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▶ To cite this version:

A. Hafezalkotob, S. Arisian, Raziyeh Reza-Gharehbagh, L. Nersesian. Joint Impact of CSR Policy and Market Structure on Environmental Sustainability in Supply Chains. Computers & Industrial Engineering, 2023, 185 (109654), 10.1016/j.cie.2023.109654 . hal-04435514

HAL Id: hal-04435514

https://normandie-univ.hal.science/hal-04435514

Submitted on 26 Apr 2024

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Computers & Industrial Engineering 185 (2023) 109654

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Joint impact of CSR policy and market structure on environmental sustainability in supply chains

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ARTICLE INFO

Keywords:
Environmental sustainability
Smart manufacturing
Sustainable supply chain
Corporate social responsibility
Government intervention
Market Structure

ABSTRACT

The integration of Corporate Social Responsibility (CSR) and Smart Manufacturing (SM) has emerged as a promising strategy for addressing carbon emissions. Governments can play a crucial role in promoting sustainable practices and environmental sustainability by implementing targeted policies and regulations. In this study, we examine the sustainability performance of competing smart supply chains that offer substitutable products under different CSR regulatory policies. Specifically, we investigate five CSR policies: *Deregulation*, *Direct Tariff on Market*, *Sustainability Penalty and Credits*, *Direct Limitation on Sustainability*, and *Government Cooperative Sustainability Efforts*. Using a game theoretical framework, we model and analyze the effectiveness of each CSR policy within monopoly and oligopoly market structures. Our results uncover the importance of considering the synergistic effects of market structure and CSR when designing sustainability strategies for policymakers and supply chain managers. For instance, the *Direct Tariff on Market* policy in the monopoly market is shown to be the preferred regulatory approach as it effectively enhances both supply chain profitability and environmental sustainability. Furthermore, the *Direct Tariff on Market* policy in the oligopoly market, along with the *Direct Limitation on Sustainability* policy in the monopoly market, results in a greater market share of sustainable products. Understanding these dynamics enables policymakers to make informed decisions that maximize the environmental benefits of CSR practices, considering varying market structures.

1. Introduction

In recent years, the detrimental effects of carbon emissions on the environment have become increasingly apparent, leading to a growing emphasis on the decarbonization of global supply chains (GSCs). The manufacturing sector is a significant contributor to carbon emissions and addressing this issue is crucial in the fight against climate change (Aoun et al., 2021). To address this, governments have implemented various measures, such as stricter regulations and emission targets, to minimize carbon emissions. One promising solution is the implementation of Smart Manufacturing (SM) (Javadi et al., 2019; Bueno et al., 2020; Arunmozhi et al., 2022), which involves integrating various subsystems for data exchange to conserve energy and reduce emissions throughout the entire supply chain. Moreover, many countries have also included carbon neutrality programs and other climate change initiatives in their Corporate Social Responsibility (CSR) agendas with the goal of reducing greenhouse gas emissions.

CSR has become an increasingly important concept in the business world as it holds businesses and organizations accountable for the impact their actions have on society and the environment (European Commission, 2011). To evaluate, measure, and promote overall CSR performance, several international standards and guidelines exist. For instance, ISO 26000 provides recommendations and principles for conducting operations in a way that considers the impact on society and the environment, emphasizing ethical behavior, accountability, and transparency.[1] In addition, the European Commission has outlined a plan for EU enterprises to achieve the objectives of the Europe 2020 strategy for sustainable development, which is relevant to the broader competitive social market economy (Asian et al., 2019; European Commission, 2011). Furthermore, the Conference of the Parties (COP21) agreement requires participating governments to act towards reducing greenhouse emissions, adapting to climate change, providing finance, and

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[1] https://www.c2es.org/international/negotiations/cop21-paris/summary.

https://doi.org/10.1016/j.cie.2023.109654

Available online 29 September 2023
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promoting transparency. These international plans and commitments should be translated into effective CSR regulatory policies that can be applied in both conventional and SM settings in accordance with the COP21 agreement, with governments implementing policies to reach specific targets.

Innovative companies have recently come to realize the potential of SM in reducing carbon emissions and are taking CSR considerations more seriously considering regulatory policies (Hsueh, 2014). Implementing a well-thought-out CSR strategy can provide SM players with various advantages such as better risk management, cost reduction, access to funding, stronger customer relationships, improved employee management and greater capacity for innovation, thus making them more competitive in the market (European Commission, 2011). Governments assess the overall performance of supply chains (SCs) and are increasingly promoting smart sustainable supply chains (SSCs) by incorporating CSR regulatory policies as part of decisions related to social responsibility and competitiveness (Reza-Gharehbagh et al., 2021; Reza-Gharehbagh et al., 2022).

Regulatory policies are typically composed of a set of incentives and disincentives that can influence producer and consumer behavior and are geared towards specific financial, social, and decarbonization and other environmental goals. These regulatory policies are typically classified as price-based, quantity-based, or hybrid policies (Hepburn, 2006). The use of price-based instruments, such as taxation and subsidies, is a common method employed by governments to influence consumer and producer behavior. Quantity-based regulations set limits on the quantity of smart production or the quantity of released hazardous waste or pollutants, or both. Hybrid policies incorporate a combination of these regulatory strategies in various ways.

Price-based, quantity-based, and hybrid policies each have their own advantages and disadvantages, and governments should take a holistic and systematic approach to economic, environmental, and social aspects when devising regulatory policies (Hafezalkotob, 2018). These policies can impact various factors such as the government's budget and potential revenue, inter-governmental agreements and international considerations, the effects on producers' profits and consumers, business efficiency under uncertainty, the level of business intervention, and overall regulatory feasibility and flexibility (Hepburn, 2006; Hafezalkotob, 2018). Therefore, selecting an appropriate policy to guide an effective regulatory plan is a crucial and critical phase of CSR policy-making process.

Despite the vast literature on CSR, to the best of our knowledge, previous studies have not quantitatively evaluated the various CSR regulatory policies and their impact on SSC interactions. To address this gap, we develop mathematical programming models of two competing SSCs under different government CSR regulatory policies in both monopoly and oligopoly markets. We formulate and evaluate five CSR regulatory policies for government intervention, namely Deregulation (Drg.), Direct Tariff on Market (DTM), Sustainability Penalty and Sustainability Credits (SP&SC), Direct Limitation on Sustainability (DLS), and Government Cooperative Sustainability Efforts (GCSE).[2] The DTM policy is applied as a price-based governmental instrument for SSCs selling substitutable products. The SP&SC, DLS, and GCSE are sustainability-based instruments that can be implemented for SSCs. Under the SP&SC policies, the government imposes penalties or awards sustainability credits based on predetermined thresholds. Restrictive regulatory policies, such as the DLS policy, involve direct limitations on the sustainability levels of SCs. Under the GCSE regulatory framework, the government and SC players jointly work towards achieving sustainability goals, with the government contributing to increasing the sustainability level of these SCs.

After formulating the aforementioned regulatory policies, we use Stackelberg game theory models to determine equilibrium strategies of SSCs under each policy. Subsequently, we develop 10 mathematical programming models and analyze them. Through this, we aim to address the following three research questions:

How can governments strategically formulate CSR regulatory policies to effectively foster sustainable practices in SSCs across various market structures?

How do SSCs adapt to the various CSR regulatory policies in monopoly and oligopoly market structures, and what are the implications of these responses on the overall sustainability and competitiveness of the competing SSCs?

What is the cost-benefit trade-off of implementing various CSR policies on the sustainability and profitability of SSCs across different market structures?

By considering the interplay between market dynamics and government intervention, this paper aims to address the aforementioned questions and provide insights into how different market structures influence the effectiveness of CSR regulatory policies in achieving SC profitability and sustainable outcomes simultaneously.

The remainder of this paper is organized as follows: Section 2 reviews related literature, highlights the research gap, and presents the contributions of this study. In Section 3, we first establish game models of SSCs under different CSR regulatory policies and then present the mathematical models of the regulatory agency. Section 4 provides our computational study and draws important managerial insights. Finally, Section 5 presents the research conclusion and suggests potential avenues for future research.

