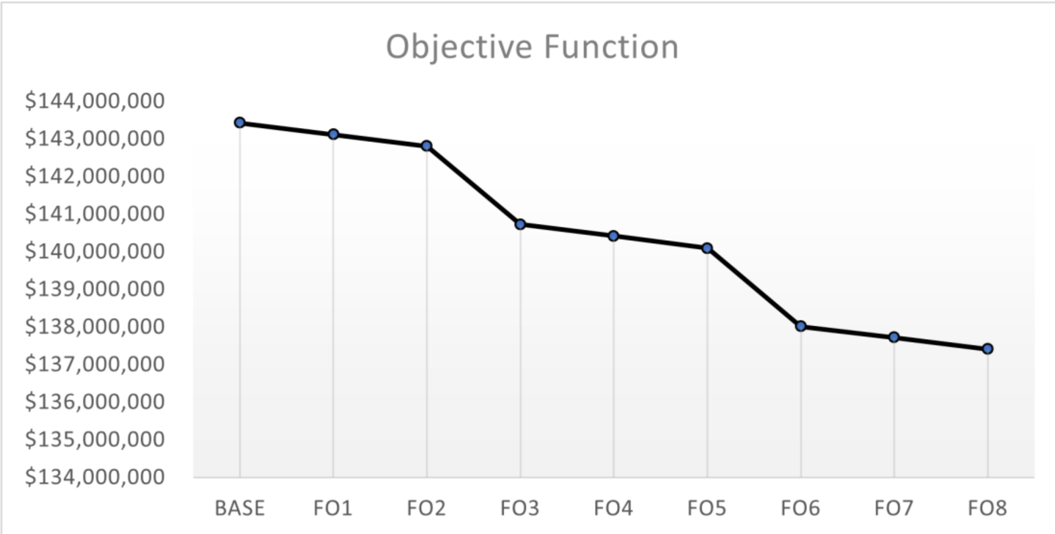
EX1	(2, 3, 5) *	(4, 6, 8)	143.115.080
EX2	(2, 3, 5) *	(6, 9, 12)	142.806.560
EX3	(4, 6, 10)	(2, 3, 4) *	140.723.600
EX4	(4, 6, 10)	(4, 6, 8)	140.415.080
EX5	(4, 6, 10)	(6, 9, 12)	140.094.560
EX6	(6, 9, 15)	(2, 3, 4) *	138.011.440
EX7	(6, 9, 15)	(4, 6, 8)	137.715.080
EX8	(6, 9, 15)	(6, 9, 12)	137.406.560

* Values are from the base model.

As for the first experiment in all treatments there was an increase in shipping costs, varying this increase in each factor, **Figure 3** shows the behavior of the experiment, it can be observed that the increase in costs is greater, the Objective Function decreases, this translates into that total profits decrease when shipping costs increase. The above is a logical behavior of the model, given its nature in the approach of the objective function, which is to maximize profits. Behavior is evidenced in three sections, which corrects to the order in which the experiments were carried out, where one value is left static and the other is changed, in this case, Cmkt is left static and Cmlkt is the one that varies. Resulting in a general way a decreasing behavior.

Figure 3

Behavior of the objective function



Experiment 2. Impact of inspection capacity

The second experiment evaluates the impact that various levels of inspection center capacity have on the number of uninspected returned products withdrawn from inventory for inspection, the number of returned products sent to inventory without inspection, and the number of returned products sent directly for inspection. This experimental design is multivariate, and unifactorial, which has a combination of crossed levels, balanced in fixed effects. The factor studied is Cls (Inspection capacity of IRDC l of size) and the response variables are quantity of uninspected returned products m removed from inventory at IRDC l to be inspected at time t (bmlt), quantity of returned products sent to inventory in IRDC l without inspection at time t (Imlt) and quantity of returned products sent directly to inspection at IRDC l at time t). The respective levels are detailed in **Table 3**, in the first row are the base values of the factor, in the second row are the values when they increase, and in the third row, are the values when they decrease.

Table 3
Levels to study of experiment 2

Cls
(150.000, 300.000, 450.000) *
(15.000.000, 3.000.000, 4.500.000)
(15.000, 30.000, 45.000)

* Values are from the base model.

The treatments carried out in this experiment are detailed in **Table 4**, where the base values of the model are found in the first row and the different factor combinations in the following rows. The last three columns show the results of the response variables.

