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Environmental Policy Making in Supply Chains under Ambiguity and Competition: A Fuzzy Stackelberg Game Approach

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Abstract: Despite the substantial efforts of governments in promoting sustainable development, there exists considerable debate regarding the environmental policy making approach under information ambiguity and competition. This study investigates market competition between a green and a non-green supply chain (SC) under two government regulation policies, namely, selling price and production quantities. To tackle the policy making challenges, a fuzzy game theoretical model was employed in a centralized and decentralized SC setting. The results revealed that SCs always achieve a higher expected profit under a decentralized structure, regardless of the type of the governments intervention policy. Also, the government's policy making success was found to be highly dependent on the channel leadership, market competition, and the SC structure. Our findings suggest that the policy makers' objectives in reducing environmental pollution and increasing revenue are highly achievable, without risk of losing channel coordination and maximum level of efficiency.

Keywords: supply chain sustainability; environmental policy making; fuzzy Stackelberg game; sequential decision-making; information ambiguity

1. Introduction

Today, many academics and practitioners believe that environmental pollution is a significant problem, threatening the lives of people, animals, and plants. The amount of carbon dioxide in the air, which was about 280 units per million before the industrial revolution, had risen to 380 units per million in 2009, and this trend is accelerating [1]. One way to mitigate the risks and reverse the situation is to make appropriate social, technological, and political reforms in managing global supply chains (SCs) and move toward sustainable development goals [2,3]. Adopting green supply chain (GSCM) management concepts offers several benefits, such as saving energy resources, reducing carbon emissions, adding more value for customers, and enhancing company competitiveness [4,5].

Some governments have recently recognized the urgency of emission reduction and proposed feasible carbon emission regulations [6]. To induce industries to produce greener products, governments employ systematic incentives and financially reward industries that produce less environmental pollution. On the other hand, environmental taxes can be used to achieve optimal allocation of resources by enforcing companies to produce and offer greener products and services [7]. Government intervention plays an important role in promoting green supply chains (GSCs) and is widely known as an instrumental factor in the successful implementation of environmental policies [8]. For example, the government of China has devised a comprehensive environmental impact taxation system to reduce pollution discharge. Such interventions create significant opportunities for the GSCs to mitigate environmental risks, while stimulating investments in green production. This eventually lead traditional SCs to move toward sustainable development goals [2,9]. In-

spired by these facts, the present study is aimed at investigating the impacts of government intervention on pricing and quantity decisions in GSCs.

The business world has witnessed the rise of consumer awareness regarding the environmental aspects of products, and recognizes the growing concerns about increasing carbon emissions and limited waste disposal capacity. The ability to respond to incomplete information and ambiguity in the consumers' demand and manufacturing costs has also become one of the key success factors in competitive markets. Hence, the existence of complete information about consumer demand and manufacturing costs is no longer a valid assumption in the business environment [10]. The existing information ambiguity has caused considerable complexity and imposed substantial pressure on policy makers, who are already challenged by the rapidly evolving socio-economic problems [11]. To address these issues, both practitioners and academics have recently started to develop robust models that incorporate SC uncertainties and information ambiguity in environmental policy making problems [12].

There are various methods that can be used in policy making problems (e.g., quantitative decision-making, simulation-based methods, operation research). Most existing studies on policy making consider SCs and the government as independent decision-makers. Game theory provides a practical approach to examine and formulate the members' interactions in a multiplayer setting, where each player seeks to maximize its goals [7,8]. Due to the power asymmetry in the policy making problem, leader–follower Stackelberg game models have been widely used as effective tools. The government is commonly considered as the game leader, with the authority to move first and implement a variety of mechanisms in target industries. In line with the prior studies, our proposed methodology is constructed based on a Stackelberg game framework in which the lower level of the decision-making structure consists of two competing green and non-green SCs, while the government leads the game as the Stackelberg leader.

The present study focuses on the interaction between two competing green and regular SCs to investigate the impact of information ambiguity on the successful implementation of environmental policies. To this aim, some of the key SC parameters are considered as fuzzy numbers to incorporate information ambiguity into the policymaker's problem regarding the characteristics of competing SCs. This paper examines two frequently studied environmental policies in competitive markets: selling price and production quantity strategy. The following research questions will be addressed in this study:

1. How do the SC structure (centralized vs. decentralized) and information ambiguity affect the competing SCs' pricing decisions under different environmental policies?

2. How do government environmental policies affect the pricing decisions, the expected profit of centralized and decentralized SCs, and the environmental impact of SCs?

3. What are the impacts of environmental protection and revenue-seeking objectives of government on the overall performance of competing SCs under centralized and decentralized structures?

The remainder of this study is organized as follows: Section 2 provides a review of existing literature. Section 3 introduces the assumptions and mathematical notations. Section 4 describes the model formulation and presents four potential decision-making scenarios. Numerical results and discussion are provided in Section 5. Finally, we conclude remarks and make suggestions for future research in Section 6.

2. Literature Review

This study touches upon two important elements in the field of GSCM; namely, Stackelberg game/fuzzy game theory and government financial intervention. Each body of relevant literature is briefly reviewed in the following subsections, and then research gaps and the key contributions of this paper are presented. A summary of previous relevant quantitative studies is shown in Table 1.

2.1. Stackelberg Game and Fuzzy Game Theory in SC

Stackelberg game models have been widely employed in applied economy and industry applications [13–15]. They deal with the leader(s)–follower(s) interaction in which the competition is not necessarily about a common goal, but players with different privileges compete to improve their own situation and increase their profits. Asian and Nie [16] used a sequential two-level optimization process as a solution approach for option contracts in a decentralized SC composed of one buyer, an unreliable main supplier, and a perfectly reliable backup supplier. They examined two benchmark and contract models under decentralized and centralized structures and analytically characterized the conditions under which the proposed option contract led to a win–win solution and coordinated the decentralized SC. Hadi et al. [17] formulated a game theoretical model in which the government applies some economic incentives to manage environmental effects under different scenarios. They considered two SCs, producing and offering non-green and green products in a shared market. The results indicated that collaboration between the recycler and retailer in the SC had a significant impact on the SC members' profit. Li and Chen [18] developed a Stackelberg game theoretical model in which the retailer sold customers a product under two different brands (quality standards), employing three strategies (i.e., selling two brands supplied by two competing manufacturers or integrating backward with either the high- or the low-quality manufacturer). Chen et al. [19] investigated the impact of the power relationship in both vertical and horizontal competition in a SC and analyzed the effects of customer demand in the bidimensional power dynamics of the SC. Yang et al. [20] used a Stackelberg game to analyze interactions between stations and roadside units that competed in an intelligent transportation system that provided information to drivers and passengers about traffic safety, traffic efficiency, autonomous driving, and entertainment.

Fuzzy game theory, with a discrete or continuous strategy domain, has been widely studied in the literature [21,22]. Cunlin and Qiang [23] investigated two-person zero-sum games in the fuzzy environment using the Nash equilibrium strategy. Oliveira and Petraglia [24] proposed an application of the fuzzy optimization algorithm for finding the Nash equilibrium in formal games. Some studies in the literature focused on the factors which cannot be determined with certainty in real-world scenarios, such as the customer demand characteristics (e.g., quality, costs, and priority). For instance, Gumus and Guneri [25] considered nondeterministic parameters for demand, delivery times, and costs in a three-level SC. In addition, various methods of operations research, expert systems, multicriteria decision-making, control theory, and artificial intelligence have been developed to incorporate fuzzy parameters in SCs.

Zhao et al. [10] studied the fuzzy game approach to analyze the interactions between two substitutable products and used a Stackelberg game method to study the SC pricing decisions in fuzzy and uncertain environments. Similarly, Zhao and Wang [26] analyzed decisions about pricing and retail services in a SC in a fuzzy and uncertain environment. They examined the natural conflicts among the decision-makers in the construction sector. Feng et al. [27] examined the Stackelberg–Nash equilibrium and proposed a new model for evaluating manufacturing and construction material suppliers in a fuzzy environment. Wei and Zhao [28] considered product collection costs as fuzzy parameters, and used a game theory approach to find equilibrium decisions of the manufacturer, retailer, and a third party in a closed loop SC. Jamali et al. [29] investigated an SC pricing problem of a manufacturer and a retailer considering two distribution channels. A game theory approach was employed to obtain equilibrium solutions for cooperative and noncooperative scenarios. It was concluded that to boost the entire SC profit, an increase in the product greenness level was essential. Wang [30] characterized consumer demands, manufacturing costs, and warranty costs as fuzzy variables and evaluated the closed form optimal values of pricing and warranty decisions in a manufacturer-led SC Stackelberg setting. Zhao et al. [31] used game theory under symmetric and asymmetric information about retailer's product collection parameters in a two-echelon closed-loop SC. Fallah et al. [32] established Nash and Stackelberg game models to study competition in a closed loop SC in an uncertain

environment. Yang and Xiao [8] used a game theory approach and studied the interaction between government and a GSC, considering fuzzy parameters for manufacturing costs and demand. Alamdar et al. [33] investigated the fuzzy price and sales effort/demand in a closed loop SC with a new decision-making structure. They also proposed a contract for coordinating a decentralized SC that was beneficial for all parties.

2.2. Government Intervention

In this section, we review the studies that focus on how governments impose environmental policies to encourage SCs to reduce environmental pollution. Tsireme et al. [34] explored the effects of managerial decisions to adopt new practices in GSCM in response to government environmental policies. Wang et al. [35] considered the relationships among governmental intervention, the provincial pollution-emission efficiency, and market development. The results showed that there was a positive correlation between market development and provincial pollution emission efficiency. Governmental intervention and market development were also found to be complementary factors in promoting China's provincial pollution-emission efficiency. Zhao et al. [10] used a game-theory model to analyze manufacturers' policies in GSCs, aiming to limit the environmental risk of materials and carbon emissions by focusing on tolerability of risk. They also showed that, by introducing a reasonable subsidy, a government can motivate producers to make appropriate restructuring decisions. Mahmoudi and Rasti-Barzoki [36] used a game theory approach under three different scenarios of government intervention in sustainable SCs. Their results showed that government policy affected the producers' activities, competitive markets, and carbon emissions. It was found that the imposed tariffs were the most effective government approach in minimizing environmental impacts. Chen et al. [37] considered a Stackelberg game between a manufacturer and a retailer in a dual channel closed loop SC under a government penalty–subsidy mechanism. The government rewarded or punished the manufacturer on the basis of the collection rate of the used products. Jin and Mei [38] established a game model between government and suppliers in a GSC under equilibrium conditions. They showed that governments can adjust their economic policy according to their supervision costs, the penalties on regular products, and the environmental damage costs of regular products. Yang and Xiao [8] studied the influence of government financial involvement in a GSC.