2. Literature review

This paper delves into the intersection of the literature surrounding the competition of sustainable SCs, CSR, and government regulatory policies. We, therefore, review related research in the following subsections.

2.1. Competition in sustainable supply chains

In consumer theory, substitutable products are defined as similar or comparable items that can be used interchangeably by consumers, thus, an increase in the consumption of one product may lead to a decrease in the consumption of the other product (Asian et al., 2020).

Recently, the significance of the green aspects of substitutable products as a purchasing criterion for consumers has been widely studied. Li and Li (2014) developed a game model for the sustainability of products in two competitive SSCs. Hafezalkotob (2015) examined the market equilibrium between substitutable green and regular products and assessed the impact of government financial intervention on the competition between two SCs that produce these products. Zhang et al. (2015) focused on the competition between environmental and traditional products that are substitutable in a market. Utilizing a multi-product newsvendor model, they examined how consumer environmental consciousness affects the coordination quality of a two-stage SC. Basiri and Heydari (2017) analyzed a two-stage SC that produces and sells non-green (traditional) and green products that are substitutable. The optimal retail price and green quality were determined under decentralized, integrated, and collaborative SC structures. Lastly, Rahimi et al. (2021) examined the competition between a green and non-green SC under two government intervention policies, production quantity and seller price, to enhance sustainability. The results showed that with government intervention under these two scenarios, players achieved higher revenue. Despite the findings suggesting that players earned more revenue with government intervention, none of these studies have investigated the behavior of SSCs that trade in interchangeable products in a monopoly or oligopoly market arrangement

[2] For brevity, these policies will be referred to as Drg., DTM, SP&SC, DLS, and GCSE throughout the remainder of this paper.

while adhering to government CSR regulatory guidelines.

In real-world markets, multiple SCs often exist, making the analysis of cooperation and competition among them a complex task (Yang et al., 2017). With increasing consumer awareness of environmental issues, the cooperation and competition of green supply chains (GSCs) has become a prevalent research area (Hafezalkotob, 2017a; Yang et al., 2017). Additionally, the sustainability dimensions of SCs, including corporate social responsibility (CSR), have garnered attention from both researchers and practitioners (Brandenburg et al., 2014). Bhardwaj (2016) found that implementing an appropriate sustainability policy in an SC can enhance its competitiveness and performance. Thus, sustainability should be considered a crucial aspect when evaluating cooperation and competition among SCs.

Leo et al. (2012) used Stackelberg game models to investigate the impact of consumer environmental awareness on the competitiveness of SCs. They discovered that consumer environmental awareness leads to an increase in eco-friendly manufacturing practices. Li and Li (2014) developed a mathematical model to analyze the equilibrium solutions for the sustainability levels of two rival SSCs under three different chain structures. They also examined cooperative scenarios between manufacturers and suppliers to adjust the wholesale price in each SSC using the Nash bargaining method.

Some researchers have studied the effects of government sustainable development objectives on the competitiveness of SCs. For example, Hafezalkotob (2017b) used a Stackelberg game model to investigate the impact of a government tariff mechanism on foreign and domestic SCs in terms of sustainable development objectives. Zhang and Wang (2017) used a similar game theory model to examine the effects of a government-imposed tariff on rival SCs, one of which was environmentally friendly and the other not. They analyzed the impact of CSR and government environmental protection strategies on the equilibrium between members of SCs. Hafezalkotob (2017a) also used a leader–follower game model to study the effects of government financial intervention on competition, cooperation, and coopetition between government and green SCs (GSCs) in the context of energy-saving efforts. Additionally, Rodríguez-González et al. (2022) examined the impact of environmentally conscious strategies on SCs, utilizing the Mexican automotive industry as a case study, and demonstrated how these strategies enhance sustainability. Liu et al. (2022) developed a pricing model that incorporates the behaviors of the players to analyze the competition between sustainable and non-sustainable SCs under centralized and decentralized structures. The results of the study revealed that players achieved higher profits under a centralized structure.

The previous studies have examined competition among SSCs under various conditions, such as centralized and decentralized structures, and information sharing (Li et al., 2021a; Li et al., 2023). However, none of these studies analyzed the impact of government intervention on SC competition in oligopoly and monopoly markets, taking into account various CSR regulatory policies.

2.2. Sustainability and CSR in SCM

The study of sustainability and CSR issues in SCs has become an interdisciplinary and critical aspect of SC evaluation. Seuring and Müller (2008), Kogg and Mont (2012), Quarshie et al. (2016), and Feng et al. (2017) have conducted systematic qualitative literature reviews on the progress of CSR and sustainability in SCM. SSCM encompasses the triple bottom line of social, environmental, and economic aspects of SC performance (Seuring and Müller, 2008). Conversely, CSR incorporates economic, social, and environmental considerations of all stakeholders and encompasses legal, economic, ethical, and discretionary responsibilities (Quarshie et al., 2016). After conducting a comprehensive literature review, Quarshie et al. (2016) found that the interpretations of sustainability and CSR significantly overlap, making it difficult to clearly define the boundaries between them.

Li et al. (2018) studied the relationship between green supply chain management (GSCM) pressures, practices, and performance in Chinese firms, considering the moderating effect of quick response technology and found that market and export pressures had a significant impact on GSCM practices. Arena et al. (2018) examined the incentives of evolving CSR strategies to meet the expectations of a wide range of a company's stakeholders. Rotter et al. (2013) studied the political barriers to implementing effective and efficient CSR programs in global SCs. Quarshie et al. (2016) found that theoretical and conceptual research heavily dominate this field, while practical and modeling analysis is important to fill research gaps. Li et al. (2021) investigated the relationship between corporate social responsibility and idiosyncratic risk in the context of artificial intelligence and operational efficiency and found a U-shaped relationship between CSR and IR and provided management recommendations.

Several studies have applied quantitative methods to evaluate SCs from a CSR perspective. For example, Hsueh (2014, 2015) developed mathematical models to identify optimal CSR investment and revenue sharing in coordination contracts and showed that both CSR performance and profits can be improved by appropriate coordination. Panda and Modak (2016) studied the impact of CSR on profit-sharing decisions in a coordinated SC and found that members favor other members pursuing CSR programs. Ni et al. (2010) and Ni and Li (2012) used game theory to incorporate CSR decisions in a two-stage SC and showed that considering CSR can benefit all members and consumers. Li et al. (2021) examined the interplay between downstream retailers and upstream manufacturers in a decentralized green product SC and found that product greening can yield positive results for firms under certain conditions and that the equilibrium strategy for manufacturers and retailers depends on specific condition. Cheng and Ding (2021) analyzed the impact of CSR on the competition of SCs under different decision-making scenarios, including centralized, decentralized, and combined. Tiwari et al. (2021) examined the negative effects of hypocrisy among firms when promoting CSR. Lastly, Chen et al. (2022) studied the impact of SC finance on CSR and innovation within food SCs.

To bridge the gap in the current literature, this paper proposes five regulatory policies for government intervention to promote CSR programs, which has not yet been thoroughly explored in previous research. Additionally, we conduct a quantifiable assessment and comparison of government policies on CSR regulations and their effects on SSC interactions.

2.3. Government regulatory policies

In many industries, price-based regulatory instruments such as subsidies and taxes are utilized to encourage or discourage green or polluting manufacturing or products. Recent research has examined the effects of these instruments on SCs (Bazan et al., 2015a, 2015b; Guo et al., 2016; Hafezalkotob, 2017a, 2017b, 2015; Heydari et al., 2017; Liu et al., 2017; Madani and Rasti-Barzoki, 2017; Sheu, 2011; Sheu and Chen, 2012; Yang and Xiao, 2017; Zhang and Wang, 2017). However, the use of quantity-based regulatory instruments, such as setting limitations on the quantity of production or hazardous waste, is less common.

