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Optimizing the Interaction Between Two Closed-Loop Supply Chains Based on Inverse Logistics Using the Game Theory Method

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Abstract. Over the past few years, attention to environmental problems, legal necessities, and economic advantages emerging from reproduction activities has attracted attention to reverse logistics activities in the form of a closed-loop supply chain, whether in industry or scientific research. The current study aims to model competitiveness and comparison between two closed-loop three-level supply chains, each of which includes a manufacturer, a retailer, and a third party to collect the products used by the customer, taking into account the concepts of game theory and the existence of aggregates. Moreover, a separate supplier for each chain is considered. In the forward supply chain, the manufacturer produces new products using new components or re-used products that have been collected from the consumer, then sells these products mainly to the retailer, and the retailer sells them. In the

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reverse chain, the collector provides the used products to the manufacturer after collection. The study utilized the definitions and concepts of game theory to model this closed loop chain as a Stackelberg game to obtain the optimal value of wholesale and retail price and the optimal value of the product return coefficient for the collector. Finally, the models based on some numerical examples are solved. Given the results, the remanufacturing costs have a significant role in making more profits for all members in such chains, and competitive chains should attempt to remanufacture the products at lower costs.

Keywords: Closed-loop supply chain, game theory, out-of-chain competition, reverse logistics, Stackelberg game.

1. Introduction

Generally, a closed-loop supply chain (CLSC) is regarded as a system that utilizes a combination of production and reproduction systems [1-4]. The CLSC comprises two distinct cycles of forward logistics and reverse logistics. Furthermore, a reverse supply chain could be recognized as logistic activities for gathering used products of customers to reproduce and re-introduce them into the market [5-8]. As a matter of fact, a simple CLSC can incorporate a manufacturer (wholesaler), a distributor (retailer), and a section for collecting the products used by customers, which are interconnected in the form of information, transportation, and financial infrastructures. Some studies demonstrated that coordination between the members of a CLSC could enhnace the chain's overall performance [9-12]. Nonetheless, there are other coordinated alterations in the real world, the competitive impact of which on each other should not be overlooked. A brief look at the real-world problems shows that there are many examples of competition between two CLSCs. An example would be two automotive CLSCs, which not only compete over meeting the demand of a group of customers but also compete over decreasing the costs of collecting the used products and reproducing them. According to a report by the Deloitte Consulting Company, from now on, companies will no longer compete; rather, competition will be between supply chains [13-16].

Game theory has grown to be a significant means in assessing and examining supply chains with numerous agents, often conflicting objectives [17,18]. The utilization of game theory in the design and redesign of supply chain logistics strategies permits the economic rationalization of those chains through indicating and estimating decision routes that guarantee a rise in profits, a reduction in costs, or an improvement in resource management [19-21].

An overview of the supply chain management literature showed a growing trend of studies related to competition and cooperation in a supply chain. Almost all previous models have assessed reproduction models, where only one reproduced product is considered without a competitive environment or there are competing models used for only one price factor. In the study by Wu [4], the researcher considered a supply chain consisting of two manufacturers and a retailer. The first manufacturer is a traditional manufacturer that produces the new product, while the second manufacturer operates a reverse channel producing remanufactured products from used cores. In the research by Wei and Zhao [5], the researchers proposed a CLSC with a manufacturer, a retailer, and a third party. In the foregoing study, the factors of consumer demand, remanufacturing costs, and product collection costs were considered in Fuzzy form. Three product collection modes were

considered for the reverse supply chain. The results of the three methods were analyzed using the game theory method in the form of the Stackelberg game and its integration with fuzzy theory. In addition, the expected profit of each method was assessed and calculated. In the study of Qiaolun et al. [6] , the main objective was to decide on the pricing of the product collection process in a reverse chain based on different scenarios and compare them with each other in the form of theory-based game models. Given the study of Qiaolun et al. [7], a CLSC encompassing one manufacturer, one retailer and a third party was considered. In the foregoing study, used products were collected from end customers over different scenarios in the reverse chain. Therefore, the used product return rate is influenced by customer desire for consumption, which is affected by collection costs.