The effect of government environmental policies on the competitiveness of SCs is another relevant topic. Hafezalkotob [39,40] investigated equilibrium solutions between green and regular products under different government intervention schemes in which the government was considered as a leader. They found that specific boundaries existed for government tariffs that guarantee a stable competitive market. Wu [41] considered a similar case in which the government intervened in a closed loop SC by imposing penalties or subsidies to reduce the environmental burden. After proposing six different policies, the results demonstrated that the proposed policies could effectively reduce the environmental burden and mitigate the intensity of price competition. Reza-Gharehbagh et al. [42] developed a model for two competing financial chains under governmental interventions. They analyzed the developed models by minimizing the arbitrages caused by speculative transactions to prohibit an excessively high interest rate.

Wang et al. [43] used a two-stage Stackelberg game model to develop an optimal scheme for a carbon emission tax. They analyzed how carbon emissions affect the selection of transportation modes and social welfare. Their study indicated that inflicting a greenhouse gas tax on a product at higher production costs, larger product volumes, or higher product density can increase the possibility of social welfare improvement. Similarly, Sheu and Chen [9] considered the government as a leader player in cooperative and noncooperative settings, and studied different green taxation strategies. Results indicated that a higher efficiency reduced the impact of financial interventions on the GSCs players' profits. Hafezalkotob et al. [44] considered the importance of government regulations and customer demands in managing the environmental issues. They found that such regulations may

lead the organizations to review the critical measures that are required for the implementation of the GSCM while maintaining profits. Moradinasab et al. [45] modeled competition between government-led and private sector-led petroleum SCs by using Stackelberg and Nash game approaches. Hafezalkotob [46,47] developed price-energy-saving cooperation models for two GSCs competing under government intervention.

Table 1. A summary of previous relevant quantitative studies.

Reference	Fuzzy Variables	Game Theory		Intervention Policy	
		Stackelberg	Nash	Price	Others
Yang et al. [8]	Manufacturing cost; consumer demand; market scale; green manufacturer's profit; retailer's profit; green SC profit; retailer's profit; price elasticity of the green product; green level sensitivity coefficient of the product	√	×	√	×
Sheu et al. [9]	×	×	√	√	×
Zhao et al. [10]	Consumer demand; manufacturing cost	×	√	×	×
Wei et al. [11]	Customer demand; remanufacturing cost; the collecting cost	×	√	×	×
Gao et al. [14]	×	√	×	×	×
Hadi et al. [17]	×	√	×	√	×
Cunlin et al. [23]	Players' profit	×	√	×	×
Zhao et al. [26]	Customer demands; manufacturing cost; service cost coefficients	√	√	×	×
Feng et al. [27]	Production cost coefficient; inventory cost coefficient; transportation cost coefficient; transportation time coefficient; quantity of materials; demand for materials	√	√	×	×
Wei et al. [28]	Demand; manufacturing cost; used products collection costs	×	√	×	×
Jamali et al. [29]	Wholesale; price, greening level of the product	×	√	×	×
Wang [30]	Consumer demand; manufacturing cost; warranty cost	√	×	×	×
Fallah et al. [32]	Demand of SC; self-price and cross-price elasticity coefficients	√	×	×	×
Alamdar et al. [33]	Price; sales effort–dependent demand	×	√	×	×
Tsireme et al. [34]	×	√	×	√	×
Mahmoudi et al. [36]	×	√	×	√	√
Hafezalkotob [39]	×	√	×	√	×
Hafezalkotob [40]	×	√	×	√	√
Moradinasab et al. [45]	×	√	√	√	×
Hafezalkotob [47]	×	√	×	√	√
Liu et al. [48]	Manufacturing cost; demand	√	×	×	×
This paper	Market demand for the retailers; costs; manufacturers' profit	√	×	√	√

2.3. Research Gaps and Key Contributions

Due to the lack of accurate data and incomplete information, environmental policy goals are often set based on several assumptions and approximations. Traditionally, such ambiguities were simply ignored by the analysts and policy makers. With the rise of their awareness, some governments have started to consider information ambiguity more seriously by understanding, accepting, and managing different aspects of the problem.

The literature review confirmed that there is only a limited number of studies that incorporate information ambiguity in policy making problems. Some studies suggest that the existing ambiguities in environmental policy making can be captured and quantified through fuzzy estimation [48,49]. However, none of the existing studies simultaneously considered SC competition and information ambiguity, which are in fact the key characteristics of today's competitive business environment. To bridge the gap, we propose a

Fuzzy game theoretical model between a GSC and an RSC (i.e., regular SC) and investigate government environmental intervention under competition and ambiguity. Using a bilevel multi-objective fuzzy optimization and considering both centralized and decentralized settings for two competing SCs, we investigate the impact of government environmental policies (i.e., selling price and production quantity) under different scenarios. A detailed sensitivity analysis and a numerical study are conducted to validate our theoretical results. Practical implications and managerial insights are also provided.

3. Assumptions and Mathematical Notations

We considered two competing green and regular (non-green) SCs. For simplicity, let *GSC* represent the SC that produces green products, and *RSC* denote the SC that produces regular products. Table 2 lists the mathematical notations that are used throughout this paper.

Table 2. A list of notations.

Notations	Description
$\widetilde{a}_i$	the market scale of product i (fuzzy variable)
$\widetilde{c}_i$	the marginal manufacturing cost of product i (fuzzy variable)
$\widetilde{d}$	the substitutability coefficient of product types $0 \leq \widetilde{d} \leq 1$ (fuzzy variable)
p_i	the retailer price of product i presented by retailer in SC type i
θ_i	the environmental impact of product i presented by SC type i
F	the minimum net revenue of the government
E	the maximum environmental impact of products
$\widetilde{L}_i$	the reservation profit of SC type i, (fuzzy variable)
$\widetilde{L}_{Mi}$	the reservation profit of manufacturer in SC type i
$\widetilde{L}_{Ri}$	the reservation profit of retailer in SC type i
w_i	the unit wholesale price of product i determined by the manufacturer in SC type i
t_i	the tariff for a unit of product i set by the government
$G\widetilde{N}R$	the government's net revenue obtained from tax, punishment, or incentive (fuzzy variable)
$E\widetilde{I}s$	the total environmental impacts of the SCs' products (fuzzy variable)
$\widetilde{Q}$	the production quantity goal set by government for product i
$\widetilde{x}_i$	the government's tax or subsidy value

To avoid trivial cases and ensure the tractability of the mathematical models, the following assumptions were made:

(1) Following Hafezalkotob [39], we used environmental impact factors to represent and differentiate the pollution levels of green and regular products. This can be justified by the fact that, depending on the industry, different products cause different level of pollutions that can be measured by factors, such as a reversible index of products, reproduction or recycling index, and annual exhausting CO_2 or NO_x of products [47].

(2) In the real-world environment, the key parameters affecting policy making are usually vague and incomplete and, hence, cannot be estimated accurately. In this paper, information ambiguity is represented in the form of fuzzy numbers. Following Yang and Xiao [8], we considered some of our game parameters as trapezoidal fuzzy numbers.

(3) In all studied scenarios, the government was a Stackelberg leader who financially intervenes in the market with a tax or subsidy that indirectly influences the selling price of final products.

4. Model Formulation and Analysis

In this section, we first describe the research problem and analyze the basic concepts of the implemented game models. We then formulate the mathematic models and characterize the decision-making behavior of the SC members and government in different scenarios.

Consider two competing SCs, one manufacturer and one retailer, in a specific industry with one offering a green product and another a regular product in a shared market. These

two products are substitutable with fuzzy variable $\tilde{d}$ in the shared market. Following Bertrand's pricing competition model [50], customer demand is a function of the retailer's announced price, and the manufacturers must decide on the wholesale price. In general, SC decisions are made in either a centralized or a decentralized environment, referred to as the SC structure [16]. In a centralized structure, a single decision maker, with enough authority within the SC, makes decisions for the entire chain's members. In this case, the members are in line with the decision made by the centralized planner. However, since the SC members are often separate entities, they may be reluctant to follow decisions adopted for the whole SC and try to achieve their individual goals instead of optimizing the whole system. Therefore, the decentralized SC seems to be a more realistic model in most of the cases [51].

In this study, we consider both centralized and decentralized SC settings and investigate the competing SCs' decision-making when the government financially intervenes to control and reduce the environmental impact of the promoted products. Fuzzy decision-making can be generally divided into two groups: symmetric and asymmetric formulations. In a symmetric formulation, there is no significant difference between the weights of constraints and objective functions. However, in an asymmetric formulation, goals and constraints are not treated equally, and the weights applied have different meanings. In this paper, we follow Hafezalkotob [39] and Jiménez, Arenas, Bilbao, and Rodrı [52], and consider the fuzzy numbers rating based on their expectancy comparison.

From the government point of view, two main policies are often utilized to enhance the SC performance; namely, price-based and production quantity-based instruments. A price-based instrument is a market policy that can reduce or increase the market price of the products while contributing to the government's objectives. On the other hand, quantity-based instruments focus on the supply side of the SCs and are aimed to moderate the production quantity of products. Figure 1 depicts the different decision-making scenarios studied in this paper.

Figure 1. The different decision-making scenarios.

4.1. Government Tariff on Selling Price under a Centralized SC (Scenario 1)

Scenario 1 considers competition between two centralized SCs in which the government imposes its environmental policy on selling prices. The operational decisions made by manufacturers and retailers are often affected by the power of both vertical and horizontal members of the competitive game [19]. SCs consist of one manufacturer and one retailer playing a follower role, while the government is the leader. Thus, our main objective is to examine the effects of the government strategy by considering the payoff function for each follower (i.e., SC). Figure 2 illustrates the centralized structure of the SCs.
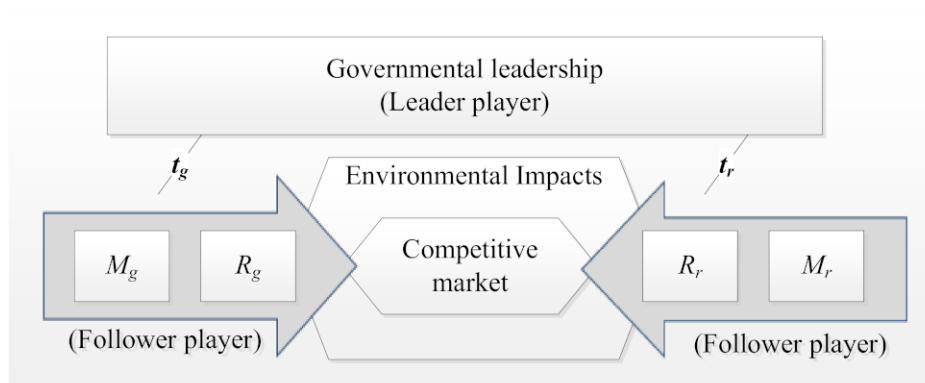
Figure 2. The schematic of SCs in a centralized structure under government tariffs.