Dong et al. (2016) examined the effects of carbon emission regulations on decentralized and centralized SCs. Optimal order quantity and sustainability investments were determined under this regulation. Zhang and Yang (2016) and Yang et al. (2017) evaluated the impact of a cap-and-trade scheme on the competition between two decentralized SCs. Hafezalkotob (2018) analyzed the effects of two government regulatory policies (direct tariffs and tradable permits) on the competition between green and non-green SCs and found that these policies result in varying levels of satisfaction for stakeholders including the government, SCs, consumers, and the environment. Li et al. (2020a) examined the association between green manufacturing firms and their performance in the Chinese fashion industry, with the aim of enhancing environmental awareness and green manufacturing processes. They found a positive relationship between corporate stakeholders and green manufacturing, as well as between green manufacturing and practice performance in Chinese fashion companies. The study suggests enforcing mandatory policies and regulations, encouraging businesses with preferential policies, and improving green manufacturing practices through technology and management advancement.

The energy sector has long been at the forefront of implementing policies and regulations to encourage the production and consumption of green electricity in many developed countries (Hepburn, 2006). For example, Tamás et al. (2010) analyzed the effects of feed-in-tariff and tradable green certificate policies on the equilibrium between non-green and green energy in the UK electricity market, and their impact on social welfare. Xie (2015) examined the pricing and energy-saving decisions of a GSC under government regulations on energy conservation and analyzed the competition and coordination of GSC members when the government sets a threshold for the GSC's energy-saving level. Similarly, Hafezalkotob (2017a) looked at the effects of regulations on pricing and energy-saving decisions in GSCs but proposed a price-based regulatory policy for the competition, cooperation, and coopetition of GSCs. Other industries have also implemented alternative policies to enhance sustainability (Ruan et al., 2022). Taleizadeh et al. (2022) developed a game theoretic model between an SSC and the government and showed that the government's-imposed emission tax improves both environmental and social responsibility. Chen and Ye (2022) investigated government intervention that leads to the formation of oligopolies in order to encourage collaboration among SCs. The results revealed that by creating oligopolies, it is easier to identify the SC member with high pollution emissions and implement appropriate measures to reduce them.

The aforementioned studies fail to analyze the relationship between sustainability and government CSR regulations. This paper provides valuable insights for policy makers and SSC managers by revealing the correlation between government CSR regulations and environmental sustainability.

2.4. Research gap and contributions

Our research aligns with the work of Bhardwaj (2016) and Formentini and Taticchi (2016), who have examined the impact of governance mechanisms on SSCM. In particular, Formentini and Taticchi (2016) conducted a qualitative study of seven case studies, and found that regulatory measures and competitive advantages drive the evolution of corporate sustainability approaches. Our study builds on this research by using quantitative models to analyze the effects of various governance mechanisms on SSC interactions.

To the best of our knowledge, the present study represents one of the pioneering endeavors to quantitatively evaluate and compare the combined influence of various government CSR regulatory policies and market structures on environmental sustainability performance. In particular, this paper makes three significant contributions to the field: (i) We propose five regulatory policies for government intervention to promote CSR programs, which are formulated using Stackelberg game models between government and SSCs. The government's objective function incorporates social utility, including the sustainability levels of SSCs, policy expenditure, and SSC profits. (ii) In the lower level of the Stackelberg game, we model the competition of substitutable products in both monopoly and oligopoly markets. We investigate 10 possible scenarios, considering the impact of the five regulatory policies in two market structures. (iii) We show that, when provided with adequate incentives, SSCs may opt to reassess their profit maximization approach and prioritize sustainability based on CSR and market structure considerations.

3. Problem statement

In this paper, we examine the interactions of SSCs under different government regulatory policies in monopoly and oligopoly markets. Specifically, we consider two substitutable types of products manufactured by SSCs, with a single SSC in the monopoly market and two SSCs in the oligopoly market. Each SSC consists of a smart manufacturer who sets the wholesale price and sustainability level and a retailer who sets the retail price. The government, acting as a regulatory authority (RA), has the power to introduce regulations on CSR policy to influence the sustainability level and product price of SSCs.

The government utilizes price-based and sustainability-based instruments to influence consumer and producer behavior. We focus on the DTM policy as a price-based governmental instrument for SSCs selling substitutable products. Under the SP&SC policies, the government imposes penalties or awards sustainability credits based on predetermined thresholds. Restrictive regulatory policies, such as the DLS policy, involve direct limitations on the sustainability levels of SCs. On the other hand, the GCSE regulatory framework involves collaborative efforts between the government and SC players to achieve sustainability goals, with the government contributing to increasing the sustainability level of these SCs. Our research aims to investigate the impact of these different CSR regulatory policies on the interactions of SSCs under monopoly and oligopoly market structures (Figs. 1 and 2).

It is worth noting that the primary objective of the government is to achieve an effective strategy that increases the total utility and attains a higher market share of sustainable products. Therefore, the determination of the most effective strategy requires a comprehensive comparison and investigation of all the possible scenarios illustrated in Fig. 2.

3.1. Notations and assumptions

Two substitutable product types of SSCs are represented by subscripts i and j $(i,j = 1,2)$. We introduce the following indices, parameters, and notations.

Notations.

i,j the subscript indices for the substitutable product type i $(i,j = 1, 2)$;
k The superscript index for the scenarios.

Parameters:

α_i the baseline for market demand of product type i;
β the demand sensitivity to sustainability level of SSCs;
θ the degree to which the two products are competitive on sustainability;
D_i the least market demand that needs to be satisfied;
d the substitutability coefficient between products, $0 \leqslant d \leqslant 1$;
τ the coefficient of shared sustainability cost between retailer and smart manufacturer;
ρ_M the coefficient denoting the smart manufacturer's inclination to sustainability improvement;
ρ_R the coefficient denoting the retailer's inclination to sustainability improvement;
ρ_G the coefficient denoting the government's inclination to sustainability improvement;
$\underline{u}_R$ the reservation utility of retailer, $\underline{u}_R \geqslant 0$;
$\underline{u}_M$ the reservation utility of smart manufacturer, $\underline{u}_M \geqslant 0$;
$\underline{u}_{R_i}$ the reservation utility of retailer in an oligopoly market, $\underline{u}_{R_i} \geqslant 0$;
$\underline{u}_{M_i}$ the reservation utility of smart manufacturer in an oligopoly market, $\underline{u}_{M_i} \geqslant 0$;

Decision variables:

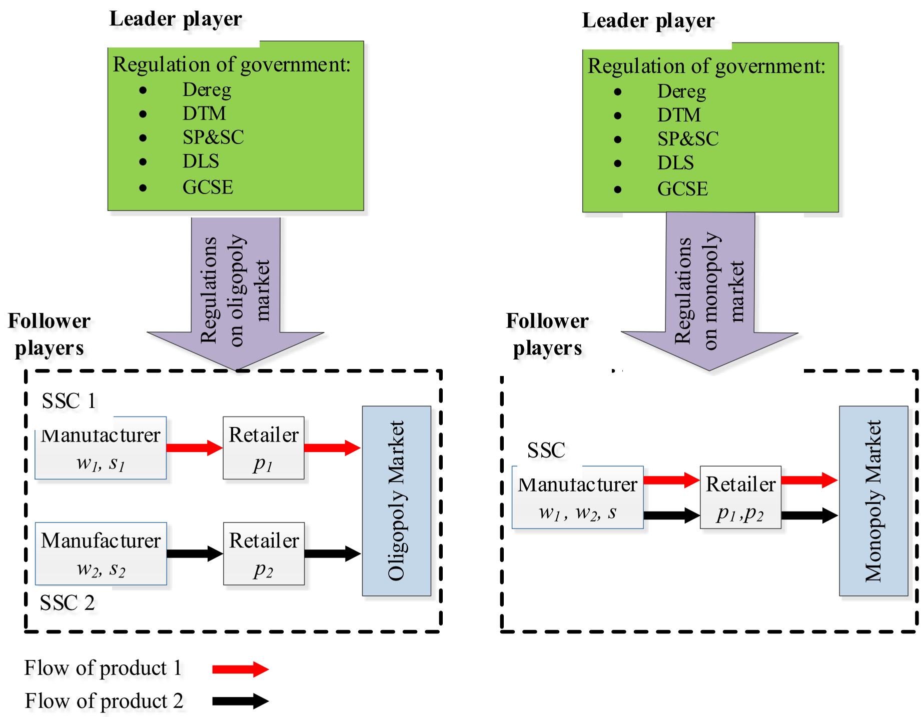


Fig. 1. Regulations on substitutable products of SSCs.

