Pricing and Ordering Decisions in a Supply Chain with Remanufacturing Operations: A Game-Theory Approach with Customer Choice Dynamics

Matthieu Godichaud
Computer Sciences and Digital Society Laboratory (LIST3N)
University of Technology of Troyes (UTT)
Troyes, France
matthieu.godichaud@utt.fr

Abstract— **This paper investigates the joint pricing and ordering decisions in a two-level supply chain with remanufacturing operations. The supply chain consists of a manufacturer performing both manufacturing and remanufacturing activities and two competing retailers serving overlapping market segments, one for new products and another for remanufactured products. The objective of this study is to determine the optimal decisions that maximize the profits of all stakeholders while accounting for competitive interactions and coordination mechanisms. To model the decision-making process, a hierarchical coordination framework is adopted: (1) A Stackelberg game is formulated between the manufacturer and each retailer, where the manufacturer acts as the leader and the retailers respond as followers, while (2) the two competing retailers seek a Nash equilibrium in their pricing and ordering strategies. Additionally, inventory and flow coordination is captured through a Joint Economic Lot Sizing (JELS) approach. The resulting model is a non-linear program solved using a general solver. A numerical study is conducted to validate the resolution and to analyze the impact of retailer competition.**

Keywords—Closed Loop Supply Chain, Pricing, Joint Economic Lot Sizing, Stackelberg, Remanufacturing.

I. Introduction

Driven by environmental pressures from society and government, product recovery (repair, refurbishing, remanufacturing) is increasingly a fundamental activity for companies at the same level as other traditional production and logistics activities. In this context, optimisation models are of interest to help save costs and make product recovery more profitable. That is the case in inventory management, where matching return and demand processes are more complicated, even more so if we consider interactions with new product processes. Dedicated models are necessary. In the case of Economic Production Quantity (EPQ) models, the basic models are presented in [1], and more recent works are reviewed in [2][3]. In most of the works reviewed in these two papers, newly manufactured and remanufactured products serve the same demands. In a few papers [4][5][6], two distinct demands are considered for the two types of products but without consideration of their selling prices.

The price decisions within EPQ models with returned product are investigated in [7] but in a single-company perspective in which one manufacturer handles both manufacturing and remanufacturing operations. In this paper, we extend the work presented in [7] by incorporating a multi-actor supply chain perspective, where each participant seeks to maximize their profit. We consider a two-tier closed-loop supply chain involving a manufacturer responsible for production and remanufacturing operations, as well as the collection of returned products. These products are then distributed to two distinct retailers: one selling new products and the other selling remanufactured products. Although these products target separate markets, a segment of customers is indifferent and chooses between them based on price differences. The retailers set the selling prices in their respective markets, while the manufacturer determines the wholesale prices at which they purchase the products. Furthermore, product flows are managed based on the assumptions of EOQ models, aiming to minimize inventory holding costs relative to fixed ordering costs. Since the manufacturer and retailers operate as independent entities, coordinating their flows is crucial, making this a multi-echelon EOQ optimization problem.

This work is related to three main research areas: studies on EOQ/EPQ models with returns, studies on JELS models for coordinating different tiers in supply chains, and studies on pricing decisions in closed-loop supply chains. The reader can refer to [7] for a detailed description of related work. We focus on references that motivate the extension presented in this paper.

Regarding the first category of studies on EOQ/EPQ models with returns, recent papers [2][8] provide literature reviews on this topic. Similar to the work in [7], we differentiate ourselves by considering separate markets for new and remanufactured products while integrating pricing decisions with competition between these two markets. These aspects are further combined here with coordination decisions among different supply chain actors.