Demand for product type i $(i = g, r)$ in both SCs can be defined as follows:

$$\widetilde{q}_i(p_i, p_j, t_i, t_j) = \widetilde{a}_i - (p_i + t_i) + \widetilde{d}(p_j + t_j); i, j = g, r; i \neq j \tag{1}$$

We next derive the expected profit of the SCs as follows:

$$E\left[\widetilde{\pi}_i(p_i, p_j, t_i, t_j)\right] = E\left[(p_i - \widetilde{c}_i)\left(\widetilde{a}_i - (p_i + t_i) + \widetilde{d}(p_j + t_j)\right)\right]; i, j = g, r; i \neq j \tag{2}$$

Transforming Equation (2), we have:

$$E\left[\widetilde{\pi}_i(p_i, p_j, t_i, t_j)\right] =$$
$$p_i E[\widetilde{a}_i] + p_i(p_j + t_j) E\left[\widetilde{d}\right] - E[\widetilde{c}_i \widetilde{a}_i] + (p_i + t_i) E[\widetilde{c}_i] - (p_j + t_j) E\left[\widetilde{d}\widetilde{c}_i\right] - p_i(p_i + t_i) \tag{3}$$

The expected profit in Equation (3) can be rewritten as:

$$E\left[\widetilde{\pi}_i(p_i, p_j, t_i, t_j)\right]$$
$$\begin{aligned}
&= \text{1/2} \int_0^1 p_i\left(\widetilde{a}_{i\alpha}^L + \widetilde{a}_{i\alpha}^U\right) d\alpha \\
&+ p_i(p_i + p_j) \int_0^1 \left(\widetilde{d}_{i\alpha}^L + \widetilde{d}_{i\alpha}^U\right) d\alpha \\
&+ (p_i + t_i) \int_0^1 \text{1/2}\left(\widetilde{c}_{i\alpha}^L + \widetilde{c}_{i\alpha}^U\right) d\alpha \quad \int_0^1 \text{1/2}\left(\widetilde{c}_{i\alpha}^U \widetilde{a}_{i\alpha}^L + \widetilde{c}_{i\alpha}^L \widetilde{a}_{i\alpha}^U\right) d\alpha \\
&- (p_j + t_j) \int_0^1 \text{1/2}\left(\widetilde{c}_{i\alpha}^U \widetilde{d}_{i\alpha}^L + \widetilde{c}_{i\alpha}^L \widetilde{d}_{i\alpha}^U\right) d\alpha - p_i(p_i + t_i),
\end{aligned} \tag{4}$$

where $\widetilde{a}_\alpha^U = Sup\left\{r : \left\{\widetilde{C} \geq r\right\} \geq \alpha\right\}$ is the α-optimistic and $\widetilde{a}_\alpha^L = Inf\left\{r : \left\{\widetilde{C} \leq r\right\} \geq \alpha\right\}$ is the α-pessimistic value of $\widetilde{\alpha}$ $(0 \leq \alpha \leq 1)$. Similarly, this definition can be applied to other fuzzy parameters. Proposition 1 provides the optimal prices of products in Scenario 1.

Proposition 1. *Under the centralized SC structure and when government tariffs are imposed on the selling price, the optimal price of SCs can be obtained as follows:*

$$p_i^*(t_i, t_j) = A_i + \frac{E\left[\widetilde{d}\right]^2 - 2}{4 - E\left[\widetilde{d}\right]^2} t_i + \frac{E\left[\widetilde{d}\right]}{4 - E\left[\widetilde{d}\right]^2} t_j; i, j = g, r; i \neq j \tag{5}$$

where, $A_i = \frac{E\left[2\widetilde{a}_i + 2\widetilde{c}_j + \widetilde{d}\widetilde{a}_j + \widetilde{d}\widetilde{c}_i\right]}{4 - E\left[\widetilde{d}\right]^2}$.

All proofs are provided in the Appendix A.

The government aims to maximize its net revenue (*GNR*) and environmental impacts (*EIs*) [39]. Therefore, the government's objectives function can be formulated as follows:

$$Max_{x_i, x_j} E\left[G\widetilde{N}R(p_i, p_j, t_i, t_j)\right] = \sum_{i \in \{r,g\}} t_i \widetilde{q}_i(p_i, p_j, t_i, t_j) \tag{6}$$

$$Min_{x_i, x_j} E\left[E\widetilde{I}s(p_i, p_j, t_i, t_j)\right] = \sum_{i \in \{r,g\}} \theta_i \widetilde{q}_i(p_i, p_j, t_i, t_j) \tag{7}$$

s.t.

$$G\widetilde{N}R(p_i, p_j, t_i, t_j) \geq F \tag{8}$$

$$E\widetilde{I}s(p_i, p_j, t_i, t_j) \leq E \tag{9}$$

$$\widetilde{\pi}_g(p_i, p_j, t_i, t_j) \geq \widetilde{L}_g \tag{10}$$

$$\widetilde{\pi}_r(p_i, p_j, t_i, t_j) \geq \widetilde{L}_r \tag{11}$$

$$t_i \geq 0; i = r, g \tag{12}$$

Constraints (8) and (9) ensure that *GNR* and *EIs* from both products are restricted to values *F* and *E*, respectively. In addition, (10) and (11) are individual rational (IR) constraints in which minimum profits $\widetilde{L}_g$ and $\widetilde{L}_r$ are guaranteed for the green and regular SCs, respectively. The government model can be considered as a fuzzy multi-objective nonlinear problem (FMONLP) in that all parameters in objective functions and constraints are fuzzy. Therefore, for finding the government's tariffs, first of all, in Equations (6)–(12), p_g and p_r can be replaced with the best response strategies, $p_g^*(t_g, t_r)$ and $p_r^*(t_g, t_r)$, provided in Proposition 1. Because of fuzzy constraints, the space solution of the model will also be a fuzzy set. Let A^U and A^L represent the upper and lower levels of a fuzzy variable $\widetilde{A}$, with α-cut as the confidence level (i.e., $\widetilde{A}_\alpha = \{x \in X : \mu_A(x) \geq \alpha, \alpha \in [0,1]\}$). Considering an asymmetric fuzzy decision-making approach, the proposed fuzzy model (6)–(12) can be rewritten as follows:

$$Max \; \zeta(t_i, t_j) = Max \; \{(\omega_{k1}\lambda_{k1}) + (\omega_{k2}\lambda_{k2}) + (\omega_{k3}\varphi_{k3}) + (\omega_{k4}\varphi_{k4}) + (\omega_{k5}\varphi_{k5}) + (\omega_{k6}\varphi_{k6})\} \tag{13}$$

s.t.

$$\lambda_{k1} \leq \frac{GNR - GNR_\alpha^L}{GNR_\alpha^U - GNR_\alpha^L} \tag{14}$$

$$\lambda_{k2} \leq \frac{EIs_\alpha^U - EIs}{EIs_\alpha^U - EIs_\alpha^L} \tag{15}$$

$$\varphi_{k3} \leq \frac{F + GNR_\alpha^U}{GNR_\alpha^U - GNR_\alpha^L} \tag{16}$$

$$\varphi_{k4} \leq \frac{E - EIs_\alpha^L}{EIs_\alpha^U - EIs_\alpha^L} \tag{17}$$

$$\varphi_{k5} \leq \frac{\widetilde{\pi}_g(p_i, p_j, t_i, t_j) - \widetilde{L}_g^L}{\widetilde{L}_g^U - \widetilde{L}_g^L} \tag{18}$$

$$\varphi_{k6} \leq \frac{\widetilde{\pi}_r(p_i, p_j, t_i, t_j) - \widetilde{L}_r^L}{\widetilde{L}_r^U - \widetilde{L}_r^L} \tag{19}$$

$$\lambda_{k1} + \lambda_{k2} + \varphi_{k3} + \varphi_{k4} + \varphi_{k5} + \varphi_{k6} = 1 \tag{20}$$

$$\lambda_{k1} \geq \alpha, \; \lambda_{k2} \geq \alpha, \; \varphi_{k3} \geq \alpha, \; \varphi_{k4} \geq \alpha, \; \varphi_{k5} \geq \alpha, \; \varphi_{k6} \geq \alpha, \; \alpha \in [0,1] \tag{21}$$

$$0 \leq \lambda_{k1}, \; \lambda_{k2}, \; \varphi_{k3}, \; \varphi_{k4}, \; \varphi_{k5}, \; \varphi_{k6} \leq 1 \tag{22}$$

$$t_i \geq 0; i = r, g \tag{23}$$

where λ_{k1} and λ_{k2} are the level access of the government's objective functions $(6)-(7)$, and φ_{k3}, φ_{k4}, φ_{k5} and φ_{k6} refer to the level access of the fuzzy constraints $(8)-(11)$. GNR_α^L, GNR_α^U, EIs_α^L, and EIs_α^U are lower bounds and upper bounds of GNR and EIs, respectively. The above single objective nonlinear programming model can be solved using an available nonlinear programming solver package, such as GAMS or Lingo.

4.2. Government Tariff on Selling Price under a Decentralized SC (Scenario 2)

In this scenario, the manufacturer and the retailer make their decisions independently in a decentralized setting. So, the power structure of SC channels is different from the previous scenario. The model setting is graphically illustrated in Figure 3.
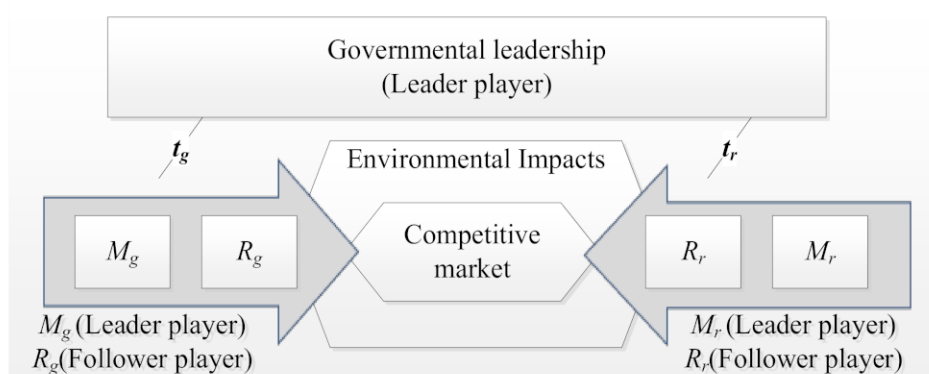

Figure 3. The schematic of SCs in a decentralized structure with government tariffs.