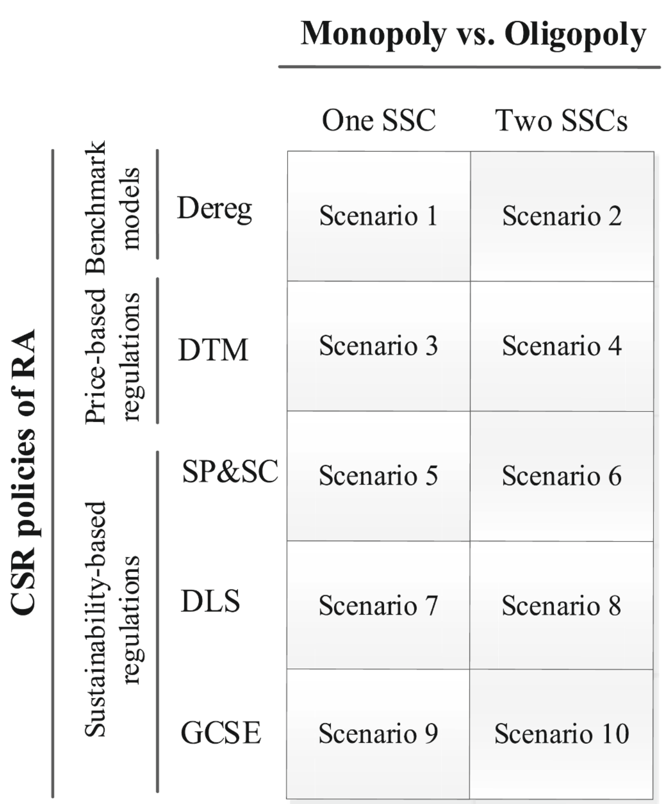


Fig. 2. Regulatory scenarios for the research.

w_i the wholesale price of the product i charged by the smart manufacturer ($w_i \geqslant c_i \geqslant 0$);
p_i the retail price of the product i charged by the retailer ($p_i \geqslant w_i$);
s the sustainability level determined by the smart manufacturer in monopoly market ($s \geqslant 0$);
s_i the sustainability level determined by the smart manufacturer i in oligopoly market ($s_i \geqslant 0$);
t_i the tariff imposed by RA on each unit of product i(under DTM);
s_T the target sustainability level for SCs in monopoly market set by RA (under SP&SC);
s_{T_i} the target sustainability level for SC i in oligopoly market set by RA (under SP&SC);
x the penalty or credit determined by RA on sustainability levels of SSC in monopoly market (under SP&SC);
x_i the penalty or credit determined by RA on sustainability levels of SSC i in oligopoly market (under SP&SC);
s_L the minimum level for SC sustainability in monopoly market set by RA (under DLS);
s_{L_i} the minimum level for SC sustainability i in oligopoly market set by RA (under DLS);
s_g The sustainability level of government for supporting SSC in monopoly market (under GCSE).
s_{g_i} The sustainability level of government for supporting SSC i in an oligopoly market (under GCSE).

In addition, we define the following decision variable vectors $\boldsymbol{w} = (w_1, w_2)$, $\boldsymbol{s} = (s_1, s_2)$, $\boldsymbol{p} = (p_1, p_2)$, $\boldsymbol{t} = (t_1, t_2)$, $\boldsymbol{x} = (x_1, x_2)$, $\boldsymbol{s_L} = (s_{L_1}, s_{L_2})$, and $\boldsymbol{s_g} = (s_{g_1}, s_{g_2})$.

We make the following assumptions throughout the paper:

Assumption 1. All demand and cost parameters are certain and determined in advance. Moreover, the game between RA and SSC is considered under sympatric information (Mahmoudi and Rasti-Barzoki, 2018; Zand and Yaghoubi, 2022).

Assumption 2. Similar to Pakseresht et al. (2020) and He et al. (2007), given the authority of the RA in imposing CSR regulations on industries, the RA is assumed to be the leader player and then the SSC(s), as the follower player(s), adopt(s) the best strategy in response to the RA's decisions. For each CSR regulatory policy, the RA aims to maximize social utility, i.e. the sustainability levels and profits of SSCs, and government net revenue.

Assumption 3. Regarding the demand functions, employed by Lin and Li (2014) and Hafezalkotob (2015), we consider the following demand function for the product i offered by SSC i in an oligopoly market:

$$q_i(\boldsymbol{p},s) = \alpha_i - p_i + dp_j + \beta(s_i - \theta s_j), \quad i = 1,2;\ j = 3-i. \tag{1}$$

in which $\alpha_i(\geqslant 0)$ is the baseline for market demand of the product i, $d(0\leqslant d\leqslant 1)$ represents demand substitutability coefficient between two products, θ $(\geqslant 0)$ is the competition degree of the two products on sustainability levels, and $\beta(\geqslant 0)$ denotes the demand sensitivity to the cumulative effect of sustainability levels of two SSCs. $\beta = 0$ implies exclusive price competition between two SCs (Hafezalkotob (2015)). However, considering a fixed product price (i.e. $\alpha_i - p_i + dp_j = \beta = cte$), the SSC competition model is transformed to chain-to-chain competition on product sustainability by normalizing the demand function (Li and Li (2014)). In addition, the value of α_i means the potential intrinsic demand for products introduced by SSC i, and the larger value α_i implies the SSC i has relative desirability for consumers because of superior quality, brand, image, and position (Hafezalkotob, 2017a).

In a monopoly market, there is one SSC that determines sustainability level s; thus, the demand function for the product i is expressed as:

$$q_i(\boldsymbol{p},s) = \alpha_i - p_i + dp_j + \beta s, \quad i = 1,2;\ j = 3-i. \tag{2}$$

Assumption 4. In the oligopoly market, the cost functions of the smart manufacturer and retailer in SSC i are assumed as follows:

$$C_{M_i} = c_i q_i + f_{M_i} + \tau_i \eta_i s_i^2, \quad i = 1,2;\ j \neq i. \tag{3}$$

$$C_{R_i} = w_i q_i + f_{R_i} + (1-\tau_i)\eta_i s_i^2, \quad i = 1,2;\ j \neq i. \tag{4}$$

The c_i $(c_i\geqslant 0)$ is unit production cost and w_i $(w_i\geqslant 0)$ is unit wholesale price, thus, $c_i q_i$ and $w_i q_i$ represent procurement cost of manufacturer and retailer, respectively (Zand and Yaghoubi, 2022). f_{M_i} and $f_{R_i}(f_{R_i}, f_{M_i}\geqslant 0)$ are manufacturer and retailer fixed costs independent of q_i and s_i, respectively. $\eta_i s_i^2$ $(c_i\geqslant 0)$ implies a variable cost dependent upon s_i which is distributed by τ_i and $1-\tau_i$ coefficients between manufacturer and retailer, respectively (Hafezalkotob, 2018). Consequently, both C_{M_i} and C_{R_i} are increasing and convex functions on s_i. Because both substitutable products are produced by one SSC in the monopoly market, the cost functions of the manufacturer and retailer are transformed as follows:

$$C_M = \sum_{i=1}^{2} c_i q_i + f_M + \tau\eta s^2, \tag{5}$$

$$C_R = \sum_{i=1}^{2} w_i q_i + f_R + (1-\tau)\eta s^2, \tag{6}$$

Assumption 5. Similar to Ni and Li (2012) we define the utility functions of retailer and manufacturer as $u_R = \pi_R + \rho_R s$ and $u_M = \pi_M + \rho_M s$ respectively, in which π_R and π_M are, in turn, profit functions of retailer and manufacturer. These utility functions mean that retailers and manufacturers make a trade-off between profit and CSR aspects of their businesses. $\rho_R = \rho_M = 0$ shows pronounced profit maximization tendency of retailers and manufacturers as for-profit organizations. The larger the coefficient ρ_R and ρ_M, the more CSR behaviour of retailer and manufacturer there will be, such that $\rho_R\to\infty$ and $\rho_M\to\infty$ imply that retailer and manufacturer are non-profit organizations, respectively. It is essential to note that the utility function of each enterprise is calculated as the sum of its profit and its individual CSR behavior, rather than shared or cooperative CSR behavior.