The coordination among supply chain actors under EOQ model assumptions corresponds to the Joint Economic Lot Sizing (JELS) problem. The fundamental features of JELS were first introduced in [9] in the context of a single-vendor, single-buyer system. Since then, numerous studies have expanded the problem by incorporating additional features and more complex supply chain structures [10]. A recent literature review [11] highlights the significance of the JELS problem; however, it does not address the combined decisions of ordering and pricing. In the context of traditional supply chains, these aspects have been explored in [12], where the authors model a Vendor Managed Inventory (VMI) system within a JELS framework using a Stackelberg game approach. In this model, a manufacturer (leader) determines inventory and pricing decisions, while multiple retailers (followers) optimize their profits. The study derives equilibrium conditions and investigates cooperative contracts to enhance supply chain profitability, analyzing the influence of market and raw material parameters. More recently, studies such as [13][14] extend the JELS framework to a three-tier supply chain, examining different structural configurations (non-integrated, integrated, and a novel semi-integrated structure). These works employ Stackelberg and Nash game approaches to optimize pricing, replenishment, and consignment decisions. our study extends JELS models by incorporating returned products and remanufacturing operations, thus addressing the challenges specific to closed-loop supply chains.

Studies on pricing decisions in closed-loop supply chains examine the relationship between prices and demand among supply chain actors. However, these studies do not consider material flows, a gap we address in this paper by explicitly modeling them using EOQ and JELS assumptions to analyze their impact on pricing decisions. As reviewed in [7], several studies have focused on the pricing problem in distinct markets and under competition between new and remanufactured products [15][16][17]. These studies consistently assume a linear relationship between demand and price, which facilitates model analysis and the derivation of closed-form optimal solutions [18]. In the case of a two-echelon supply chain, wholesale prices are often considered decision variables. For instance, in [19] a two-level supply chain is investigated where a manufacturer sells products at a wholesale price to a retailer, analyzing four configurations depending on who performs remanufacturing operations (manufacturer, retailer, or a third party). Their model incorporates emission costs into profit functions but assumes a market size normalized to one, which does not account for inventory-related decisions. Similarly, in [20], a pricing model is developed considering various supply chain actors, where demand depends on price, quality, collection effort, and return policy. In [21], the authors examine a closed-loop supply chain with a manufacturer/remanufacturer and a retailer, incorporating unit production costs and carbon tax into pricing decisions. More recently, in [22], a CLSC for electric vehicle batteries is studied, including a manufacturer, retailer, third-party recycler, and an echelon firm. Their model explores four mixed-channel recycling scenarios depending on the role of the retailer, echelon firm, and third-party recycler, with decision variables including the selling price per unit, the retailer's advertising effort, the wholesale price, and the number of retired batteries returned by customers. Overall, these studies rely on a linear relationship between quantities and prices to model the profit of different CLSC entities. However, these studies do not consider material flows, which we explicitly model in this paper using EOQ and JELS assumptions to analyze their impact on pricing decisions.

This paper proposes a novel model for a Closed-Loop Supply Chain (CLSC) that integrates Joint Economic Lot Sizing (JELS) coordination with pricing decisions under a game-theoretic framework. The model considers two distinct markets, one for new products and another for remanufactured products, while incorporating a shared competitive segment between retailers. A non-linear programming formulation is developed to capture these interactions, and the problem is solved using a general solver. The remainder of the paper is structured as follows: Section 2 introduces the overall problem, detailing the assumptions and notation used to construct the model. Section 3 presents the mathematical formulation of the model. In Section 4, a numerical example is analyzed to illustrate the resolution process and assess the impact of competition on supply chain decisions. Section 5 concludes the paper by summarizing key findings and outlining future research directions.

II. Problem Statement

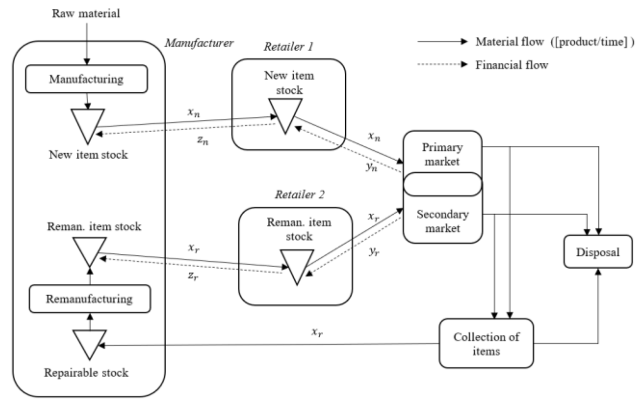


Fig. 1. Material and financial flows for the supply chain studied.