For $i = r, g$, there are three players in the game, including the government (the game leader), a manufacturer M_i (the game subleader), and a retailer R_i (the game follower). Government tariffs are imposed on retail prices of SCs decided by the retailers.

Following the backward induction procedure, we first focus on the followers' problem. Using the previously derived demand function (Equation (1)), the expected profit of the manufacturer and retailer (for $i, j = g, r; i \neq j$) can be derived using Equations (24) and (25), respectively.

$$
\begin{aligned}
E\left[\tilde{\pi}_{Ri}\left(p_i,\ p_j\ ,t_i\ ,t_j,\quad w_i\ ,w_j\right)\right]] &= E\left[(p_i - w_i)\tilde{q}_i\left(p_i,\ p_j\ ,t_i\ ,t_j\right)\right] \\
&= \frac{p_i - w_i}{2}\int_0^1\left(\tilde{a}_{i\alpha}^U + \tilde{a}_{i\alpha}^L\right)\mathrm{d}\alpha \\
&\quad + \frac{(p_j + t_j)(p_i - w_i)}{2}\int_0^1\left(\tilde{d}_\alpha^U + \tilde{d}_\alpha^L\right)\mathrm{d}\alpha - (p_i + t_i)(p_i - w_i)
\end{aligned}
\tag{24}
$$

$$
\begin{aligned}
E\left[\tilde{\pi}_{Mi}\left(p_i,\ p_j\ ,t_i\ ,t_j, w_i\ ,w_j\right)\right]] &= E\left[(w_i - \tilde{c}_i)\tilde{q}_i\left(p_i,\ p_j\ ,t_i\ ,t_j\right)\right] = w_i\int_0^1 1/2\left(\tilde{a}_{i\alpha}^U + \tilde{a}_{i\alpha}^L\right)\mathrm{d}\alpha + \\
\frac{w_i(p_j + t_j)}{2}&\int_0^1\left(\tilde{d}_\alpha^U + \tilde{d}_\alpha^L\right)\mathrm{d}\alpha + (p_i + t_i)\int_0^1\left(\tilde{c}_{i\alpha}^U + \tilde{c}_{i\alpha}^L\right)\mathrm{d}\alpha - (p_j + t_j)\int_0^1\left(\tilde{d}_\alpha^L\tilde{c}_{i\alpha}^U + \tilde{d}_\alpha^U\tilde{c}_{i\alpha}^L\right)\mathrm{d}\alpha - \\
\int_0^1&\left(a_{i\alpha}^L\tilde{c}_{i\alpha}^U + \tilde{a}_{i\alpha}^U\tilde{c}_{i\alpha}^L\right)\mathrm{d}\alpha - w_i(p_i + t_i)
\end{aligned}
\tag{25}
$$

Proposition 2. *Under the decentralized SC structure and when government tariffs are imposed on retail price, the optimal retail price of each SC can be obtained as follows:*

$$
p_i^*\left(t_i, t_j, w_i, w_j\right) = B_i + \frac{2}{4 - E\left[\tilde{d}\right]^2}(w_i) + \frac{E\left[\tilde{d}\right]}{4 - E\left[\tilde{d}\right]^2}(w_j)
\tag{26}
$$

where, $B_i = \dfrac{E\left[2\tilde{a}_i + \tilde{d}\tilde{a}_j\right] - \left(E\left[\tilde{d}\right]^2 - 2\right)t_i + E\left[\tilde{d}\right]t_j}{4 - E\left[\tilde{d}\right]^2}.$ *$i, j = g, r;\ i \neq j$*

Using $p_i^*(t_i, t_j w_i, w_j)$, the manufacturer's profit functions can be updated, and their optimal wholesale price is provided in Proposition 3.

Proposition 3. *Under the decentralized SC structure and when government tariffs are imposed on retail price, the manufacturer's optimal wholesale price can be obtained as follows:*

$$w_i^*(t_i, t_j) = C_i + C_1 t_i + C_2 t_j; \quad i, j = g, r; \quad i \neq j \tag{27}$$

where,
$$C_i = \left(E\left[\left(2\tilde{d}^4 - 8\tilde{d}^2 + 8\right)\tilde{c}_i \right] - E\left[\left(\tilde{d}^3 - 2\tilde{d}\right)\tilde{c}_j \right] - E\left[\left(-2\tilde{d}^3 + 6\tilde{d}\right)\tilde{a}_j \right] + E\left[\left(-3\tilde{d}^2 + 8\right)\tilde{a}_i \right] \right) /$$
$$\left(E\left[4\tilde{d}^4 - 17\tilde{d}^2 + 16 \right] \right)$$
$$C_1 = E\left[-5\tilde{d}^4 - 2\tilde{d}^3 + 25\tilde{d}^2 + 4\tilde{d} - 24 \right] / E\left[4\tilde{d}^4 - 17\tilde{d}^2 + 16 \right] \; and$$
$$C_2 = E\left[2\tilde{d}^5 + 2\tilde{d}^4 - 2\tilde{d}^3 + 14\tilde{d} \right] / E\left[4\tilde{d}^4 - 17\tilde{d}^2 + 16 \right]$$

Replacing $w_i^*(t_i, t_j)$ in the government's objective functions (28)–(38), the model can be formulated as follows:

$$Max_{t_i,t_j} E\left[G\tilde{N}R(p_i, p_j, t_i, t_j, w_i, w_j) \right] = E\left[\sum_{i \in \{g,r\}} t_i \tilde{q}_i(p_i, p_j, t_i, t_j) \right] \tag{28}$$

$$Min_{t_i,t_j} E\left[E\tilde{I}s(p_i, p_j, t_i, t_j, w_i, w_j) \right] = E\left[\sum_{i \in \{g,r\}} \theta_i \tilde{q}_i(p_i, p_j, t_i, t_j) \right] \tag{29}$$

s.t.

$$G\tilde{N}R(p_i, p_j, t_i, t_j, w_i, w_j) \geq F \tag{30}$$

$$E\tilde{I}s(p_i, p_j, t_i, t_j, w_i, w_j) \leq E \tag{31}$$

$$\tilde{\pi}_g(p_i, p_j, t_i, t_j, w_i, w_j) \geq \tilde{L}_g \tag{32}$$

$$\tilde{\pi}_r(p_i, p_j, t_i, t_j, w_i, w_j) \geq \tilde{L}_r \tag{33}$$

$$\tilde{\pi}_{Mg}(p_i, p_j, t_i, t_j, w_i, w_j) \geq L_{Mg} \tag{34}$$

$$\tilde{\pi}_{Mr}(p_i, p_j, t_i, t_j, w_i, w_j) \geq L_{Mr} \tag{35}$$

$$\tilde{\pi}_{Rg}(p_i, p_j, t_i, t_j, w_i, w_j) \geq L_{Rg} \tag{36}$$

$$\tilde{\pi}_{Rr}(p_i, p_j, t_i, t_j, w_i, w_j) \geq L_{Rr} \tag{37}$$

$$t_i \geq 0; i = r, g \tag{38}$$

As in Scenario 1, we assume that the government's objectives are maximizing the expected revenue and minimizing the environmental impacts of SCs. Solving the model, the best solutions for government tariffs can be obtained. The game-theoretical model in (28)–(38) can be converted to a single objective model, and after using α-cut, w_g^* and w_r^* can be obtained. For the sake of brevity, details of the solution process are omitted.

4.3. Government Tariff on Production Quantity under a Centralized SC (Scenario 3)

In this scenario, all SC decisions are made under a centralized structure, and the environmental tariff is imposed on the production quantity. The government is the game leader and determines a production quantity threshold (Q_g and Q_r), above which the SCs receive a government subsidy (x_g, x_r with a positive value). Otherwise, the SCs will incur a penalty fee (x_g, x_r with a negative value). In response to the government's decision, the centralized SCs (i.e., the followers) choose their retail price (p_g^* and p_r^*). Figure 4 illustrates the schematic of decision-making under this scenario.
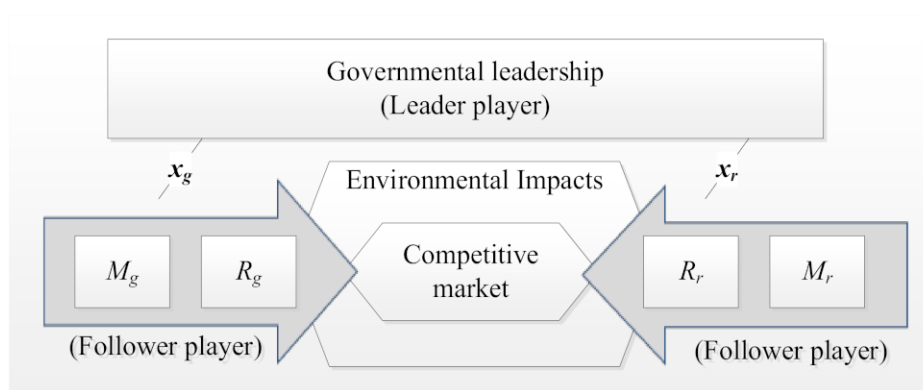
Figure 4. Centralized SC competition under government policy on production quantities.

Under Scenario 3, the market demand for product type i ($i = g, r$) can be defined as follows:

$$\widetilde{q}_i(p_i, p_j) = \widetilde{a}_i - p_i + \widetilde{d}p_j; \quad i, j = g, r; \quad i \neq j \tag{39}$$

The expected profit of centralized SCs can be derived as follows:

$$E\left[\widetilde{\pi}_g(p_i, p_j, x_i, x_j)\right] = E\left[(p_g - \widetilde{c}_g)\widetilde{q}_g(p_g, p_r) + x_g(\widetilde{q}_g(p_g, p_r) - Q_g)\right] \tag{40}$$

$$E\left[\widetilde{\pi}_r(p_i, p_j, x_i, x_j)\right] = E\left[(p_r - \widetilde{c}_r)\widetilde{q}_r(p_g, p_r) - x_r(\widetilde{q}_r(p_g, p_r) - Q_r)\right] \tag{41}$$