The hierarchical decision-making between RA and SSCs (see Assumption 2) allows us to treat the problem as a Stackelberg game that can be analyzed by backward induction. In this regard, the best response strategies of SSCs for the five given CSR regulatory policies are first computed in Section 3.2. Decision-making models of the RA under the 10 different scenarios are provided in Section 3.3.

3.2. SSC models under different CSR regulatory policies

This section is organized in line with the scenario structure of Fig. 2 in which the Drg. policy option is a cornerstone for other policies. In fact, in Scenarios 1 and 2 Drg. provides the benchmark models for both odd scenarios (monopoly market) and even scenarios (oligopoly market). To distinguish the formulations and optimal values in different scenarios, we use superscripts (1)-(10) for corresponding scenarios.

3.2.1. Drg. Policy as a benchmark model (Scenarios 1–2)

In the monopoly market, the RA does not enforce any regulations on SSCs under Drg. policy (Scenario 1). This scenario is compared to an alternative policy scenario 2 to determine the effect of RA policies on SSCs. Both scenarios serve as benchmarks for the analysis. As per Assumption 5, we assume that SSCs will strive to increase their sustainability level if it results in a positive impact on their profits. Therefore, the utility functions of retailers and manufacturers can be written as

$$u_R^{(1)}(\boldsymbol{p},s,\boldsymbol{w}) = \pi_R^{(1)}(\boldsymbol{p},s,\boldsymbol{w}) + \rho_R s = \sum_{i=1}^{2} p_i q_i(\boldsymbol{p},s) - C_R + \rho_R s; \tag{7}$$

$$u_M^{(1)}(\boldsymbol{p},s,\boldsymbol{w}) = \pi_M^{(1)}(\boldsymbol{p},s,\boldsymbol{w}) + \rho_M s = \sum_{i=1}^{2} w_i q_i(\boldsymbol{p},s) - C_M + \rho_M s; \tag{8}$$

The retailer and manufacturer determine corresponding decisions to maximize their utility functions. Hence, considering demand function (2) and cost functions (5) and (6), the game model through the SSC can be formulated as

$$\max_{\boldsymbol{p}}\ u_R^{(1)}(\boldsymbol{p},s,\boldsymbol{w}) = \sum_{i=1}^{2}(p_i - w_i)(\alpha_i - p_i + dp_j + \beta s) - f_R - (1-\tau)\eta s^2 + \rho_R s; \tag{9}$$

$$\max_{\boldsymbol{w},s}\ u_M^{(1)}(\boldsymbol{p},s,\boldsymbol{w}) = \sum_{i=1}^{2}(w_i - c_i)(\alpha_i - p_i + dp_j + \beta s) - f_M - \tau\eta s^2 + \rho_M s. \tag{10}$$

The following Proposition gives the optimal retail price, wholesale price and sustainability level. Appendix A presents the proofs of all subsequent propositions and corollaries.

Proposition 1. *Under Drg. policy in Scenario 1, if* $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right)-d\right]$*, the optimal values for* $p_i^{(1)}$ *and* $w_i^{(1)}$ *and* $s^{(1)}$ *for an SSC are obtained as follows:*

$$p_i^{(1)} = w_i^{(1)} + m_{R_i}^{(1)}, \tag{11}$$

$$w_i^{(1)} = c_i + m_{M_i}^{(1)}, \tag{12}$$

$$s^{(1)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(1)} + \rho_M V\right] \Big/ 2\eta\tau V, \tag{13}$$

In which $m_{M_i}^{(1)} = \left[E_i^{(1)}B^{(1)} - E_j^{(1)}A^{(1)}\right] \Big/ \left[\left(A^{(1)}\right)^2 - \left(B^{(1)}\right)^2\right]$, $m_{R_i}^{(1)} = \left[2(\alpha_i - w_i^{(1)} + dw_j^{(1)}) + d(\alpha_j - w_j^{(1)} + dw_i^{(1)}) + \beta(2+d)s^{(1)}\right] \Big/ V$, $E_i^{(1)} = 2(\alpha_i - c_i + dc_j) + d(\alpha_j - c_j + dc_i) + \beta(2+d)\rho_M/2\eta\tau$, $A^{(1)} = 2d + \beta^2(2+d)^2/2\eta\tau V$, $B^{(1)} = -2(2-d^2) + \beta^2(2+d)^2/2\eta\tau V$, $V = 4-d^2$, $i =$

$1, 2$, and $j = 3 - i$

For the product i of SSC, $m_{M_i}^{(1)}$ and $m_{R_i}^{(1)}$ represent the unit marginal profits of manufacturer and retailer, respectively. Thus, inequalities $m_{M_i}^{(1)}, m_{R_i}^{(1)} > 0$ ensure that the manufacturing and retailing of the product i are profitable. Substituting $m_{R_i}^{(1)}$ and $m_{M_i}^{(1)}$ into Eqs. (2), (9), and (10) results in $q_i^{(1)} = m_{R_i}^{(1)}$, $u_R^{(1)} = \sum_{i=1}^{2}\left(m_{R_i}^{(1)}\right)^2 - f_R - (1-\tau)\eta\left(s^{(1)}\right)^2 + \rho_R s^{(1)}$, and $u_M^{(1)} = \sum_{i=1}^{2} m_{R_i}^{(1)} m_{M_i}^{(1)} - f_M - \tau\eta\left(s^{(1)}\right)^2 + \rho_M s^{(1)}$ after some simplifications. Condition $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right)-d\right]$ guarantees the concavity of the manufacturer's utility function and states that sustainability improvement should not carry a very low cost for the manufacturer; otherwise the manufacturer excessively increases sustainability, which yields the manufacturer a negative utility.

We now evaluate Drg. policy as it applies to the competition of two SSCs in an oligopoly market (Scenario 2). According to Assumption 5, the utility functions of manufacturers and retailers in SSC i are

$$u_{R_i}^{(2)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}) = \pi_{R_i}^{(2)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}) + \rho_{R_i} s_i = p_i q_i(\boldsymbol{p}, \boldsymbol{s}) - C_{R_i} + \rho_{R_i} s_i; \quad i = 1, 2, \ j = 3 - i, \tag{14}$$

$$u_{M_i}^{(2)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}) = \pi_{M_i}^{(2)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}) + \rho_{M_i} s_i = w_i q_i(\boldsymbol{p}, \boldsymbol{s}) - C_{M_i} + \rho_{M_i} s_i; \quad i = 1, 2, \ j = 3 - i. \tag{15}$$

Considering demand function (1) and cost functions (3) and (4), the retailer and manufacturer in SSC i take corresponding decisions to maximize their utility function, which can be expressed by

$$\max_{p} \ u_{R_i}^{(2)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}) = \left\{ \begin{array}{c} (p_i - w_i)\left[\alpha_i - p_i + dp_j + \beta(s_i - \theta s_j)\right] \\ -f_{R_i} - (1-\tau_i)\eta_i s_i^2 + \rho_{R_i} s_i \end{array} \right\}, \quad i = 1, 2; \ j = 3 - i; \tag{16}$$

$$\max_{w,s} \ u_{M_i}^{(2)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}) = \left\{ \begin{array}{c} (p_i - c_i)\left[\alpha_i - p_i + dp_j + \beta(s_i - \theta s_j)\right] \\ -f_{M_i} - \tau_i \eta_i s_i^2 + \rho_{M_i} s_i \end{array} \right\}, \quad i = 1, 2; \ j = 3 - i. \tag{17}$$

The following proposition gives the optimal retail price, wholesale price and sustainability level of competing SSCs.