In a forward supply chain, the optimal wholesale and retail costs are obtained in the form of a Stackelberg game under the influence of collection costs. In another research by Savaskan and Van Wassenhove [8], the researchers focused on the interaction between a manufacturer's reverse channel choice to collect post-consumer goods and the strategic product pricing decisions in the forward channel when retailing is competitive. To this end, they proposed two models, including a direct and an indirect product collection system, in which the manufacturer collected used products from the consumers directly and indirectly, respectively. Each of the two models was tested in two decentralized modes. Wei and Zhao [9] considered the optimal pricing decision problem of a fuzzy closed-loop supply chain with retail competition. Researchers focused on customer demands, rework and collection costs in fuzzy form. Optimal decisions were made about the wholesale price, the retail price, and the rework rate under different centralized and non-centralized scenarios using game theory and fuzzy theory methods. In a study, Pahlevan et al. [10] proposed a new model for designing a supply chain network. These researchers optimized human resource utilization and pollutant emission rates by creating new formulations. In addition, the problem was solved using the red deer algorithm (RDA). Nagurney [11] developed a supply chain game theory network framework that captured labor constraints under different scenarios, each having a certain event probability level. Afterward, they defined appropriate equilibrium constructs. Chen et al. [12] modeled a green supply chain in the hotel industry. The competition was considered between different hotels, and the government's role was regarded as a controller. They used the game theory approach to establish equilibrium.

Weighing up the literature review, it can be seen that the majority of these studies have merely focused on one supply chain, thereby neglecting the effect of other supply chains. Most models have assessed competition between one CLSC. Consequently, there seems to be a gap in the use of game theory in a competition between two CLSCs. On the other hand, we can find several examples of competition between two CLSCs. Hence, given the application of the mentioned problem in the real world, the current research intends to generate a model for competition between CLSCs on the basis of product price employing game theory under various scenarios in addition to filling the gap of the literature in the respective arena.

2. Methods

2.1. Statement of the Problem

The present study uses two three-layer CLSCs encompassing one manufacturer, one retailer, and a third party for collecting the used products, which compete with each other regarding wholesale and retail prices and optimal product return coefficient for the collector. In this competition, the manufacturer reproduces in addition to creating the product. The manufacturer sells the product to the retailer at a wholesale price, and the retailer sells the same product to the customer at the retail price. The third party collects the used, and returned products and sends them to the manufacturer for reproduction. To consider competition between chains, the mentioned CLSCs, each having a separate collector, are modeled in the form of a Stackelberg game, where the manufacturer plays the role of a leader and the retailer and collector play the role of followers, and the equilibrium points are obtained and compared.

2.2. Assumptions

- Both chains manufacture identical products with the same quality
- The produced and remanufactured products have the same quality
- The product is considered to be single-period. In other words, the game is considered to be single-stage and non-repetitive
- Chain members have symmetric information
- Chain members have rational risk and wise and conscious behavior
- The demand function is considered in the linear and definitive mode
- The remanufacturing cost of each used product unit is lower than the production cost of each product unit (reproduction profit)
- The collection cost of each product unit is less than the cost of delivery of each used product unit to the manufacturer (third-party profit)

2.3. Definition of Symbols, Variables and Parameters

To simplify matters, indexes of t, R and M are used for the manufacturer, retailer and third party, respectively.

2.3.1. Variables

$\prod R_i$, Retailer profit for the i-th chain
$\prod M_i$ manufacturer profit for the i-th chain
D_i product demand for the i-th chain $i, j =$ 1,2 $(i \neq j)$

$\prod t_i$ third party profit for the i-th chain.

2.3.2. Parameters

β Product price elasticity coefficient ($0 \leq \beta \leq 1$)
P_i Retail price of the product in the i-th chain
C_{m_i} production price of each product unit for the i-th chain
b Fixed collection cost parameter

a_i The potential market size for the product of the i-th chain
θ Price competitive coefficient ($0 \leq \theta \leq 1, \beta \geq \theta$)
W_i Wholesale price of the product in the i-th chain
C_{r_i} The remanufacturing price of each product unit for the i-th chain $C_{m_i} \geq C_{r_i}$
P_{b_i} The cost of delivery of each product unit from the collector to the manufacturer for the i-th chain
P_{c_i} Cost of collection of each product unit by the collector for the i-th chain ($P_{b_i} \geq P_{c_i}$)
τ_i Rate of collecting the used products by the collector for the i-th chain ($0 \leq T_i \leq 1$)

2.4. Problem mathematical Modelling and Equilibrium Points Estimation

The objective function used in the present research is considered in linear and definitive mode with a decreasing property toward its own price and an increasing property toward the price of its competitor. We use the same objective function used in [14], as presented below:

The total cost of collecting used products $C(\tau)$ is shown in the form of $C(\tau) = b.\tau^2 + P_c.\tau.D_i$, where $b.\tau^2$ is indicative of the fixed cost of collection of products used by costumers and $P_c.\tau.D_i$ shows the cost of the collection variable and $\tau.D_i$ shows the total number of used products collected by the collector [13,14]. Therefore, the model is assessed based on the following scenario:

Each chain has a separate collector, as shown schematically in Figure 1.

$$D_i = a_i - \beta.P_i + \theta.P_j \quad (1)$$
$$i,j = 1,2\ (i \neq j)$$

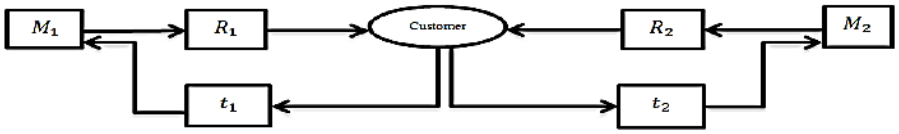


Figure 1. A schematic illustration of extra-chain competition between two closed-loop chains

According to the mentioned model and estimation of the total cost of collection of used products based on $C(\tau_i) = b.\tau_i^2 + P_{c_i}.\tau_i.D_i$, the profit functions of each member are defined as follows:

$$\prod\nolimits_{R_i} = (P_i - W_i).D_i \qquad i,j = 1,2\ (i \neq j) \qquad (2)$$

$$\prod\nolimits_{t_i} = \left(P_{b_i} - P_{c_i}\right).\tau_i.D_i - b.\tau_i^2 \qquad i,j = 1,2\ (i \neq j) \qquad (3)$$

$$\prod\nolimits_{m_i} = \left[W_i - (1-\tau_i).C_{m_i} - \left(C_{r_i} + P_{b_i}\right).\tau_i\right].D_i \qquad i,j = 1,2\ (i \neq j) \qquad (4)$$

To simplify the calculations and analysis of the problem, if $\Omega_i = P_{b_i} - P_{c_i}$ is regarded as the collector revenue for the i-th chain, which is received due to the collection of each used product unit from the manufacturer, and if $\Delta_i = C_{m_i} - C_{r_i}$ is considered as the amount of revenue that the producer earns for the i-th chain for reproducing each used product unit, the profit function of the collector and manufacturer will be, as follows:

$$\prod\nolimits_{t_i} = \Omega_i.\tau_i D_i - b.\tau_i^2 \qquad i,j = 1,2\ (i \neq j) \qquad (5)$$

$$\prod\nolimits_{M_i} = \left[W_i - C_{m_i} + \left(\Delta_i + P_{b_i}\right).\tau_i\right].D_i \qquad i,j = 1,2\ (i \neq j) \qquad (6)$$

Obviously, the manufacturer revenue obtained from the reproduction of each returned used product unit must be higher than the delivery cost of each product unit from the collector so that the remanufacturing process would yield profit $\left(\Delta_i \geq P_{b_i}\right)$. In this model, the manufacturers determine the wholesale price W^*_i, which maximizes the profit function, as the leaders of the Stackelberg game. Afterwards, retailers and collectors determine the optimal retail price P^*_i based on the determined wholesale price and the return rate of the used products τ_i^* as the followers of the game. To this end, the backward method is used based on the optimal wholesale price and following determining the retailer and collector response functions. It is notable that the optimal points are obtained based on the extra-chain competition of chain members, which is the main innovation of the current research.

Theorem) Based on the best retail response function, the optimal retailer price is determined, as follows:

$$P_i^* = \frac{2\beta(\beta W_i + \alpha_i) + \theta(\beta W_j + \alpha_j)}{4\beta^2 - \theta^2} \qquad i,j = 1,2\ (i \neq j) \qquad (7)$$

Proof) The best retailer response function and optimal wholesale price will be estimated as follows after first-order reaction derivation of the retailer profit function to P_i and equating it to zero:

$$\frac{\partial \Pi_{R_i}}{\partial P_i} = 0 \qquad (8)$$

$$\alpha_i - \beta P_i + \theta P_j - (P_i - W_i)\beta = 0 \Rightarrow P_i^* = \frac{2\beta(\beta W_i + \alpha_i) + \theta(\beta W_j + \alpha_j)}{4\beta^2 - \theta^2} \qquad i,j = 1,2\ (i \neq j) \qquad (9)$$

The second-order derivation of the retailer profit function is obtained to evaluate optimality and the second condition of retailer profit maximization:

$$\frac{\partial^2 \Pi_{R_i}}{\partial P_i^2} = -2\beta \leq 0 \tag{10}$$

Considering the assumption that $0 \leq \beta$, the second-order derivative is negative, which demonstrates the optimality of the retailer price.