Using α-optimistic and α-pessimistic, the expected profit of GSC and RSC can be derived as follows:

$$
\begin{aligned}
2E\left[\widetilde{\pi}_g(p_i, p_j, x_i, x_j)\right] = {} & (p_g + x_g) \int \left(a_{g\alpha}^L + a_{g\alpha}^U\right) d\alpha + p_r(x_g - p_g) \int \left(d_\alpha^L + d_\alpha^U\right) d\alpha \\
& - p_r \int \left(d_\alpha^U c_{g\alpha}^L + d_\alpha^L c_{g\alpha}^U\right) d\alpha - \int \left(a_\alpha^U c_{g\alpha}^L + a_\alpha^L c_{g\alpha}^U\right) d\alpha + p_g \int \left(c_{g\alpha}^L + c_{g\alpha}^U\right) d\alpha \\
& - 2p_g^2 - 2x_g Q_g - 2x_g p_g
\end{aligned}
\tag{42}
$$

$$
\begin{aligned}
2E\left[\widetilde{\pi}_r(p_i, p_j, x_i, x_j)\right] = {} & (p_r + x_r) \int \left(a_{r\alpha}^L + a_{r\alpha}^U\right) d\alpha + p_g(p_r - x_r) \int \left(d_\alpha^L + d_\alpha^U\right) d\alpha + \\
& 2x_r Q_r - \int \left(a_{\alpha r}^U c_{r\alpha}^L + a_{r\alpha}^L c_{r\alpha}^U\right) d\alpha + p_r \int \left(c_{r\alpha}^L + c_{r\alpha}^U\right) d\alpha - p_g \int \left(d_\alpha^U c_{r\alpha}^L + d_\alpha^L c_{r\alpha}^U\right) d\alpha - 2p_r^2 + \\
& 2x_r p_r
\end{aligned}
\tag{43}
$$

Proposition 4. *Under the centralized SC structure and when government tariffs are imposed on the production quantity of SCs, the manufacturer's optimal wholesale price can be obtained as follows:*

$$p_g^*(x_i, x_j) = D_{1g} - \frac{2}{4 - E\left[\widetilde{d}\right]^2} x_g + \frac{E\left[\widetilde{d}\right]}{4 - E\left[\widetilde{d}\right]^2} x_r \tag{44}$$

$$p_r^*(x_i, x_j) = D_{2r} - \frac{E\left[\widetilde{d}\right]}{4 - E\left[\widetilde{d}\right]^2} x_g + \frac{2}{4 - E\left[\widetilde{d}\right]^2} x_r \tag{45}$$

where, $D_{1g} = \dfrac{2E\left[\widetilde{a}_g + \widetilde{c}_g\right] + E\left[\widetilde{a}_r \widetilde{d} + \widetilde{c}_r \widetilde{d}\right]}{4 - E\left[\widetilde{d}\right]^2}$ *and* $D_{2r} = \dfrac{2E\left[\widetilde{a}_r + \widetilde{c}_r\right] + E\left[\widetilde{a}_g \widetilde{d} + \widetilde{c}_g \widetilde{d}\right]}{4 - E\left[\widetilde{d}\right]^2}$

Similar to Scenario 1, the government's objectives maximize the *GNR* and minimize the *EIs*.

$$Max_{x_i, x_j} E\left[\widetilde{GNR}(p_i, p_j, x_i, x_j)\right] = E\left[\sum_{i \in \{g, r\}} x_i \widetilde{q}_i(p_i, p_j, x_i, x_j)\right] \tag{46}$$

$$Min_{x_i,x_j} E\left[E\widetilde{I}s\left(p_i, p_j, x_i, x_j\right)\right] = E\left[\sum_{i\in\{g,r\}} \theta_i \widetilde{q}_i\left(p_i, p_j, x_i, x_j\right)\right] \tag{47}$$

s.t.

$$G\widetilde{N}R\left(p_i, p_j, x_i, x_j\right) \geq F \tag{48}$$

$$E\widetilde{I}s\left(p_i, p_j, x_i, x_j\right) \leq E \tag{49}$$

$$\widetilde{\pi}_g\left(p_i, p_j, x_i, x_j\right) \geq \widetilde{L}_g \tag{50}$$

$$\widetilde{\pi}_r\left(p_i, p_j, x_i, x_j\right) \geq \widetilde{L}_r \tag{51}$$

$$x_g, x_r \geq 0 \tag{52}$$

Substituting $p_g^*\left(x_i, x_j\right)$ and $p_r^*\left(x_i, x_j\right)$, which were presented in Proposition 4, into the above model (46)–(52), the government's optimal decision variables can be obtained.

4.4. Government Tariff on Production Quantity under a Decentralized SC (Scenario 4)

In this scenario, SC decisions are made independently under a decentralized structure, and the environmental policy of the government is applied to the production quantity of the SCs. Figure 5 depicts a three-player game model (among the government, manufacturers, and retailers) with a hierarchical power structure.
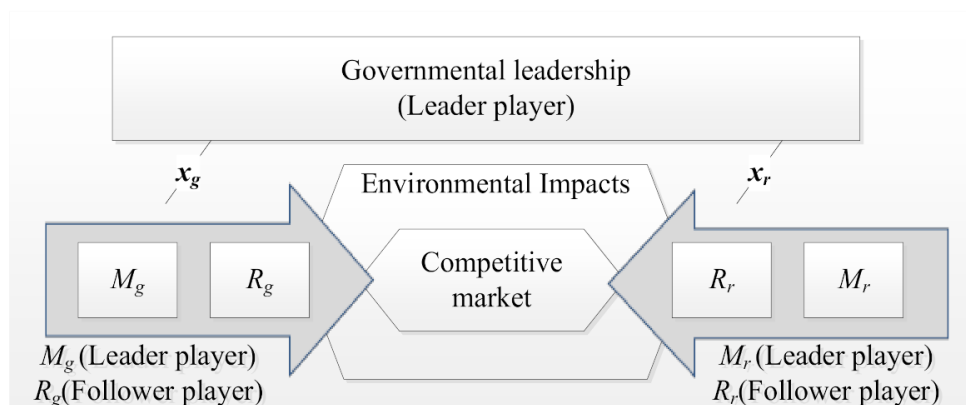

Figure 5. The schematic of SCs in a decentralized structure under governmental tariffs.

In response to the government's policies (i.e., x_g and x_r which can be positive or negative values), the expected profit of retailers and manufacturers (green and regular) in SCs are derived in Equations (53)–(55):

$$E\left[\widetilde{\pi}_{Ri}\left(p_i, p_j, x_i, x_j, w_i, w_j\right)\right] = E[(p_i - w_i)\widetilde{q}_i] = \frac{p_i - w_i}{2}\int\left(a_{i\alpha}^L + a_{i\alpha}^U\right)d\alpha +$$
$$\frac{p_j(p_i - w_i)}{2}\int\left(d_\alpha^L + d_\alpha^U\right)d\alpha - p_i(p_i - w_i); i, j = g, r; i \neq j \tag{53}$$

The expected profit of green and regular manufactures can be derived as follows:

$$E\left[\widetilde{\pi}_{Mg}\left(p_g, p_r, x_g, x_r, w_g, w_r\right)\right] = \frac{x_g + w_g}{2}$$
$$\int\left(a_{g\alpha}^L + a_{g\alpha}^U\right)d\alpha + \frac{p_r(x_g + w_g) + p_g + x_r}{2}\int\left(d_\alpha^L + d_\alpha^U\right)d\alpha +$$
$$\frac{p_g}{2}\int\left(c_{g\alpha}^L + c_{g\alpha}^U\right)d\alpha - \frac{1}{2}\int\left(a_{\alpha g}^U c_{g\alpha}^L + a_{g\alpha}^L c_{g\alpha}^U\right)d\alpha - p_r \tag{54}$$
$$\int\left(d_\alpha^U c_{g\alpha}^L + d_\alpha^L c_{g\alpha}^U\right)d\alpha - w_g p_g - x_g\left(p_g - Q_g\right)$$

$$E\left[\widetilde{\pi}_{Mr}\left(p_g, p_r, x_g, x_r, w_g, w_r\right)\right] = \frac{w_r - x_r}{2} \int \left(a_{r\alpha}^L + a_{r\alpha}^U\right) d\alpha + \frac{p_g w_r}{2} \int \left(d_\alpha^L + d_\alpha^U\right) d\alpha - Q_r x_r - p_r(w_r + x_r) - \frac{1}{2} \int \left(a_{\alpha r}^U c_{r\alpha}^L + a_{r\alpha}^L c_{r\alpha}^U\right) d\alpha + p_r \int \frac{1}{2} \left(c_{r\alpha}^L + c_{r\alpha}^U\right) d\alpha - p_g \int \frac{1}{2} \left(d_\alpha^U c_{r\alpha}^L + d_\alpha^L c_{r\alpha}^U\right) d\alpha \tag{55}$$

Proposition 5. *Under the decentralized SC structure and when government tariffs are imposed on production quantity of SCs, the optimal retail price of each SC can be derived as follows:*

$$p_i^*\left(x_i, x_j, w_i, w_j\right) = H_i + \frac{2}{1 - E\left[4\widetilde{d}^2\right]} w_i + \frac{E\left[\widetilde{d}\right]}{4 - E\left[\widetilde{d}\right]^2} w_j; \quad i, j = g, r; \quad i \neq j \tag{56}$$

where

$H_i = \frac{E\left[2\widetilde{a}_i + \widetilde{d}\widetilde{a}_j\right]}{1 - E\left[4\widetilde{d}^2\right]}.$

After obtaining $p_i^*\left(t_i, t_j, w_i, w_j\right)$ for each SC, the manufacturers' optimal wholesale prices are computed by Proposition 6.

Proposition 6. *Under the decentralized SC structure and when government tariffs are imposed on the production quantity of SCs, the manufacturer's optimal wholesale price can be obtained as follows:*

$$w_g^*\left(x_g, x_r\right) = \frac{E\left[\widetilde{d}^4\right](2x_g + 4) + E\left[\widetilde{d}^3\right]\left(2E[\widetilde{a}_r] + 4E[\widetilde{c}_g] + E[\widetilde{c}_r] + 4\right) + E\left[\widetilde{d}^2\right]\left(3E[\widetilde{a}_g] + 4E[\widetilde{c}_g] - 8x_g - 8\right)}{4E\left[\widetilde{d}^4\right] - 17E\left[\widetilde{d}^2\right] + 16} + \frac{-E\left[\widetilde{d}\right]\left(6E[\widetilde{a}_r] + 8E[\widetilde{c}_g] + 2E[\widetilde{c}_r] - 2x_r + 8\right) + 8\left(x_g - E[\widetilde{a}_g] - E[\widetilde{c}_g]\right)}{4E\left[\widetilde{d}^4\right] - 17E\left[\widetilde{d}^2\right] + 16}. \tag{57}$$

$$w_r^*\left(x_g, x_r\right) = \frac{2E\left[\widetilde{d}^4\right]E[\widetilde{c}_r] + E\left[\widetilde{d}^3\right]\left(-3E[\widetilde{a}_r] + 2E[\widetilde{c}_g] - 8E[\widetilde{c}_r] + 2\right) + E\left[\widetilde{d}^2\right]\left(2 - 3E[\widetilde{a}_r] + 2E[\widetilde{c}_g] - 8E[\widetilde{c}_r] + 8x_r\right)}{4E\left[\widetilde{d}^4\right] - 17E\left[\widetilde{d}^2\right] + 16} + \frac{E\left[\widetilde{d}\right]\left(6E[\widetilde{a}_g] + 2E[\widetilde{c}_g] - 2x_g\right) + 8\left(-x_r + E[\widetilde{a}_r] + E[\widetilde{c}_r]\right)}{4E\left[\widetilde{d}^4\right] - 17E\left[\widetilde{d}^2\right] + 16} \tag{58}$$