Table 4
Results of experiment 2

Treatments	Cls	bmlt	Imlt	Nmlt
BASE	(150.000, 300.000, 450.000) *	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0	(1, 1, 1) 19.660.0 (2, 1, 1) 45.000.0 (3, 1, 1) 18.000.0 (1, 1, 2) 19.660.0 (2, 1, 2) 45.000.0 (3, 1, 2) 18.000.0 (1, 1, 3) 19.660.0 (2, 1, 3) 45.000.0 (3, 1, 3) 18.000.0
IN1	(15.000.000, 3.000.000, 4.500.000)	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0	(1, 1, 1) 19.660.0 (2, 1, 1) 45.000.0 (3, 1, 1) 18.000.0 (1, 1, 2) 19.660.0 (2, 1, 2) 45.000.0 (3, 1, 2) 18.000.0 (1, 1, 3) 19.660.0 (2, 1, 3) 45.000.0 (3, 1, 3) 18.000.0
IN2	(15.000, 30.000, 45.000)	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0	(1, 1, 1) 11.820.0 (2, 1, 1) 20.360.0 (3, 1, 1) 12.320.0 (1, 1, 2) 11.820.0 (2, 1, 2) 20.360.0 (3, 1, 2) 12.320.0 (1, 1, 3) 11.820.0 (2, 1, 3) 20.360.0 (3, 1, 3) 12.320.0

* Values are from the base model.

In the Experiment 2, which seeks to see the effect between the increase in the capacity of the IRDC centers and the dynamics of the inventory center, it is shown that the first two variables bmlt and Imlt respond according to the capacity of the inventory center, this behavior is because both interact directly with the inventory, that is, by bmlt, the products that are delivered from the inventory towards the IRDC center are those that the IRDC center can receive according to its capacity, but also, they are the products that the inventory can deliver; As for Imlt, the products returned by customers and sent to inventory are those that the inventory can receive according to its capacity.

And finally, for the nmlt variable, its behavior shows that when the capacity of the IRDC centers increases the products that are sent from the clients to the centers are the same, this behavior is due to the number of products that are delivered by the clients to recondition is limited, but when the capacity of the centers decreases, the number of products shipped also decreases, this result proves that nmlt depends on the capacity when it is limited, since it cannot receive all the products shipped from the clients. In this experiment, it is shown that the inspection capacity of IRDC centers limits the behavior of inventory and products that are shipped from customers.

Experiment 3. Finding out the impact of demand

As that demand is a crucial parameter in the model, it is of interest to know what its impact of the demand increase on the inventory of the product. To analyze it, the experimental design to be used is univariate, and multifactorial, with a combination of balanced and crossed levels, and fixed effects. The factors to be studied are dmkt (Demand for new product m in customer zone k at time t) and dRmkt (Demand for refurbished product m in customer zone k at time t), the response variable is Imlt (Quantity of returned products m sent to inventory in IRDC l without inspection at time t) and the levels to be worked on can be seen in the **Table 5**, in this Table, in the first row are the base values of each factor and in the second and third row, are the values to be studied.

Table 5
Levels to study of experiment 3

dmkt	dRmkt
(30.000, 30.000, 30.000) *	(5.000, 5.000, 2.320) *
(60.000, 60.000, 60.000)	(10.000, 10.000, 4.640)
(90.000, 90.000, 90.000)	(15.000, 15.000, 6.960)

* Values are from the base model.

Table 6 shows the different treatments that are going to be considered, for example, in the row are the base values to be able to contrast with the other results, and in the following rows are the different values and combinations that are they are going to study and in the last column are the results of each run.

Table 6
Results of experiment 3

Treatments	dmkt	dRmkt	Imlt
BASE	(30.000, 30.000, 30.000) *	(5.000, 5.000, 2.320) *	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0
IM1	(30.000, 30.000, 30.000) *	(10.000, 10.000, 4.640)	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0

IM2	(60.000, 60.000, 60.000)	(5.000, 5.000, 2.320) *	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0
IM3	(60.000, 60.000, 60.000)	(10.000, 10.000, 4.640)	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0
IM4	(30.000, 30.000, 30.000) *	(15.000, 15.000, 6.960)	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0
IM5	(90.000, 90.000, 90.000)	(5.000, 5.000, 2.320) *	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0

IM6	(90.000, 90.000, 90.000)	(15.000, 15.000, 6.960)	(1, 1, 1) 500.0 (2, 1, 1) 0.0 (3, 1, 1) 0.0 (1, 1, 2) 500.0 (2, 1, 2) 0.0 (3, 1, 2) 0.0 (1, 1, 3) 500.0 (2, 1, 3) 0.0 (3, 1, 3) 0.0

* Values are from the base model.