Theorem) Regarding the best collector response function, the optimal rate of returned used products for the collector will be, as follows:

$$\tau_i^* = -\frac{\beta\Omega_i}{2} \times \frac{(-2\beta\alpha_i - \theta\alpha_i + 2\beta^2 W_i - \theta\beta W_j - W_i\theta^2)}{b.(4\beta^2 - \theta^2)} \qquad i,j = 1,2\ (i \neq j) \tag{11}$$

Proof) By placing the value of P_i^* in the collector profit function and equating the first-order derivative of the collector profit function to τ_i, the best collector response function and τ_i^* are, as follows:

$$\frac{\partial \Pi_{t_i}}{\partial \tau_i} = 0 \Rightarrow \Omega_i\left(\alpha_i - \beta P_i^* + \theta P_j^*\right) - 2b\tau_i = 0 \tag{12}$$

$$\Omega_i\left(\alpha_i - \beta\frac{2\beta(\beta W_i + \alpha_i) + \theta(\beta W_j + \alpha_j)}{4\beta^2 - \theta^2} + \theta\frac{2\beta(\beta W_j + \alpha_j) + \theta(\beta W_i + \alpha_i)}{4\beta^2 - \theta^2}\right) - 2b\tau_i = 0 \tag{13}$$

$$\tau_i^* = -\frac{\beta\Omega_i}{2} \times \frac{(-2\beta\alpha_i - \theta\alpha_i + 2\beta^2 W_i - \theta\beta W_j - W_i\theta^2)}{b.(4\beta^2 - \theta^2)} \qquad i,j = 1,2\ (i \neq j) \tag{14}$$

To evaluate the optimality and second condition of maximization of the collector profit, the second-order derivative of the collector profit function is obtained, as follows:

$$\frac{\partial^2 \Pi_{t_i}}{\partial \tau_i^2} = -2b \leq 0 \qquad i,j = 1,2\ (i \neq j) \tag{15}$$

Assuming that $0 \leq b$, the second-order derivative is negative, which shows the optimality of τ_i^*. In the end, in order to obtain the optimal wholesale price of the manufacturer W_i^*, the values of P_i^* and τ_i^* are placed in the manufacturer profit function and the first-order derivative of the manufacturer profit function is equated to zero relative to W_i.

$$\frac{\partial \Pi_{M_i}}{\partial W_i} = 0 \tag{16}$$

$$\left(1 - \frac{1}{2}\frac{\left(\Delta_i - P_{b_i}\right)\beta\Omega_i(2\beta^2 - \theta^2)}{b.(4\beta^2 - \theta^2)}(\alpha_i - \beta P_i^* + \theta P_i^*) + \left(W_i - C_{m_i} - \left(\Delta_i - P_{b_i}\right).\tau_i^*\right)\left(-\frac{2\beta^3}{4\beta^2 - \theta^2} + \frac{\theta^2\beta}{4\beta^2 - \theta^2}\right) = 0 \right) \qquad i, j = 1,2\ (i \neq j) \tag{17}$$

In fact, the value of W_i^* can be explained by the mentioned model and in the form of a numerical example.

$$Max_{W_i}\,\Pi_{M_i} = max_{W_i}\left[W_i - C_{m_i} + \left(\Delta_i - P_{b_i}\right).\tau_i^*\right].(\alpha_i - \beta P_i^* + \theta P_i^*) \tag{18}$$

s.t:

$$P_i^* = \frac{2\beta(\beta W_i + \alpha_i) + \theta\left(\beta W_j + \alpha_j\right)}{4\beta^2 - \theta^2} \qquad i, j = 1,2\ (i \neq j) \tag{19}$$

$$\tau_i^* = -\frac{\beta\Omega_i}{2} \times \frac{(-2\beta\alpha_i - \theta\alpha_i + 2\beta^2 W_i - \theta\beta W_j - W_i\theta^2)}{b.(4\beta^2 - \theta^2)} \qquad i, j = 1,2\ (i \neq j) \tag{20}$$