After obtaining the retailers' and the manufacturers' best response solutions, the government's model can be formulated as follows:

$$Max_{x_i, x_j} E\left[G\widetilde{N}R\left(p_i, p_j, x_i, x_j\right)\right] = E\left[\sum_{i,j=g,r} x_i \widetilde{q}_i\left(p_i, p_j\right)\right] \tag{59}$$

$$Min_{x_i, x_j} E\left[E\widetilde{I}s\left(p_i, p_j, x_i, x_j\right)\right] = E\left[\sum_{i,j=g,r} \theta_i \widetilde{q}_i\left(p_i, p_j\right)\right] \tag{60}$$

s.t.

$$G\widetilde{N}R\left(p_i, p_j, x_i, x_j\right) \geq F \tag{61}$$

$$E\widetilde{I}s\left(p_i, p_j, x_i, x_j\right) \leq E \tag{62}$$

$$\widetilde{\pi}_g\left(p_i, p_j, w_i, w_j, x_i, x_j\right) \geq \widetilde{L}_g \tag{63}$$

$$\widetilde{\pi}_r\left(p_i, p_j, w_i, w_j, x_i, x_j\right) \geq \widetilde{L}_r \tag{64}$$

$$\widetilde{\pi}_{Mg}\left(p_i, p_j, w_i, w_j, x_i, x_j\right) \geq L_{Mg} \tag{65}$$

$$\widetilde{\pi}_{Mr}\left(p_i, p_j, w_i, w_j, x_i, x_j\right) \geq L_{Mr} \tag{66}$$

$$\widetilde{\pi}_{Rg}\left(p_i, p_j, w_i, w_j, x_i, x_j\right) \geq L_{Rg} \tag{67}$$

$$\widetilde{\pi}_{Rr}\left(p_i, p_j, w_i, w_j, x_i, x_j\right) \geq L_{Rr} \tag{68}$$

$$x_g, x_r \geq 0 \qquad (69)$$

Substituting p_g^*, p_r^*, w_g^*, and w_r^* (i.e., the best response strategies of decentralized SCs), presented in Propositions 5 and 6, into the government's model in (59)–(69), the government's decision variables (x_g^* and x_r^*) can be obtained. To this end, as in Scenario 1, the model can be converted to a single objective using the α-cut method.

4.5. The Proposed Methodology for Decision-Making under Ambiguity

We now describe different steps of the developed methodology that can be used by policy makers in real policy making environments.

Step 1: Specify a key product. The key product is considered a critical product for society when its resultant pollution and environmental footprint are above a certain threshold and require special control regulations and intervention by the government.

Step 2: Identify the key rival SCs that produce and offer green and regular types of the selected product in Step 1. These SCs are leading representatives of green and regular products in the market. The design policy can be imposed on the representative SCs and applied for other SCs with some modifications and adjustments.

Step 3: Evaluate the financial dimensions of members of rival SCs and the environmental impacts of their products in society. In ambiguous environments, key parameter values can be estimated based on the highest and lowest possible values of the parameters and by using triangular or trapezoidal fuzzy numbers.

Step 4: Determine the policy type and identify the structure of the SCs. The model scenario can be determined based on the adopted policy and structure of the SCs (Figure 1).

Step 5: Determine the control parameters of the corresponding policy. The parameters such as the minimum government net income, maximum environmental impact, and lowest reserved profit for SCs and their members should be specified using local or international standards, the opinions of industry experts, and official documentation and regulations. The confidence level (α) should also be determined.

Step 6: Solve the fuzzy mathematical models of government. Given the selected scenario, the corresponding model of government (Sections 4.1–4.4) must be solved.

Step 7: Evaluate the obtained results and perform sensitivity analysis. Once results are obtained, sensitivity analysis on key parameters must be performed to further characterize the alternative solutions for the adopted policy. If the obtained values are not desirable, go to Step 4 and modify the control parameters or policy type.

5. Computational Study and Discussion

In this section, we conduct a numerical study to explain theoretical findings, examine the model properties, and compare the SC members' optimal solutions under different scenarios. Our numerical study is inspired by the Canadian government's exemplary program that promotes sustainable development goals.

Off-road vehicles and mobile equipment are known as major sources of air pollution and greenhouse gas emissions in Canada. To reduce the pollution and address the public concerns, the Canadian government has been encouraging a paradigm shift among industries and public to adopt more environmentally friendly transportation options, with the reframing of the transportation infrastructure system set as the cornerstone of their future actions (https://bit.ly/3qlzvGc). The government goals include reducing national greenhouse gas emissions by 40% by 2030 and by 80% by 2050, respectively. Table 3 depicts the relationship of the trapezoidal fuzzy variables with their linguistic expressions, which are used as fuzzy estimations in our models.

Table 3. Relationship between triangular fuzzy variables and their linguistic expressions.

Parameter	Linguistic Expression	Trapezoidal Fuzzy Variables
$\widetilde{a}_g$	High	(10.5 11 13 13.5)
	Medium	(9 10 11 12)
	Small	(7 8 8.5 10)
$\widetilde{a}_r$	High	(10 12 12.5 14)
	Medium	(8.5 9.5 10 12)
	Small	(7 8 9 10)
$\widetilde{c}_g$	High	(6 6.5 7.5 9)
	Medium	(4.5 6 6.5 8)
	Low	(3 5 6 7)
$\widetilde{c}_r$	High	(4 5.5 6.5 7)
	Medium	(3 4 4.25 4.75)
	Low	(2.5 3 3.5 4.25)
$\widetilde{L}_g$	High	(8.5 10 11.5 12.5)
	Medium	(8 9.5 11 11.5)
	Low	(6 7 7.5 8)
$\widetilde{L}_r$	High	(8 9.5 10.5 12)
	Medium	(7 8 8.5 9)
	Low	(6 6.5 7 8)
$\widetilde{d}$	Very sensitive	(0.5 0.6 0.8 0.9)
	Sensitive	(0.4 0.48 0.57 0.7)
	Not very sensitive	(0.08 0.11 0.26 0.35)
$\widetilde{L}_{Mg}$	High	(7.5 8.5 9 10)
	Medium	(7 7.5 8.5 9)
	Low	(6.5 7.25 7.5 8.5)
$\widetilde{L}_{Mr}$	High	(7 8 8.5 10)
	Medium	(7.5 8 9 9.5)
	Low	(6.5 7 7.5 8)
$\widetilde{L}_{Rg}$	High	(1 1.25 2 2.5)
	Medium	(1 1.5 2.5 3)
	Low	(1 1.25 1.5 2)
$\widetilde{L}_{Rr}$	High	(2.5 3 4 4.5)
	Medium	(2 2.5 3.5 4)
	Low	(1.5 2 2.5 3)

The following fuzzy linguistic variables are considered to test the fuzzy parameters: green market scale: high; regular market scale: medium; green manufacturing cost: high; regular manufacturing cost: low; GSC reservation profit: low; RSC reservation profit: high; sustainability coefficient: not very sensitive; reservation profit of manufacturers and retailers in each SC: medium.

From Table 3, we have: $\widetilde{a}_g$ = (10.5 11 13 13.5), $\widetilde{a}_r$ = (8.5 9.5 10 12), $\widetilde{c}_g$ = (6 6.5 7.5 9), $\widetilde{c}_r$ = (2.5 3 3.5 4.25), $\widetilde{L}_g$ = (6 7 7.5 9), $\widetilde{L}_r$ = (8 9.5 10.5 12), $\widetilde{d}$ = (0.08 0.11 0.26 0.35). The values of the nonfuzzy input parameters are: E=12, F=150, θ_g=1, θ_r=2, Q_g=40, Q_r=11, and $\omega_{k1} = \omega_{k2} = \omega_{k3} = \omega_{k4} = \omega_{k5} = \omega_{k6} = 0.167$. Note the expected value of the fuzzy numbers were adopted from Jiménez et al. [51].

The impact of α-cuts on the expected profit of SCs in different scenarios is illustrated in Figure 6a–d. Figure 6a shows the impact of α-cut on the value of the decision variables.

(a) **Scenario 1**

(b) **Scenario 2**

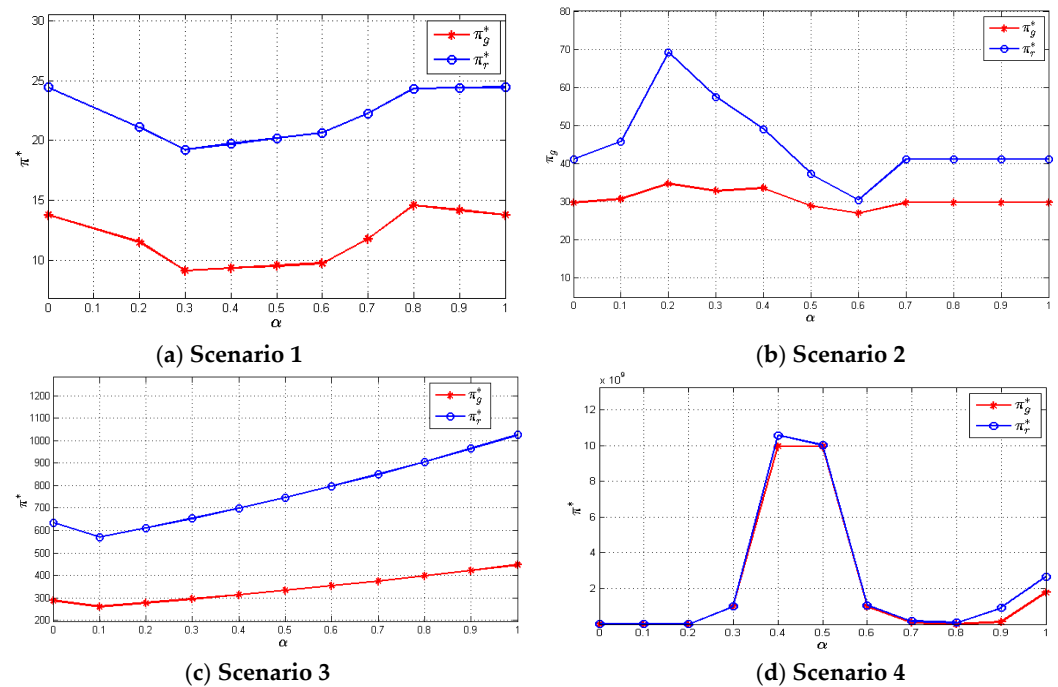(c) **Scenario 3**

(d) **Scenario 4**

Figure 6. Impact of α-cuts on the expected profit of SCs in different scenarios.