The results of the experiment show that when demand increases, the inventory continues to work at its capacity without changing its values, which means that the inventory works at its maximum capacity, as established in the model. In contrast, by decreasing the demand for new products, the inventory changes and decreases its value, working according to the dynamics of demand, this can be seen in **Table 7**.

Table 7
Results of inventory dynamics (Imlt)

dmkt	dRmkt	Imlt
(300, 300, 300)	(5.000, 5.000, 2.320) *	(1, 1, 1) 0.0 (2, 1, 1) 450.0 (3, 1, 1) 50.0 (1, 1, 2) 450.0 (2, 1, 2) 50.0 (3, 1, 2) 0.0 (1, 1, 3) 230.0 (2, 1, 3) 0.0 (3, 1, 3) 270.0

* Values are from the base model.

Experiment 4. Impact of demand on shipping to customers

As the importance of demand was already mentioned in the previous experiment, this last experiment seeks to analyze the impact that its variation has on the number of reconditioned products sent to customers, since it is important to be able to comply with what the market requires and that its behavior can be seen reflected in the dynamics of the model. A univariate, and multifactorial esperiments is considered, it takes into account the combination of crossed and balanced levels, and fixed effects. The factors studied are dmkt (Demand for new product m in customer zone k at time t) and dRmkt (Demand for refurbished product m in customer zone k at time t) and the response variable is fRmlkt (Quantity of refurbished products m shipped from IRDC l to CZ k). Where the levels to be analyzed are those described in the **Table 8**, in the first row are the base values of the model, in the second row are the values considering an increase, and in the third row a decrease.

Table 8

Levels to study of experiment 4

dmkt	dRmkt
(30.000, 30.000, 30.000) *	(5.000, 5.000, 2.320) *
(60.000, 60.000, 60.000)	(10.000, 10.000, 4.640)
(15.000, 15.000, 15.000)	(2.500, 2.500, 1.160)

* Values are from the base model.

The treatments that are going to be studied are described in the **Table 9**, in this table, all the combinations that are going to be worked are shown, in the first row are the base values of the model and in the last column are the results, taking consider the factor values.

Table 9

Results of experiment 4

Treatments	dmkt	dRmkt	fRmlkt
BASE	(30.000, 30.000, 30.000) *	(5.000, 5.000, 2.320) *	(1, 1, 1, 1) 5000.0 (1, 1, 2, 1) 5000.0 (1, 1, 3, 1) 2320.0 (2, 1, 1, 2) 5000.0 (2, 1, 2, 2) 5000.0 (2, 1, 3, 2) 2320.0 .

			. .
FR1	(30.000, 30.000, 30.000) *	(10.000, 10.000, 4.640)	(1, 1, 1, 1) 10000.0 (1, 1, 2, 1) 10000.0 (1, 1, 3, 1) 4640.0 (2, 1, 1, 2) 10000.0 (2, 1, 2, 2) 10000.0 (2, 1, 3, 2) 4640.0 . . .
FR2	(60.000, 60.000, 60.000)	(5.000, 5.000, 2.320) *	(1, 1, 1, 1) 5000.0 (1, 1, 2, 1) 5000.0 (1, 1, 3, 1) 2320.0 (2, 1, 1, 2) 5000.0 (2, 1, 2, 2) 5000.0 (2, 1, 3, 2) 2320.0 . . .
FR3	(60.000, 60.000, 60.000)	(10.000, 10.000, 4.640)	(1, 1, 1, 1) 10000.0 (1, 1, 2, 1) 10000.0 (1, 1, 3, 1) 4640.0 (2, 1, 1, 2) 10000.0 (2, 1, 2, 2) 10000.0 (2, 1, 3, 2) 4640.0 . . .
FR4	(30.000, 30.000, 30.000) *	(2.500, 2.500, 1.160)	(1, 1, 1, 1) 2500.0 (1, 1, 2, 1) 2500.0 (1, 1, 3, 1) 1160.0 (2, 1, 1, 2) 2500.0 (2, 1, 2, 2) 2500.0 (2, 1, 3, 2) 1160.0 . .