To evaluate the optimality and second condition of manufacturer profit maximization, the second-order derivative of the manufacturer profit function is obtained:

$$\frac{\partial \Pi_{M_i}}{\partial {W_i}^2} = 2\left(1 - \frac{1}{2}\frac{\left(\Delta_i - P_{b_i}\right)\beta\Omega_i(2\beta^2 - \theta^2)}{b.(4\beta^2 - \theta^2)}\right)\left(-\frac{2\beta^3}{4\beta^2 - \theta^2} + \frac{\theta^2\beta}{4\beta^2 - \theta^2}\right) \leq 0 \tag{21}$$

Assuming that $\beta \geq 0$, the value of $\left(-\frac{2\beta^3}{4\beta^2-\theta^2} + \frac{\theta^2\beta}{4\beta^2-\theta^2}\right)$ is always negative and since $0 \leq \beta, \theta \leq 1$; $\Delta_i \geq P_{b_i}$ and given the large value of the fixed parameter of collection cost (b), we have:

$$0 \leq \frac{1}{2}\frac{\left(\Delta_i - P_{b_i}\right)\beta\Omega_i(2\beta^2 - \theta^2)}{b.(4\beta^2 - \theta^2)} \leq 1 \tag{22}$$

Therefore:

$$2\left(1 - \frac{1}{2}\frac{\left(\Delta_i - P_{b_i}\right)\beta\Omega_i(2\beta^2 - \theta^2)}{b(4\beta^2 - \theta^2)}\right) \geq 0 \tag{23}$$

Since the positive value coefficient (22 and 23) is always negative in a negative value (21), the second-order derivative of the manufacturer profit function is always a negative amount relative to W_i, and this optimality guarantees the value of W_i^*.

3. Results and Discussion

The resulting equations are explained in this section by providing two numerical examples. To this end, the following parameters are used for comparison and the effect of $\Omega_i = P_{b_i} - P_{c_i}$ on the profit of each chain member is used in the form of the presented Figures:

$\alpha_1 = \alpha_2 = 200, \beta = 0.9, \theta = 0.6, C_{m_1} = 40, C_{m_2} = 38, P_{b_1} = P_{b_2} = 12, \Delta_1 = 26, \Omega_1 = \Omega_2 = 8, b = 1000$

Accordingly, two chains that attempt to produce a similar product with the same quality and potential market size are considered. To analyze and determine their trend of changes, the production cost is considered higher in the first chain, compared to the second chain, while the reproduction cost is lower than the second chain. According to Figure 2, increased collector revenue results in higher retail profit in a chain with a lower reproduction cost. In fact, the retailer earns more money for collecting used products.

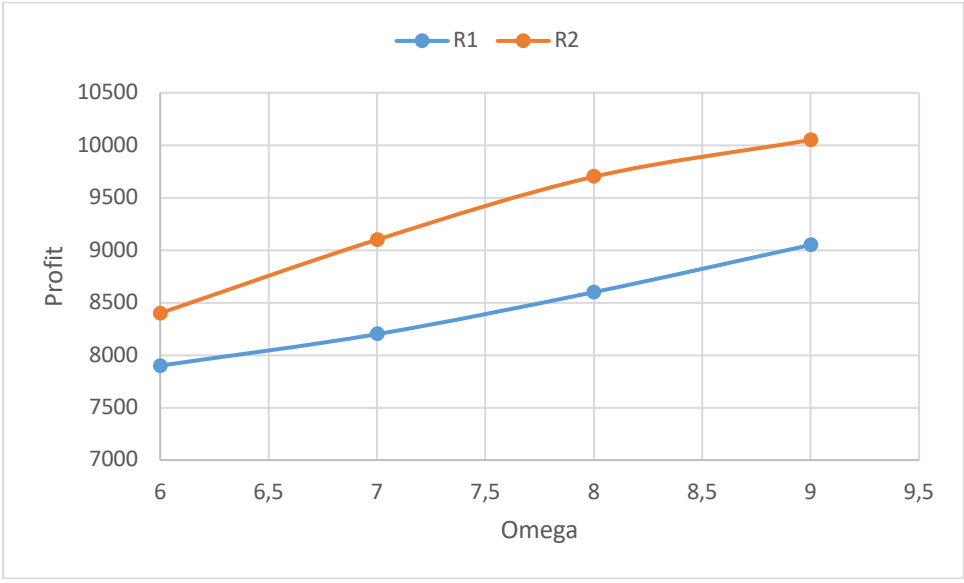


Figure 2. Effect of collector revenue on retailer profit function

Given the Figure 3, the rise of Ω regarding manufacturers' profit is more affected by the reproduction costs. Although the second chain holds a lower production cost, the collector revenue increase doesn't raise the manufacturer's profit.