The material and financial flows of the problem under study are shown in Fig. 1. The supply chain consists of a manufacturer and two retailers as presented before. We study the case in which the manufacturer and the retailers are distinct entities (companies) that maximize their own profit. A Stackelberg game is used to represent the relationship between the manufacturer and the retailers, where the manufacturer acts as the leader and the retailers act as followers. The manufacturer (vendor) determines the wholesale prices for new and remanufactured products (denoted by z_n and z_r) and their order cycle lengths (denoted by t_{vn} and t_{vr}). The retailers decide on the price for new and remanufactured products (denoted by x_n and x_r) and their order intervals (denoted by t_{bn} and t_{br}). The two retailers compete for the overlapping share of the markets and seek to reach a Nash equilibrium.

The model integrates the parameters related to the two processes – manufacturing and remanufacturing – as well as the five inventories: new and remanufactured products at both the retailer and the remanufacturer, and repairable products. The data and variables are indexed as follows: v for the manufacturer (vendor), b for the retailers (buyers), n for new products, and r for remanufactured product.

Cost data are those of the basic EPQ/EOQ model for each product stream (the time unit is written in days but can be changed depending on the context):

- s_{bn}, s_{br}, s_{vn}, s_{vr} setup costs, [€/lot],
- h_{bn}, h_{br}, h_{vn}, h_{vr} h_u inventory holding costs (index u is for returned products), [€/product.day],
- c_n , c_r unit production costs (at the manufacturer) [€/product],
- z_n, z_r wholesale prices from the manufacturer, for the two types of products, to the retailers.

The two types of products are processed on distinct lines at the manufacturer, with distinct process data and variables. The notations are as follows:

- m_n, m_r production rates [product/day],
- $t_{bn}, t_{br}, t_{vn}, t_{vr}$ cycle lengths [day],

The notations for the demand and prices of each type of product are as follows and the relationships between demand rates and selling prices are defined by equations (1) and (2).

- x_n, x_r demand rates [product/day],
- y_n, y_r selling prices [€].

$$x_n = d_n - a_n y_n + e y_r \tag{1}$$

$$x_r = d_r - a_r y_r + e y_n \tag{2}$$

For linear demand-to-price relationships, the interpretation of the parameters is as follows:

- d_n , d_r maximum demand for new items and remanufactured items (market size),
- a_n, a_r, e price to demand function parameters (linear relationships).

We note that we must have $c_n \leq z_n \leq y_n$ and $c_r \leq z_r \leq y_r$ to ensure positive profit for all the stakeholders

The same competition parameter, e , is used for both equations (1) and (2), based on the following interpretation of the competition. Some undecided customers are hesitating between buying a new product or a remanufactured one. Their decision depends on the price difference $y_n - y_r$. For a given price difference, $e(y_n - y_r)$ represents the number of customers (per unit of time) who switch their willingness from buying a new product to purchasing a remanufactured one. Initially, (1) and (2) can be defined by $x_n = d_n - a'_n y_n - e(y_n - y_r)$ and $x_r = d_r - a'_r y_r + e(y_n - y_r)$. By setting $a_n = a'_n + e$ and $a_r = a'_r + e$, we retrieve the previous equations. Additionally, given this interpretation of competition, we impose the constraint $y_n > y_r$; otherwise, undecided customers prefer to buy a new product.

The problem assumptions follow those of traditional EPQ and JELS problems:

- Demands, production and returns are characterised by rates (items per day, for instance), and they are constant,
- Inventories are continuously reviewed (continuous time inventory model),
- Cost and profit indicators are defined on average (unit of money per unit of time) on an infinite time horizon,
- There is a fixed cost incurred for each production setup (before starting a production lot), and one unit in inventory per unit of time generates a holding cost,
- Backlogs or lost sales are not allowed in this work.