Proposition 2. *Under Drg. policy in Scenario 2, if $\eta_i \geqslant \beta^2(2-d\theta)^2/4(2-d^2)$, the optimal values for $p_i^{(2)}$ and $w_i^{(2)}$ and $s^{(2)}$ for SSC i are obtained as follows:*

$$p_i^{(2)} = w_i^{(2)} + m_{R_i}^{(2)}, \tag{18}$$

$$w_i^{(2)} = c_i + m_{M_i}^{(2)}, \tag{19}$$

$$s_i^{(2)} = \left[\beta(2-d\theta)m_{M_i}^{(2)} + \rho_{M_i} V\right] \Big/ 2\eta_i \tau_i V, \tag{20}$$

In which $m_{M_i}^{(2)} = \left[E_i^{(2)} B_j^{(2)} - E_j^{(2)} A_j^{(2)}\right] \Big/ \left[A_i^{(2)} A_j^{(2)} - B_i^{(2)} B_j^{(2)}\right]$, $m_{R_i}^{(2)} = \left\{ \begin{array}{c} 2(\alpha_i - w_i^{(2)} + dw_j^{(2)} + \beta(s_i^{(2)} - \theta s_j^{(2)})) + \\ d(\alpha_j - w_j^{(2)} + dw_i^{(2)} + \beta(s_j^{(2)} - \theta s_i^{(2)})) \end{array} \right\} \Big/ V$, $E_i^{(2)} = 2(\alpha_i - c_i + dc_j) + d(\alpha_j - c_j + dc_i) + \frac{\beta(2-d\theta)\rho_{M_i}}{2\eta_i\tau_i} + \frac{\beta(d-2\theta)\rho_{M_j}}{2\eta_j\tau_j}$, $A_i^{(2)} = d + \beta^2(2-d\theta)(d-2\theta)/2\eta_i\tau_i V$, $B_i^{(2)} = \beta^2(2-d\theta)^2/2\eta_i\tau_i V - 2(2-d^2)$, $i = 1, 2$, and $j = 3 - i$

In SSC i, $m_{M_i}^{(2)}$ and $m_{R_i}^{(2)}$ respectively denote the marginal profit of manufacturer and retailer, which should be positive. Therefore, inequalities $m_{M_i}^{(1)}, m_{R_i}^{(1)} > 0$ ensure that the manufacturing and retailing of the product i in SSC i are profitable, respectively. Substituting $m_{R_i}^{(2)}$ and $m_{M_i}^{(2)}$ into Eqs. (1), (9), and (10) result in $q_i^{(2)} = m_{R_i}^{(2)}$, $u_{R_i}^{(2)} = \left(m_{R_i}^{(2)}\right)^2 - f_{R_i} - \eta_i(1-\tau_i)\left(s_i^{(2)}\right)^2 + \rho_{R_i} s_i^{(2)}$, and $u_{M_i}^{(2)} = m_{R_i}^{(2)} m_{M_i}^{(2)} - f_{M_i} - \eta_i \tau_i \left(s_i^{(2)}\right)^2 + \rho_{M_i} s_i^{(2)}$ after some simplifications. Inequality $\eta_i \geqslant \beta^2(2-d\theta)^2/4(2-d^2)$ ensures the concavity of the manufacturer's utility function.

Propositions 1 and 2 reveal the outcomes of the Stackelberg game model under the Drg. policy, which aims to determine the optimal retailer price, wholesale price for the products, and sustainability level. These findings are crucial for SSCs to adapt to different CSR regulatory policies. From Propositions 1 and 2 we know that an increase in ρ_M improves the sustainability level of the SSC; however, an increase in η reduces the sustainability level of the SSC in both oligopoly and monopoly markets. In addition, the following corollary can be derived from these propositions.

Corollary 1. *A unique equilibrium for price and sustainability level of substitutable products exists in both oligopoly and monopoly markets when there is no regulation. Hence, the market equilibriums in Scenarios 1 and 2 are benchmarks for possible market equilibriums that can be obtained from other regulatory policies (mentioned in Fig. 1).*

3.2.2. DTM policy (Scenarios 3–4)

The DTM policy has gained popularity among governments as an effective means to promote competition among enterprises, reduce their costs, and facilitate the pursuit of their environmental goals. Its application has been demonstrated in various sectors such as power (Matinfard et al., 2022), healthcare, and automobile industries. For instance, Dai et al. (2023) have shown its effectiveness in the production of vaccine and blood bank refrigerators in the health system. Rasti-Barzoki and Moon (2021) have explored its impact on the automobile industry in South Korea. However, enterprises remain concerned about the potential negative impact of DTM on their performance and customer satisfaction, as highlighted by Mu et al. (2021). According to DTM policy, the RA directly levies a tariff $\boldsymbol{t} = (t_1, t_2)$ on the market price of substitutable products in the SSC, causing changes in their prices. Note that t_i is a free decision variable of RA which has positive or negative values (implying a subsidy or tax) per unit of the sold product, respectively. Therefore, the utility functions of the retailer and the smart manufacturer in an SSC under a DTM policy (Scenario 3) are given by

$$\max_{p} \ u_R^{(3)}(\boldsymbol{p}, s, \boldsymbol{w}, \boldsymbol{t}) = \sum_{i=1}^{2}(p_i - w_i)(\alpha_i - (p_i + t_i) + d(p_j + t_j) + \beta s) - f_R - (1-\tau)\eta s^2 + \rho_R s; \tag{21}$$

$$\max_{w,s} \ u_M^{(3)}(\boldsymbol{p}, s, \boldsymbol{w}, \boldsymbol{t}) = \sum_{i=1}^{2}(w_i - c_i)(\alpha_i - (p_i + t_i) + d(p_j + t_j) + \beta s) - f_M - \tau\eta s^2 + \rho_M s. \tag{22}$$

Proposition 3 characterizes the optimal retail price, wholesale price, and sustainability level.

Proposition 3. *Under DTM policy $\boldsymbol{t} = (t_1, t_2)$ in Scenario 3, if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right)-d\right]$, the optimal values for $p_i^{(3)}$ and $w_i^{(3)}$ and $s^{(3)}$ for a SSC are obtained as follows:*

$$p_i^{(3)} = w_i^{(3)} + m_{R_i}^{(3)}, \tag{23}$$

$$w_i^{(3)} = c_i + m_{M_i}^{(3)}, \tag{24}$$

$$s^{(3)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(3)} + \rho_M V\right] \Big/ 2\eta\tau V, \tag{25}$$

In which $m_{M_i}^{(3)} = m_{M_i}^{(1)} - \frac{(2-d^2)B^{(1)} + dA^{(1)}}{\left(A^{(1)}\right)^2 - \left(B^{(1)}\right)^2} t_i + \frac{dB^{(1)} + (2-d^2)A^{(1)}}{\left(A^{(1)}\right)^2 - \left(B^{(1)}\right)^2} t_j$, $m_{R_i}^{(3)} =$

$\frac{2(\alpha_i - w_i^{(3)} + dw_j^{(3)}) + d(\alpha_j - w_j^{(3)} + dw_i^{(3)}) + \beta(2+d)s^{(3)} - (2-d^2)t_i + t_j}{V}$, and $j = 3 - i$

Here $m_{R_i}^{(3)}$ and $m_{M_i}^{(3)}$ are the optimal marginal profit of retailer and manufacturer obtained from the product i under DTM policy; therefore, conditions $m_{R_i}^{(3)}, m_{M_i}^{(3)} > 0$ states profitability of retailing and manufacturing of product i for the SSC. Substituting $m_{R_i}^{(3)}$ and $m_{M_i}^{(3)}$ into Eqs. (2), (21), and (22), we have $q_i^{(3)} = m_{R_i}^{(3)}$, $u_R^{(3)} = \sum_{i=1}^{2}\left(m_{R_i}^{(3)}\right)^2 - f_R - (1-\tau)\eta\left(s^{(3)}\right)^2 + \rho_R s^{(3)}$, and $u_M^{(3)} = \sum_{i=1}^{2} m_{R_i}^{(3)} m_{M_i}^{(3)} - f_M - \tau\eta\left(s^{(3)}\right)^2 + \rho_M s^{(3)}$ after some mathematical simplifications.