Comparing the two centralized and decentralized structures Figure 6b,d illustrate more benefit obtained by decentralized structures than a centralized one under the same conditions. In addition, in the decentralized structure, when the government's policies are based on production quantity, the expected total benefit for GSC and RSC is approximately similar.

Figure 7a,b summarize the result of sensitivity analysis that was conducted based on the changes in *GNR* and *EIs* under different α-cuts. The impacts of *F* and *E* on the government's objectives are illustrated in Figure 8a,b.

Our results reveal that, by choosing an appropriate level of confidence (α-cut), managers can make a balance between reducing information ambiguity and their SC costs under different strategies (Figure 6 As reducing information ambiguity requires extra effort and carries additional costs, the preferred strategy is highly dependent on the manager's optimism and pessimism in decision-making ($0 \leq \alpha \leq 1$). However, considering fuzzy numbers to represent information ambiguity leads to a more flexible solution space, and hence, does not necessarily increase the model complexity and solution time, especially for smaller sized problems.
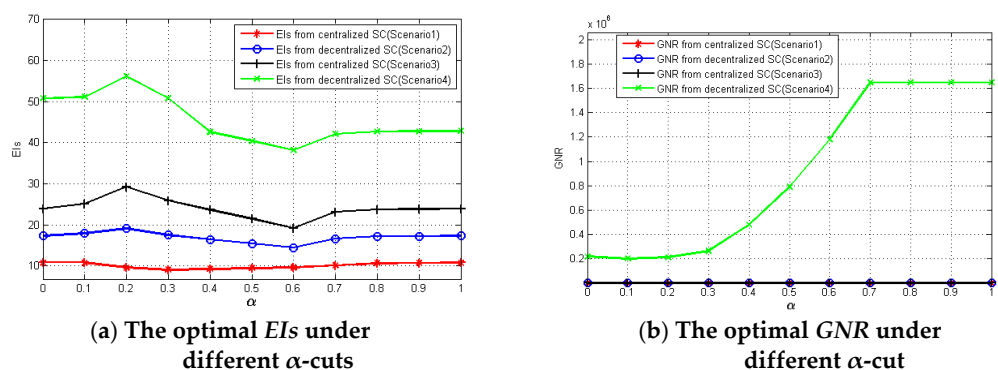

(a) **The optimal *EIs* under different α-cuts**

(b) **The optimal *GNR* under different α-cut**

Figure 7. Impact of α-cuts on the government's objectives.

(a) **The optimal *GNR* vs. the minimum net revenue**　　　　(b) **The optimal *EIs* vs. the maximum environmental impact**
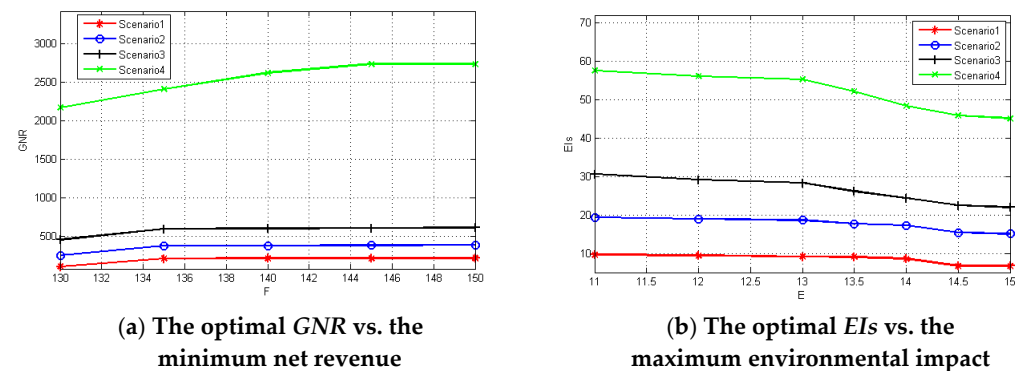
Figure 8. Impact of *F* and *E* on the government's objectives.

6. Conclusions

Motivated by the growing concern regarding environmental issues, this study examined the impact of government intervention on the price and production quantity of two competing SCs (i.e., green and non-green). Considering both centralized and decentralized SC structures, a fuzzy game theoretical model was developed to capture the impact of information ambiguity on the competing game players' decisions. In this environment, we provided a step-by-step procedure for analyzing the government's policy making and examining the competing SCs' decision-making behavior. The main results of our study are as follows:

- Despite challenges, our results revealed that it is critical to incorporate information ambiguity in real-world policy making environments in which SCs' decisions are highly influenced by the fuzzy parameters.
- Regardless of the government's policy, a decentralized structure always leads to better results compared to a decentralized setting. However, taking governmental intervention into account, a green SC's manufacturer has more incentive to produce and offer green products to the shared market. Moreover, strategy intentions and the leader's attitudes toward information ambiguity strongly influence these results.
- The proposed model was optimized according to different levels of α-cut. Hence, choosing an appropriate level of confidence (α-cut), managers would be able to strike a balance between efforts needed to lower information ambiguity and the SC costs associated with different environmental intervention strategies.
- When government policies are focused on production quantities, a higher *GNR* can be obtained. Thus, when evaluating environmental policies for competing SCs, it would be more effective for governments to focus on the production quantity rather than price under the same conditions.

Like any fuzzy multi-objective optimization problem, our results were highly dependent on the decision-maker's personal beliefs. So, the results may vary in different environments depending on the decision-maker's attitude towards information ambiguity and the dynamics of environmental policy making ecosystem. Some possible directions for future research can be proposed. For instance, considering a multi-player or multi-product model could result in selecting different intervention strategies with different combinations of tariffs and subsidies. The presented model can be generalized by adding more fuzzy variables and/or employing other fuzzy programming approaches. Following the mainstream research on SC and logistics risk management [53–57], the developed models in this paper can be extended to incorporate and address both risk and ambiguity.

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Appendix A

Proof of Proposition 1. p_g and p_r are independent variables of each chain's profit function. Hence, using Equation (2), we have:

$$\frac{\partial E\left[\tilde{\pi}_i\left(p_i, p_j, t_i, t_j\right)\right]}{\partial p_i} = 0 \rightarrow -2p_i\left(t_i, t_j\right) + p_j\left(t_i, t_j\right) \int_0^1 1/2\left(\tilde{d}_\alpha^L + \tilde{d}_\alpha^U\right)\mathrm{d}\alpha - t_i +$$

$$1/2\int_0^1\left[\left(\tilde{a}_{i\alpha}^L + \tilde{a}_{i\alpha}^U\right) + \left(\tilde{c}_{i\alpha}^L + \tilde{c}_{i\alpha}^U\right)\right]\mathrm{d}\alpha + \tag{A1}$$

$$t_j\left[\int_0^1 1/2\left(\left(\tilde{d}_\alpha^L + \tilde{d}_\alpha^U\right)\mathrm{d}\alpha\right)\right]^2 = 0; i,j = g,r; i \neq j$$

After simplification, the optimum price of each SC can be obtained as follows:

$$p_i^*\left(t_i, t_j\right) = A_i + \frac{E\left[\tilde{d}\right]^2 - 2}{4 - E\left[\tilde{d}\right]^2}t_i + \frac{E\left[\tilde{d}\right]}{4 - E\left[\tilde{d}\right]^2}t_j; i,j = g,r; i \neq j \tag{A2}$$

where, $A_i = \frac{E\left[2\tilde{a}_i + 2\tilde{c}_j + \tilde{d}\tilde{a}_j + \tilde{d}\tilde{c}_i\right]}{4 - E\left[\tilde{d}\right]^2}$ □

Proof of Proposition 2. Under a decentralized structure in Scenario 2, the expected profit of SCs' members should be calculated separately. The expected profit of retailer i(see Equation (24)) can be calculated as:

$$E\left[\tilde{\pi}_{Ri}\left(p_i, p_j, t_i, t_j, \quad w_i, w_j\right)\right] = E\left[(p_i - w_i)\tilde{q}_i\right]$$
$$= E\left[(p_i - w_i)\left(\tilde{a}_i - (p_i + t_i) + \tilde{d}\left(p_j + t_j\right)\right)\right]$$

using α-optimistic and α-pessimistic value, we have:

$$E\left[\tilde{\pi}_{Ri}\left(p_i, p_j, t_i, t_j, \quad w_i, w_j\right)\right]$$
$$= (p_i - w_i)\int_0^1 \frac{1}{2}\left(\left(\tilde{a}_{i\alpha}^L + \tilde{a}_{i\alpha}^U\right)\right)\mathrm{d}\alpha - (p_i - w_i)(p_i + t_i) \tag{A3}$$
$$+ (p_i - w_i)\left(p_j + t_j\right)E\left[\tilde{d}\right]$$

As in the proof of Proposition 1, considering $\frac{\partial E\left[\widetilde{\pi}_{Ri}\left(p_i,p_j,t_i,t_j,w_i,w_j\right)\right]}{\partial p_i}=0$, we have:

$$-2p_i(t_i,t_j,w_i,w_j) \quad +p_j(t_i,t_j,w_i,w_j)\int_0^1 \frac{1}{2}\left(\widetilde{d}_\alpha^L + \widetilde{d}_\alpha^U\right)d\alpha - t_i$$
$$+t_j\left[\int_0^1 \frac{1}{2}\left(\widetilde{d}_\alpha^L + \widetilde{d}_\alpha^U\right)d\alpha\right]^2 + \frac{1}{2}\int_0^1 \left(\widetilde{a}_{i\alpha}^L + \widetilde{a}_{i\alpha}^U\right)d\alpha + w_i = 0 \tag{A4}$$

As a result, the optimum retail price of each SC can be obtained as follows:

$$p_i^*(t_i,t_j,w_i,w_j) = B_i + \frac{2}{4-E\left[\widetilde{d}\right]^2}(w_i) + \frac{E\left[\widetilde{d}\right]}{4-E\left[\widetilde{d}\right]^2}(w_j) \tag{A5}$$

where, $B_i = \frac{E\left[2\widetilde{a}_i + \widetilde{d}\widetilde{a}_j\right] - \left(E\left[\widetilde{d}\right]^2 - 2\right)t_i + E\left[\widetilde{d}\right]t_j}{4-E\left[\widetilde{d}\right]^2}; i,j = g,r; i \neq j$ $\square$