In addition to the previous presentation of the relationship between prices and demands, we add the following assumptions more specific to the problem under study:

- There are two markets, one for new products and one for remanufactured products, the manufacturer has distinct production line to produce new and remanufactured products,
- Production rate, holding and setup costs are different for the two types of product,
- The demands or prices for both markets are determined once at the beginning of the planning horizon,
- Only the returned products that will be remanufactured are kept in the return inventory; if the returns are superior to the remanufacturing quantity, the surplus is disposed of (i.e., directed to others' recovery channels).

These assumptions justify the rate associated with the material flows in Fig. 1. The product availability from the production line must be x_n and x_r to satisfy demands in each market. We assume that there are enough returns and x_r products per day can be remanufactured, i.e., the return inventory is replenished continuously at a rate x_r.

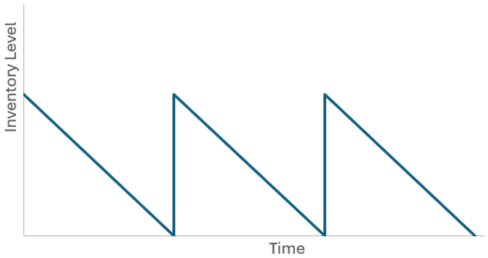
III. Model Formulation and Resolution

Based on previous assumptions, the evolution of the three inventories over time is presented in Fig. 2. At the retailers, the curve shape is basic saw tooth profiles due to EOQ-related assumptions. At the manufacturer, there is a repetition of two phases for each inventory: one production-consumption phase and one consumption-only phase. For the new and remanufactured product, the inventories first increases at rates $m_n - x_n$ or $m_r - x_r$ and then decrease at rates x_n or x_r. The durations of the cycles are t_{vn} and t_{vr}, and the first phases last $(x_n/m)t_n$ and $(x_r/m_r)t_r$. The curse shapes are less simple than those at the retailer as the inventories change only at the retailer order times. To compute easily the average inventory, the echelon inventory is used (dashed line in Fig. 2). The echelon inventory, defined as the sum of local and downstream inventories, follows a traditional saw-tooth pattern, making the average inventory calculation straightforward. The local average inventory is retrieved with the difference between the echelon and retailer inventories. The returned product inventory changes inversely to the remanufactured product inventory. It increases at rate x_r in a first phase and decreases at rate $m_r - x_r$ in second phase. Only the returned products that will be remanufactured are kept in the return inventory.

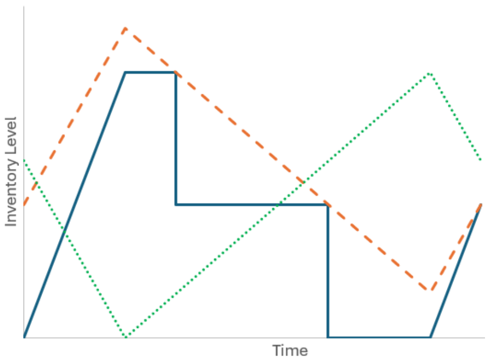
Each retailer maximizes its profit by setting the price (y_n or y_r) and the cycle time (t_{bn} or t_{br}) for its inventories, based on the wholesale prices (z_n or z_r) offered by the manufacturer. Their respective average profit per unit of time is defined by:

$$\pi_{bn}(y_n, t_{bn}) = (y_n - z_n)(d_n - a_n y_n + e y_r) - \frac{s_{bn}}{t_{bn}} - \frac{h_{bn}}{2}(d_n - a_n y_n + e y_r) t_{bn} \tag{3}$$

$$\pi_{br}(y_r, t_{br}) = (y_r - z_r)(d_r - a_r y_r + e y_n) - \frac{s_{br}}{t_{br}} - \frac{h_{br}}{2}(d_r - a_r y_r + e y_n)t_{br} \quad (4)$$