			.
FR5	(15.000, 15.000, 15.000)	(5.000, 5.000, 2.320) *	(1, 1, 1, 1) 5000.0 (1, 1, 2, 1) 5000.0 (1, 1, 3, 1) 2320.0 (2, 1, 1, 2) 5000.0 (2, 1, 2, 2) 5000.0 (2, 1, 3, 2) 2320.0 . . .
FR6	(15.000, 15.000, 15.000)	(2.500, 2.500, 1.160)	(1, 1, 1, 1) 2500.0 (1, 1, 2, 1) 2500.0 (1, 1, 3, 1) 1160.0 (2, 1, 1, 2) 2500.0 (2, 1, 2, 2) 2500.0 (2, 1, 3, 2) 1160.0 . . .

* Values are from the base model.

According to the results obtained, a direct proportion is noted between the demand for reconditioned products and the quantity of reconditioned products sent to customers, since regardless of the increase or decrease in demand, the quantity of reconditioned products is the same as the demand. The previous analysis is explained because according to the model, the demand that is established is the number of products that must be delivered.

But, according to the previous analysis, the model may be able to meet the demand assigned to it, however, by entering extreme demand values for reconditioned products, the delivery of reconditioned products was limited, and their maximum value was evidenced, as shown in **Table 10**. In these results, it can be observed the capacity of the model, in general, to be able to respond with a maximum amount of demand, to others that it could not meet in all the years or to all the clients with the delivery. Considering the results obtained from the four experiments that were conducted and explained in the previous chapter, in general, it is evident that the operation of the model responds to the interests of the supply chain, considering a temporality and an inventory that are key when making decisions in organizations.

Table 10

Results of the maximum delivery of refurbished products (fRmlkt)

dmkt	dRmkt	fRmlkt
(30.000, 30.000, 30.000) *	(50.000, 50.000, 23.200)	(1, 1, 1, 1) 45000.0
		(1, 1, 2, 1) 0.0
		(1, 1, 3, 1) 0.0
		(2, 1, 1, 2) 45000.0
		(2, 1, 2, 2) 0.0
		(2, 1, 3, 2) 0.0
		(3, 1, 1, 3) 27000.0
		(3, 1, 2, 3) 0.0
		(3, 1, 3, 3) 0.0
		.
		.
		.

* Values are from the base model.

4 Conclusions

This work was modified to model a multi-period closed-loop supply chain (CSLC) network with remanufacturing proposals, which includes suppliers, CZ customers, an IRDC inspection center, an inventory center for inspection, and a recycling center. Including the possibility of selling the products to reduce the number of products in landfills. Regarding the construction of the model and its due experiments, the following conclusions are reached.

In the first place, it is possible to describe the system, based on the construction of a supply chain in a general way, for organizations interested in remanufacturing, seeking to minimize the products sent to landfills and still obtaining a profit during the process. During construction, a multi-period model was successfully implemented, in this case, evaluated in three temporary units and with an inventory center to meet the capacity of the IRDC inspection center.

In this way, it is possible to generate and implement a CLSC mathematical model that responds to the needs of the system dynamics, from a base model it is possible to extend it, including the size of the IRDC inspection centers and the temporary unit within the indices. of the model. This model focuses on remanufacturing, with profit maximization as its main objective.

Consequently, the model is validated using the gurobipy-10.0.0 tool, in these results, it is evident that the model responds logically to the sensitivity analysis of extreme values, for example, in cases where the demand for reconditioned products is exaggerated, the inventory works at its maximum capacity, and in turn, the delivery of reconditioned products is processed according to the limitations presented by the model, since it works under established inspection and disassembly specifications.

Finally, for future work, it is recommended to implement an inventory center in the disassembly station, since in this area it is also useful to have a buffer, given the multiperiod nature of the model. On the other hand, it is suggested to carry it out in an environment where these remanufacturing processes are conducted in the furniture sector and to be able to validate its operation.

Dedication

This work could be conducted in recognition of the opportunity to have participated in the MITACS Scholarship in Canada at Dalhousie University, since it contributed to the strengthening of tools, starting this idea that could be concluded at the University of Antioquia. This process was satisfactory thanks to my two tutors for knowing how to direct me, to my family for supporting me, and to the people who indirectly contributed to the process.

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