In Scenario 4, the DTM policy is imposed on the oligopoly market. Using demand function (1) and cost functions (3) and (4), the game model between members of competing SSCs under influences of tariffs $\boldsymbol{t}$ can be formulated as follows:

$$\max_{\boldsymbol{p}} u_{R_i}^{(4)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{t}) = \left\{ \begin{array}{c} (p_i - w_i)\left[\alpha_i - (p_i + t_i) + d(p_j + t_j) + \beta(s_i - \theta s_j)\right] \\ -f_{R_i} - (1-\tau_i)\eta_i s_i^2 + \rho_{R_i} s_i \end{array} \right\}, i = 1, 2; j = 3 - i; \tag{26}$$

$$\max_{\boldsymbol{w}, \boldsymbol{s}} u_{M_i}^{(4)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{t}) = \left\{ \begin{array}{c} (p_i - c_i)\left[\alpha_i - (p_i + t_i) + d(p_j + t_j) + \beta(s_i - \theta s_j)\right] \\ -f_{M_i} - \tau_i\eta_i s_i^2 + \rho_{M_i} s_i \end{array} \right\}, i = 1, 2;\ j = 3 - i. \tag{27}$$

Proposition 4 characterizes the optimal retail prices, wholesale prices, and sustainability levels of the rival SSCs for given tariffs $\boldsymbol{t}$.

Proposition 4. *Under DTM policy $\boldsymbol{t} = (t_1, t_2)$ in Scenario 4, if $\eta_i \geqslant \beta^2(2 - d\theta)^2 / 4(2 - d^2)$, the optimal values for $p_i^{(4)}$, $w_i^{(4)}$ and $s^{(4)}$ for SSC i are obtained as follows:*

$$p_i^{(4)} = w_i^{(4)} + m_{R_i}^{(4)}, \tag{28}$$

$$w_i^{(4)} = c_i + m_{M_i}^{(4)}, \tag{29}$$

$$s_i^{(4)} = \left[\beta(2 - d\theta) m_{M_i}^{(4)} + \rho_{M_i} V\right] \Big/ 2\eta_i\tau_i V, \tag{30}$$

In which $m_{M_i}^{(4)} = m_{M_i}^{(2)} - \frac{(2-d^2)B_j^{(2)} + dA_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} t_i + \frac{dB_j^{(2)} + (2-d^2)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} t_j$, $m_{R_i}^{(4)} = \frac{\left\{ \begin{array}{c} 2(\alpha_i - w_i^{(4)} + dw_j^{(4)} + \beta(s_i^{(4)} - \theta s_j^{(4)})) \\ +d(\alpha_j - w_j^{(4)} + dw_i^{(4)} + \beta(s_j^{(4)} - \theta s_i^{(4)})) - (2-d^2)t_i + dt_j \end{array} \right\}}{V}$, $i = 1, 2$, and $j = 3 - i$

Propositions 3 and 4 present the Stackelberg game model results under the DTM policy, which aims to obtain the optimal retailer and wholesale prices for products, as well as calculate the sustainability level when the tariff $\boldsymbol{t} = (t_1, t_2)$ is imposed on the SSC. The output of these propositions presents the effect of tariffs on the marginal profits. In SSC i, $m_{M_i}^{(4)}$ and $m_{R_i}^{(4)}$ respectively represent the unit marginal profits of manufacturer and retailer under DTM policy. Thus, the profitability of manufacturing and retailing the products of SSC i are ensured by $m_{M_i}^{(4)}$, $m_{R_i}^{(4)} > 0$, respectively. Substituting $m_{R_i}^{(4)}$ and $m_{M_i}^{(4)}$ into Equations (1), (26), and (27) results in $q_i^{(4)} = m_{R_i}^{(4)}$, $u_{R_i}^{(4)} = \left(m_{R_i}^{(4)}\right)^2 - f_{R_i} - \eta_i(1-\tau_i)\left(s_i^{(4)}\right)^2 + \rho_{R_i} s_i^{(4)}$, and $u_{M_i}^{(4)} = m_{R_i}^{(4)} m_{M_i}^{(4)} - f_{M_i} - \eta_i\tau_i\left(s_i^{(4)}\right)^2 + \rho_{M_i} s_i^{(4)}$ after some simplifications. The following corollary can be derived from Propositions 3 and 4.

Corollary 2. *A unique equilibrium for price and sustainability level of substitutable products exists in both oligopoly and monopoly markets for a given tariff regulation. Recognizing the effect of DTM policy, the RA may orchestrate SSC actions to meet its CSR objectives by adjusting tariffs on retail prices.*

3.2.3. SP&SC policy (Scenarios 5–6)

The SP&SC policy is a mechanism whereby the government assigns a penalty or certificate to an SSC based on its sustainability level (Nersesian et al., 2022, Hafezalkotob, Nersesian, & Fardi, 2023). By awarding certificates, firms are incentivized to improve their sustainability performance to remain above the predetermined threshold set by the RA and to gain extra value. The additional value gained through the certificate encourages SSCs to prioritize sustainable practices and increase their sustainable performance. However, it is important to note that SSCs may face negative consequences in the form of a penalty if they fail to increase their sustainability level.

The RA determines a standard level for the sustainability of SSCs as a threshold s_T. Then, an SSC is granted certificates with price x in proportion to its sustainability level that is higher than the threshold s_{T_i}; otherwise, it is penalized in proportion to its sustainability level that is lower than the threshold s_{T_i}. The extra value $x(s - s_T)$ is distributed between retailer and manufacturer with the proportion of η; thus, the utility functions of retailer and manufacturer in Scenario 5 are formulated as follows:

$$\max_{\boldsymbol{p}} u_R^{(5)}(\boldsymbol{p}, s, \boldsymbol{w}, x, s_T) = \left\{ \begin{array}{c} \sum_{i=1}^{2}(p_i - w_i)(\alpha_i - p_i + dp_j + \beta s) \\ +(1-\tau)x(s - s_T) - f_R - (1-\tau)\eta s^2 + \rho_R s \end{array} \right\}; \tag{31}$$

$$\max_{\boldsymbol{w}, s} u_M^{(5)}(\boldsymbol{p}, s, \boldsymbol{w}, x, s_T) = \left\{ \begin{array}{c} \sum_{i=1}^{2}(w_i - c_i)(\alpha_i - p_i + dp_j + \beta s) \\ +\tau x(s - s_T) - f_M - \tau\eta s^2 + \rho_M s \end{array} \right\}. \tag{32}$$

In Proposition 5, we evaluate the best SSC member response strategies under SP&SC.

Proposition 5. *Under SP&SC policy (x, s_T) in Scenario 5, if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right) - d\right]$, the optimal values $p_i^{(5)}$ and $w_i^{(5)}$ and $s^{(5)}$ for the SSC are given by.*

$$p_i^{(5)} = w_i^{(5)} + m_{R_i}^{(5)}, \tag{33}$$

$$w_i^{(5)} = c_i + m_{M_i}^{(5)}, \tag{34}$$

$$s^{(5)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(5)} + (\rho_M + \tau x)V\right] \Big/ 2\eta\tau V \tag{35}$$

In which

$m_{M_i}^{(5)} = m_{M_i}^{(1)} - \frac{\beta(2+d)}{2\eta\left(A^{(1)} + B^{(1)}\right)} x$, $m_{R_i}^{(5)} = \left\{ \begin{array}{c} 2(\alpha_i - w_i^{(5)} + dw_j^{(5)}) + \\ d(\alpha_j - w_j^{(5)} + dw_i^{(5)}) + \beta(2+d)s^{(5)} \end{array} \right\} \Big/ V$, and $j = 3 - i$

Propositions 5 and 6, consistent with previous propositions, demonstrate the outcome of the Stackelberg game model when applying the SP&SC policy. The objective is to determine the optimal retailer and wholesale prices for products while calculating the sustainability level when (x, s_T) is imposed on the SSC. The results of these propositions reveal the impact of (x, s_T) on marginal profits.