Retailer inventory for one product



Manufacturer inventory with local (straight line), echelon (dashed line), return (dotted line) inventories

Fig. 2. Overview of the inventory changes over time for remanufactured products (Note for this illustrative example: x_r=1, t_{vr}=6, t_{br}=2, k_r=3, m_r=3)

The first parts in π_{bn} and π_{br} represent the sum of the profits without inventory related costs for the two types of product. The last two elements relate to order and inventory holding costs, which can be derived from Fig. 2 and are identical to those in the basic EOQ model. The profit (3) and (4) are concave under several conditions [18][23]. The Nash equilibrium conditions are obtained by derivation with respect to decision variables of each players:

$$d_n - 2a_n y_n + e y_r + a_n z_n + \frac{h_{bn}}{2} a_n t_{bn} = 0 \quad (5)$$

$$d_r - 2a_r y_r + e y_n + a_r z_r + \frac{h_{br}}{2} a_r t_{br} = 0 \quad (6)$$

$$\frac{s_{bn}}{(t_{bn})^2} - \frac{h_{bn}}{2}(d_n - a_n y_n + e y_r) = 0 \quad (7)$$

$$\frac{s_{br}}{(t_{br})^2} - \frac{h_{br}}{2}(d_r - a_r y_r + e y_n) = 0 \quad (8)$$

Equations (5)(6)(7)(8) correspond respectively to $\partial\pi_{bn}/\partial y_n = 0$, $\partial\pi_{br}/\partial y_r = 0$, $\partial\pi_{bn}/\partial t_{bn} = 0$, $\partial\pi_{br}/\partial t_{br} = 0$. Closed-form equation for each variable could be derived from these equations through multiple mathematical manipulations. However, we keep them in their initial form to integrate them into the overall Stackelberg game model, including the producer's profit, and use a solver for the global resolution.

The manufacturer decides the wholesale prices and its order cycle times t_{vn} and t_{vr} knowing the optimal response of the retailer. We also consider that the manufacturer manages the inventory of returned products. Its average profit per unit of time is defined by:

$$\pi_v(z_n, z_r, t_{vr}, t_{vr}) = (z_n - c_n)x_n + (z_r - c_r)x_r - \frac{s_{vn}}{t_{vn}} - \frac{s_{vr}}{t_{vr}} - h_{vn}\left[\frac{x_n^2 t_{bn}}{m_n} + \left(1 - \frac{x_n}{m_n}\right)\frac{t_{vn}x_n}{2} - \frac{x_n t_{bn}}{2}\right] - h_{vn}\left[\frac{x_r^2 t_{br}}{m_r} + \left(1 - \frac{x_r}{m_r}\right)\frac{t_{vr}x_r}{2} - \frac{x_r t_{br}}{2}\right] - h_u\left(1 - \frac{x_r}{m_r}\right)\frac{t_{vr}x_r}{2} \quad (9)$$

In the retailer's profit function, the first two terms represent the total profit excluding inventory-related costs for both product types. Revenue is calculated as the wholesale price multiplied by the demand for each product. The next two terms account for order costs. The last three expressions define the holding costs for the three inventories managed by the manufacturer. As previously explained, these costs are based on the average echelon inventory, which can be derived from Fig. 2. Similar to JELS problems, the manufacturer minimizes inventory costs by synchronizing its orders with those of the retailers. For this, the time between the manufacturer's orders must be an integer multiple of those of the retailers, i.e. $t_{vn} = k_n t_{bn}$ and $t_{vr} = k_r t_{br}$. The manufacturer decides the integer multipliers k_n and k_r.

We consider Stackelberg game framework where the leader is the manufacturer and the followers are the retailers. The manufacturer decides first, and the retailers react to that decision. In this structure, the manufacturer can anticipate the retailers' responses and optimize its strategy accordingly. The following model is formulated to solve the Stackelberg game using a commercial non-linear solver:

$$\max_{\substack{z_n, z_r, k_n, k_r \\ y_n, y_r, t_{bn}, t_{br}}} \pi_v \text{ subject to (5)(6)(7)(8)}$$

IV. Numerical Analysis

An illustrative example to highlight the output of the model. The data presented in Table I are randomly generated. In this example, the secondary market is smaller than the primary market and the maximum price of remanufactured products is lower since we assume this constraint in the model. LINGO (v21.0) commercial solver, under the default settings, is used to solve the non-linear program.