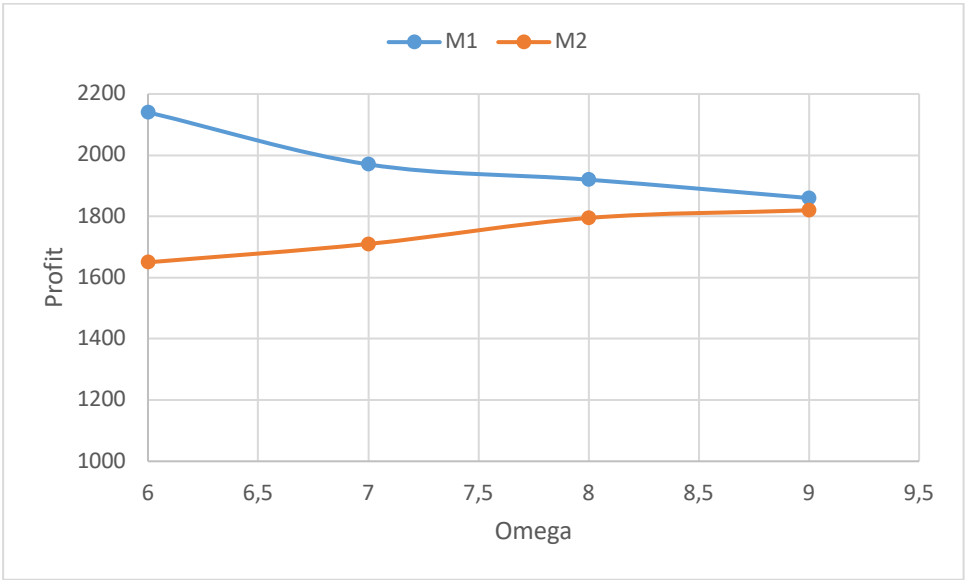


Figure 3. Effect of collector revenue amount on the manufacturer profit function

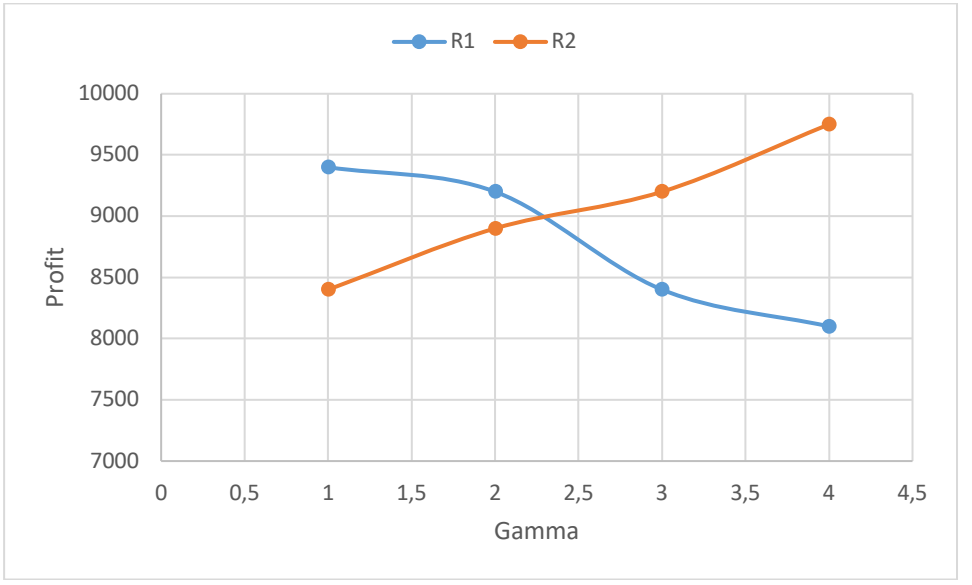


Figure 4. Effect of Γ on profit functions of retailers

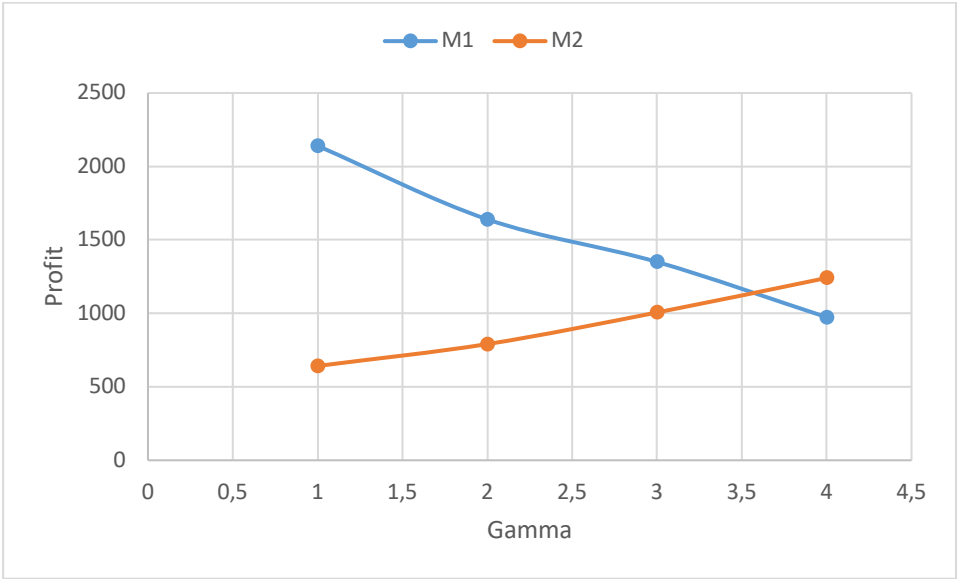


Figure 5. Effect on Γ on profit functions of manufacturers

According to Figure 4, an increase of Ω has a relatively similar effect on the profit functions of collectors, and sensitivity analysis of the parameter on the profit functions of collectors is similarly incremental. The following parameters are used to compare the level of impact of revenue of the manufacturer for reproducing each product unit in the two chains $\Gamma = \Delta_i - \Delta_j$ on the profit of chain members. The computational results are presented in the form of the Figures below:

$\alpha_1 = \alpha_2 = 200, \beta = 0.9, \theta = 0.6, C_{m_1} = 40, C_{m_2} = 38, P_{b_1} = P_{b_2} = 12, \Delta_1 = 26, \Omega_1 = \Omega_2 = 8, b = 1000$

As observed, the higher the difference in the amount of revenue obtained by manufacturers, the higher the amount of the members of the first chain and the lower the profits of the members of the second chain.

Considering Figure 5, it can be observed the amount of profit of the chain members is totally impacted by the revenues acquired by manufacturers for the reproduction of each product unit.

4. Conclusion

The current research intended to model and compare the competition between two three-layer CLSCs by considering the game theory concepts and in the presence of separate collectors for each chain. With the aid of the definitions and concept of the game theory, the CLSC was modeled in the form of a Stackelberg game to attain the optimal wholesale and retail prices and optimal return coefficient of products for collection and optimal profit values of each member by considering the extra-chain competition. The remanufacturing costs have a substantial role to play in attaining more profits for all members in such chains, and competitive chains need to try to remanufacture the products at lower costs. The profit of

chain members is completely affected by the manufacturer's profit as the leader of the game. In an extra-chain competition, higher profit of the manufacturer (with regard to the Stackelberg competition between the members) means that the chain members will earn higher profits as the followers of the game, and the market will be gradually dominated by the chain that has a stronger producer. To further expand the present study, it is recommended that each of the aforementioned assumptions be removed in future studies. In case of the dishonesty of each of the mentioned assumptions, the conditions will chain, and modeling and responses will be different. Regarding that, some of the issues include utilizing the inventory, maintenance, order, or shortage costs in the modeling process, each of which will chain the structure of the model and responses. Additionally, the dependence of demand on the price of goods is linearly a very simplistic approach. As demand depends on other factors such as quality, substitute goods, complementary goods, or even advertising and marketing costs, there will be more alignment between model outputs and reality. Solving and modeling the game in such situations is more challenging but will be more useful in practice.

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