Proof of Proposition 3. Like the proof provided for Proposition 2, the expected profit of the SCs' members should be calculated separately. The expected profit of manufacturer i (see Equation (25)) can be calculated as:

$$
\begin{aligned}
E\left[\widetilde{\pi}_{Mi}\left(p_i,p_j,t_i,t_j,\right.\right. & \left.\left. w_i,w_j\right)\right]\\
&= E[(w_i - \widetilde{c}_i)\widetilde{q}_i]\\
&= E\left[(w_i - \widetilde{c}_i)\left(\widetilde{a}_i - (p_i^* + t_i) + \widetilde{d}\left(p_j^* + t_j\right)\right)\right]\\
&= E[\widetilde{a}_i] - w_i(p_i^* + t_i) + w_i\left(p_j^* + t_j\right)E\left[\widetilde{d}\right] - E[\widetilde{c}_i\widetilde{a}_i]\\
&\quad + (p_i^* + t_i)E[\widetilde{c}_i] - \left(p_j^* + t_j\right)E\left[\widetilde{c}_i\widetilde{d}\right]\\
&= w_i\int_0^1 \frac{1}{2}\left(\widetilde{a}_{i\alpha}^L + \widetilde{a}_{i\alpha}^U\right)d\alpha - w_i(p_i^* + t_i)\\
&\quad + w_i\left(p_j^* + t_j\right)\int_0^1 \frac{1}{2}\left(\widetilde{d}_\alpha^L + \widetilde{d}_\alpha^U\right)d\alpha\\
&\quad + (p_i^* + t_i)\frac{1}{2}\int_0^1 \left[\left(\widetilde{c}_{i\alpha}^L + \widetilde{c}_{i\alpha}^U\right)\right]d\alpha\\
&\quad - \left(p_j^* + t_j\right)\int_0^1 \frac{1}{2}\left(\widetilde{d}_\alpha^L\widetilde{c}_{i\alpha}^U + \widetilde{d}_\alpha^U\widetilde{c}_{i\alpha}^L\right)d\alpha
\end{aligned} \tag{A6}
$$

After substituting the values obtained for $(p_i^*(t_i,t_j,w_i,w_j))$ in the proof of Proposition 2 into Equation (6), we have:

$$
\begin{aligned}
E\left[\widetilde{\pi}_{Mi}\left(p_i,p_j,t_i,t_j,\right.\right. & \left.\left. w_i,w_j\right)\right]\\
&= E[(w_i - \widetilde{c}_i)(\widetilde{a}_i\\
&\quad - \left(B_i + \frac{2}{4-E\left[\widetilde{d}\right]^2}(w_i) + \frac{E\left[\widetilde{d}\right]}{4-E\left[\widetilde{d}\right]^2}(w_j) + t_i\right)\\
&\quad + \widetilde{d}\left(B_j + \frac{2}{4-E\left[\widetilde{d}\right]^2}(w_j) + \frac{E\left[\widetilde{d}\right]}{4-E\left[\widetilde{d}\right]^2}(w_i) + t_j\right))]
\end{aligned} \tag{A7}
$$

Therefore, from $\frac{\partial E\left[\widetilde{\pi}_{Mi}\left(t_i,t_j,w_i,w_j\right)\right]}{\partial p_i}=0$, the manufacturer's optimal wholesale price can be obtained as follows: $w_i^*(t_i,t_j) = C_i + C_1t_i + C_2t_j$
where

$$C_i = \left(E\left[\left(2\widetilde{d}^4 - 8\widetilde{d}^2 + 8\right)\widetilde{c}_i\right] - E\left[\left(\widetilde{d}^3 - 2\widetilde{d}\right)\widetilde{c}_j\right] - E\left[\left(-2\widetilde{d}^3 + 6\widetilde{d}\right)\widetilde{a}_j\right] + E\left[\left(-3\widetilde{d}^2 + 8\right)\widetilde{a}_i\right]\right)/$$
$$\left(E\left[4\widetilde{d}^4 - 17\widetilde{d}^2 + 16\right]\right)$$

$$C_1 = E\left[-5\tilde{d}^4 - 2\tilde{d}^3 + 25\tilde{d}^2 + 4\tilde{d} - 24\right] / E\left[4\tilde{d}^4 - 17\tilde{d}^2 + 16\right]$$

and

$$C_2 = \frac{E\left[2\tilde{d}^5 + 2\tilde{d}^4 - 2\tilde{d}^3 + 14\tilde{d}\right]}{E\left[4\tilde{d}^4 - 17\tilde{d}^2 + 16\right]}$$

□

Proof of Proposition 4. Under the centralized SC structure, the expected profit of each SC can be derived as follows (Equations (40)–(41)):

Profit for GSC: $E\left[\tilde{\pi}_g\left(p_g, p_r, x_g, x_r\right)\right] = E\left[\left(p_g - \tilde{c}_g\right)\tilde{q}_g\left(p_g, p_r\right) + x_g\left(\tilde{q}_g\left(p_g, p_r\right) - Q_g\right)\right]$

Profit for RSC: $E\left[\tilde{\pi}_r\left(p_g, p_r, x_g, x_r\right)\right] = E\left[\left(p_r - \tilde{c}_r\right)\tilde{q}_r\left(p_g, p_r\right) - x_r\left(\tilde{q}_r\left(p_g, p_r\right) - Q_r\right)\right]$

To find the manufacturer's optimal wholesale price, we derive each of the equations related to variables that have control. Thus, using $\frac{\partial E\left[\tilde{\pi}_g\left(p_g, p_r, x_g, x_r\right)\right]}{\partial p_g} = 0$ and $\frac{\partial E\left[\tilde{\pi}_r\left(p_g, p_r, x_g, x_r\right)\right]}{\partial p_r} = 0$, we have:

$$\frac{1}{2}\int_0^1\left[\left(\tilde{c}_{g\alpha}^L + \tilde{c}_{g\alpha}^U\right) + \left(\tilde{a}_{g\alpha}^L + \tilde{a}_{g\alpha}^U\right)\right]d\alpha - 2p_g(x_g, x_r) - x_g + p_r(x_g, x_r)\int_0^1 \frac{1}{2}\left(\tilde{d}_\alpha^L + \tilde{d}_\alpha^U\right)d\alpha = 0 \quad \text{(A8)}$$

and

$$\frac{1}{2}\int_0^1\left[\left(\tilde{c}_{r\alpha}^L + \tilde{c}_{r\alpha}^U\right) + \left(\tilde{a}_{r\alpha}^L + \tilde{a}_{r\alpha}^U\right)\right]d\alpha - 2p_r(x_g, x_r) + x_r + p_g(x_g, x_r)\int_0^1 \frac{1}{2}\left(\tilde{d}_\alpha^L + \tilde{d}_\alpha^U\right)d\alpha = 0 \quad \text{(A9)}$$

After some simplifications, the optimal wholesale price can be found as follows:

$$p_g^*(x_i, x_j) = D_{1g} - \frac{2}{4 - E\left[\tilde{d}\right]^2}x_g + \frac{E\left[\tilde{d}\right]}{4 - E\left[\tilde{d}\right]^2}x_r$$

$$p_r^*(x_i, x_j) = D_{2r} - \frac{E\left[\tilde{d}\right]}{4 - E\left[\tilde{d}\right]^2}x_g + \frac{2}{4 - E\left[\tilde{d}\right]^2}x_r$$

$$(A10)$$

where, $D_{1g} = \frac{2E\left[\tilde{a}_g + \tilde{c}_g\right] + E\left[\tilde{a}_r\tilde{d} + \tilde{c}_r\tilde{d}\right]}{4 - E\left[\tilde{d}\right]^2}$ and $D_{2r} = \frac{2E\left[\tilde{a}_r + \tilde{c}_r\right] + E\left[\tilde{a}_g\tilde{d} + \tilde{c}_g\tilde{d}\right]}{4 - E\left[\tilde{d}\right]^2}$ □

Proof of Proposition 5. As in previous proofs, from Equation (53), we have:

$$\frac{\partial E\left[\tilde{\pi}_{Ri}\left(p_i, p_j, x_i, x_j, w_i, w_j\right)\right]}{\partial p_i} = 0$$

After simplifications, we have:

$$E[\tilde{a}_i] - 2p_i + p_j E\left[\tilde{d}\right] + w_i = 0 \quad \text{(A11)}$$

Therefore:

$$p_i^*(x_i, x_j, w_i, w_j) = H_i + \frac{2}{1 - E\left[4\tilde{d}^2\right]}w_i + \frac{E\left[\tilde{d}\right]}{4 - E\left[\tilde{d}\right]^2}w_j$$

where $H_i = \frac{E\left[2\tilde{a}_i + \tilde{d}\tilde{a}_j\right]}{1 - E\left[4\tilde{d}^2\right]}$ □

Proof of Proposition 6. After finding $p_i^*\left(x_i, x_j, w_i, w_j\right)$ in Proposition 5 and replacing them in Equations (54)–(55), we have two equations with variables x_g and x_r.

By solving those two equations, we have Equations (57)–(58) for $w_g^*(x_g, x_r)$ and $w_r^*(x_g, x_r)$.

$$
\begin{aligned}
w_g^*(x_g, x_r) = \\
\frac{E\left[\tilde{d}^4\right](2x_g+4)+E\left[\tilde{d}^3\right]\left(2E[\tilde{a}_r]+4E[\tilde{c}_g]+E[\tilde{c}_r]+4\right)+E\left[\tilde{d}^2\right]\left(3E[\tilde{a}_g]+4E[\tilde{c}_g]-8x_g-8\right)}{4E\left[\tilde{d}^4\right]-17E\left[\tilde{d}^2\right]+16} \\
+\frac{-E\left[\tilde{d}\right]\left(6E[\tilde{a}_r]+8E[\tilde{c}_g]+2E[\tilde{c}_r]-2x_r+8\right)+8\left(x_g-E[\tilde{a}_g]-E[\tilde{c}_g]\right)}{4E\left[\tilde{d}^4\right]-17E\left[\tilde{d}^2\right]+16}
\end{aligned}
\tag{A12}
$$

$$
\begin{aligned}
w_r^*(x_g, x_r) = \\
\frac{2E\left[\tilde{d}^4\right]E[\tilde{c}_r]+E\left[\tilde{d}^3\right]\left(-3E[\tilde{a}_r]+2E[\tilde{c}_g]-8E[\tilde{c}_r]+2\right)+E\left[\tilde{d}^2\right]\left(2-3E[\tilde{a}_r]+2E[\tilde{c}_g]-8E[\tilde{c}_r]+8x_r\right)}{4E\left[\tilde{d}^4\right]-17E\left[\tilde{d}^2\right]+16} \\
+\frac{E\left[\tilde{d}\right]\left(6E[\tilde{a}_g]+2E[\tilde{c}_g]-2x_g\right)+8\left(-x_r+E[\tilde{a}_r]+E[\tilde{c}_r]\right)}{4E\left[\tilde{d}^4\right]-17E\left[\tilde{d}^2\right]+16}
\end{aligned}
\tag{A13}
$$

□

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