The output results are presented in Table II. The computation time is not significant (less than 0.05s). Most of the profit is generated by the new product due to higher potential market in this instance. However, profit from the remanufactured product is substantial (30% of the manufacturer's total profit), justifying the establishment of the remanufacturing operation. The retailer of remanufactured products can also make a profit in this instance. We also note that inventory costs are not negligible in this example. In particular, the inventory holding costs in the data are high compared to the unit cost, as they aim to capture more than just the financial cost of the inventory, for example, the energy and space costs of the warehouse.

TABLE I. DATA FOR THE EXAMPLE

Parameters	n	r
d	392	223
a	18.739	14.287
e	1.696	1.696
c	8.15	6.46
s_b	82.96	74.79
h_b	2.48	1.24
s_v	94.33	94.25
h_v	0.9	0.52
m	1813.73	1552.79

With the same data but without the remanufacturing operation and market (where a_n is changed to $a_n - e$ without market competition), the manufacturer's profit decreases to 234.36 due to a smaller market size, whereas the retailer's profit for the new product increases to 175, benefiting from the absence of competition. The selling price is 19.86, the wholesale price is 13.82, and the demand is 53.55. The selling price is 19.86, the wholesale price is 13.82 and the demand is 53.55.

TABLE II. RESULTS FOR THE EXAMPLE

Variables and indicators	n	r
x (demands)	392	223
y (prices)	19.158	15.470
k	2	2
z (wholesale price)	14.680	11.899
t_b	1.063	1.871
Profit Manufacturer	314.02	132.33
Profit Retailers	109.10	43.12
Inventory Cost (Manufacturer)	70.42	55.74
Inventory cost (Retailers)	145.97	80.87

The sensitivity analysis examines the impact of the competition parameter on the profits of the manufacturer and the two retailers. All parameters remain unchanged from the previous example, except for parameter e, which is varied in increments of 0.05% within a range of -20% to +20% of its initial value. A lower value of e implies reduced competition, as fewer customers consider price differences when choosing between the two products, whereas a higher value indicates increased competition due to more customers that consider price difference. The results, depicted in Fig. 3, illustrate the percentage variations in the profits of all three entities as e changes.

From Fig. 3, it can be observed that the retailer of remanufactured products benefits the most from increased competition. As competition intensifies, this retailer can attract more customers, leading to higher demand and the ability to raise prices, to the detriment of the retailer of new products. Additionally, greater competition significantly increases the manufacturer's profit, as the total quantity of products sold, both new and remanufactured, rises.

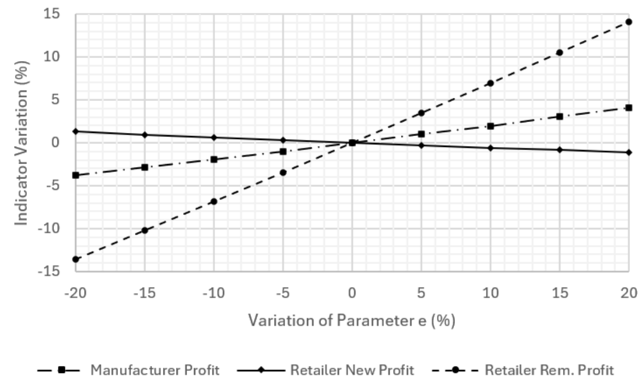


Fig. 3. Variation in the profits of the three players

Fig. 4 illustrates the influence of parameter e on the number of customers likely to choose the remanufactured product based on the price difference between new and remanufactured products. It can be observed that while the price of new products remains relatively stable, the price of remanufactured products increases, leading to a reduction in the price difference. However, despite this narrowing gap, the number of customers preferring the remanufactured product continues to rise due to the increase in parameter e.

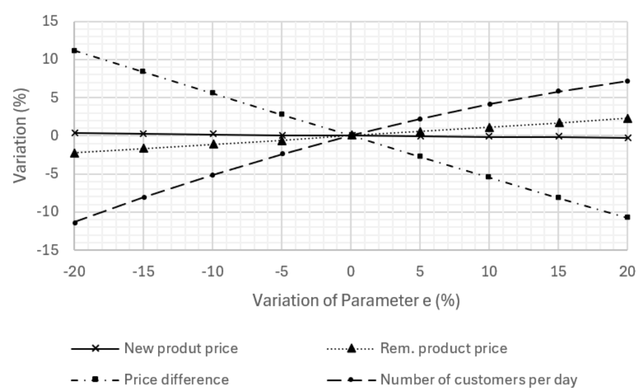


Fig. 4. Variation of the prices and market change.

The example is representative of several instances generated by varying the input parameters. The data set is generated based on examples from the literature with the same background as in [7]. Market sizes are generated with $d_n = U[100\ 1000]$ and $d_r = U[0.2\ 0.8] \times d_n$ (we study cases where the secondary market is smaller than the primary market). Maximum prices are generated with $Y_{n,max} = U[20\ 50]$ and $Y_{r,max} = U[0.5\ 0.8] \times Y_{n,max}$ (the maximum price of remanufactured products is lower since we assume this constraint in the model). To generate values for e (competition parameter), we used a maximum market change parameter, denoted here by X_c (defined for instance, generation only). It represents the percentage of customers who can change from new to remanufactured products. We used $X_c = U[0.05\ 0.2] \times d_n$ and $e = X_c / Y_{n,max}$. Price-to-demand parameters are deduced from previous parameters with $a_n = d_n / Y_{n,max} + e$ and $a_r = d_r / Y_{r,max} + e$.

Unit costs are generated with $c_n = U[0.1\ 0.5] \times u_n$ to avoid infeasible instances with $c_n > u_n$, and $c_r = U[0.2\ 0.9] \times c_n$. The results for these instances are similar to the presented example. A solution is found for all instances with the LINGO solver and all the instances are solved in negligible computational time. Only two instances out of twenty lead to a non-profit outcome for one or several stakeholders in the supply chain, but in each case, this is due to excessively high inventory-related costs. In these cases, the model can be used to detect this situation before configuring the supply chain.

One limitation of the current work is its sensitivity to fluctuations in raw material costs, which are not considered in the current formulation of the Stackelberg-Nash equilibrium model. This limitation is due to space constraints in the paper and can be addressed in future work. The advantage of conducting a study on many randomly generated data sets is that it allows the model to be tested across a wide range of possible scenarios. This approach demonstrates that the model can be adapted to real-world data with a high level of confidence. The validation provided in this paper lays the groundwork for future work, where real case applications can be developed and further explored. Incorporating sustainability constraints, such as carbon emissions, into the current model is a challenging task that deserves future research based on the validation of the results presented in this paper.

V. Conclusion

This paper developed a novel model for a closed-loop supply chain integrating JELS coordination with pricing decisions, considering distinct markets and competition between new and remanufactured products. The model's non-linear formulation captures the interactions between supply chain actors, and the numerical analysis demonstrates the model's applicability and the impact of market competition. The results highlight the importance of considering remanufacturing operations in supply chain optimization, particularly in the context of competitive markets. Future research can explore the integration of carbon emissions into supply chain models to assess sustainability and economic impacts, particularly in terms of taxation effects and customer preferences driven by environmental considerations. Additionally, alternative configurations and operational strategies for closed-loop supply chains could be examined, incorporating diverse coordination mechanisms. Finally, integrating process constraints within a bilevel programming framework requires to handle Karush-Kuhn-Tucker (KKT) conditions in Stackelberg-based optimization models

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