It is noted that $\partial m_{M_i}^{(5)} / \partial x > 0$ and $\partial s^{(5)} / \partial x > 0$ because $A^{(1)} + B^{(1)} < 0$, which means that when the RA employs an SP&SC policy, the marginal profits of the manufacturer and sustainability level of the SSC increases concerning Drg. policy. Under SP&SC, substituting marginal profits of the retailer and manufacturer for the product i (i.e., $m_{R_i}^{(5)}$ and $m_{M_i}^{(5)}$) into Eqs. (2), (31), and (32), the demand quantity, utility of retailer and smart manufacturer are simplified into $q_i^{(5)} = m_{R_i}^{(5)}$, $u_R^{(5)} = \sum_{i=1}^{2}\left(m_{R_i}^{(5)}\right)^2 - f_R + (1-\tau)x(s^{(5)} - s_T) - \eta(1-\tau)\left(s^{(5)}\right)^2 + \rho_R s^{(5)}$, and $u_M^{(5)} = \sum_{i=1}^{2} m_{R_i}^{(5)}$

$m_{M_i}^{(5)} - f_M + \tau x(s^{(5)} - s_T) - \eta\tau\left(s^{(5)}\right)^2 + \rho_M s^{(5)}$.

The oligopoly market under SP&SC is investigated in Scenario 6. Therefore, for the SP&SC policy (x, s_T) regarding competitive SSCs, the game model between the members of SSCs can be expressed as follows:

$$\max_{p} u_{R_i}^{(6)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{x}, s_T) = \left\{ \begin{array}{c} (p_i - w_i)\left[\alpha_i - p_i + dp_j + \beta(s_i - \theta s_j)\right] \\ +(1-\tau_i)x_i(s_i - s_{T_i}) - f_{R_i} - (1-\tau_i)\eta_i s_i^2 + \rho_{R_i} s_i \end{array} \right\}, \; i = 1,2; j = 3 - i; \tag{36}$$

$$\max_{w,s} u_{M_i}^{(6)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{x}, s_T) = \left\{ \begin{array}{c} (w_i - c_i)\left[\alpha_i - p_i + dp_j + \beta(s_i - \theta s_j)\right] \\ +\tau_i x_i(s_i - s_{T_i}) - f_{M_i} - \tau_i\eta_i s_i^2 + \rho_{M_i} s_i \end{array} \right\}, \; i = 1,2; \; j = 3 - i. \tag{37}$$

The following proposition characterizes the best response strategies of retailer and manufacturer in an oligopoly market under a policy of SP&SC.

Proposition 6. *Under SP&SC (x, s_T) in Scenario 8, if $\eta_i \geqslant \beta^2(2 - d\theta)^2/4(2 - d^2)$, the optimal values for $p_i^{(6)}$, $w_i^{(6)}$ and $s_i^{(6)}$ for SSC i are given by.*

$$p_i^{(6)} = w_i^{(6)} + m_{R_i}^{(6)}, \tag{38}$$

$$w_i^{(6)} = c_i + m_{M_i}^{(6)}, \tag{39}$$

$$s_i^{(6)} = \left[\beta(2 - d\theta)m_{M_i}^{(6)} + (\rho_{M_i} + \tau_i x_i)V\right] \Big/ 2\eta_i\tau_i V, \tag{40}$$

in which $m_{M_i}^{(6)} = m_{M_i}^{(2)} + \frac{\beta}{2\eta_i}\frac{(2-d\theta)B_j^{(2)} - (d-2\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}x_i + \frac{\beta}{2\eta_j}\frac{(d-2\theta)B_j^{(2)} - (2-d\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}x_j$, $m_{R_i}^{(6)} = \left\{ \begin{array}{c} 2(\alpha_i - w_i^{(6)} + dw_j^{(6)} + \beta(s_i^{(6)} - \theta s_j^{(6)})) \\ +d(\alpha_j - w_j^{(6)} + dw_i^{(6)} + \beta(s_j^{(6)} - \theta s_i^{(6)})) \end{array} \right\} \Big/ V, i = 1,2,$ and $j = 3 - i$.

Substituting marginal profits of retailer and manufacturer (i.e., $m_{R_i}^{(6)}$ and $m_{M_i}^{(6)}$) into Eqs. (1), (36), and (37), the demand quantity, utility of retailer and manufacturer are simplified into $q_i^{(6)} = m_{R_i}^{(6)}$, $U_{R_i}^{(6)} = \left(m_{R_i}^{(6)}\right)^2 - f_{R_i} + (1-\tau_i)x_i(s_i^{(6)} - s_{T_i}) - \eta_i(1-\tau_i)\left(s_i^{(6)}\right)^2 + \rho_{R_i}s_i^{(6)}$, and $u_{M_i}^{(6)} = m_{R_i}^{(6)}m_{M_i}^{(6)} - f_{M_i} + \tau_i x_i(s_i^{(6)} - s_{T_i}) - \eta_i\tau_i\left(s_i^{(6)}\right)^2 + \rho_{M_i}s_i^{(6)}$. From Propositions 5 and 6, we understand that a unique equilibrium for price and sustainability level of substitutable products exists in both oligopoly and monopoly markets for given (x, s_T). Moreover, the following corollary is derived from these propositions.

Corollary 3. *In SP&SC, the values of $x = (x_1, x_2)$ both oligopoly and monopoly markets directly affect the equilibrium between product and sustainability level(s). However, the threshold s_T only influences the utility function of members of SSCs. Recognizing these effects, the RA may orchestrate SSCs to meet CSR objectives.*

3.2.4. DLS policy (Scenarios 7–8)

The DLS policy is aimed at increasing the sustainability of firms and is considered a useful tool to improve supply chains, such as agricultural supply chain standards in the USA (Waldman and Kerr, 2014). As a sustainability-based policy, the DLS policy directly imposes limitations on the sustainability levels of SSCs. Under this policy, the RA sets a threshold for the minimum sustainability level that SSCs must meet. Consequently, SSCs are obligated to attain an acceptable sustainability level, and any level below the threshold set by the RA is deemed unacceptable.

In Scenario 7, we assume the RA places limitations s_L on the sustainability of SSC in a monopoly market; hence, the problems of the smart manufacturer and retailer can be written as

$$\max_{p} u_R^{(7)}(\boldsymbol{p}, s, \boldsymbol{w}, s_L) = \sum_{i=1}^{2}(p_i - w_i)(\alpha_i - p_i + dp_j + \beta s) - f_R - (1-\tau)\eta s^2 + \rho_R s; \tag{41}$$

$$\max_{w,s} u_M^{(7)}(\boldsymbol{p}, s, \boldsymbol{w}, s_L) = \sum_{i=1}^{2}(w_i - c_i)(\alpha_i - p_i + dp_j + \beta s) - f_M - \tau\eta s^2 + \rho_M s; \tag{42}$$

$$st. \;\; s \geqslant s_L. \tag{43}$$

The best response strategies of SSCs under DLS can be derived from the following proposition.

Proposition 7. *Under DLS policy s_L in Scenario 7, if $\eta \geqslant \beta^2(2 - d)/(2 + d)\left[2\left(2 - d^2\right) - d\right]$ the optimal values $p_i^{(7)}$ and $w_i^{(7)}$ and $s^{(7)}$ can be obtained from the following conditions.*

$$p_i^{(7)} = w_i^{(7)} + m_{R_i}^{(7)}, \tag{44}$$

$$w_i^{(7)} = c_i + m_{M_i}^{(7)}, \tag{45}$$

$$m_{M_i}^{(7)} = m_{M_i}^{(1)} - \lambda\beta(2 + d)/2\eta\tau\left(A^{(1)} + B^{(1)}\right), \tag{46}$$

$$s^{(7)} = \left[\beta(2 + d)\sum_{i=1}^{2}m_{M_i}^{(7)} + (\rho_M + \lambda)V\right] \Big/ 2\eta\tau V, \tag{47}$$

$$\lambda(s^{(7)} - s_L) = 0, \tag{48}$$

$$\lambda \geqslant 0, \tag{49}$$

$$m_{R_i}^{(7)} = \left[2(\alpha_i - w_i^{(7)} + dw_j^{(7)}) + d(\alpha_j - w_j^{(7)} + dw_i^{(7)}) + \beta(2 + d)s^{(7)}\right] \Big/ V. \tag{50}$$

For DLS, substituting $m_{R_i}^{(7)}$ and $m_{M_i}^{(7)}$ into Eqs. (1), (41), and (42), the demand quantity, utility of retailer and manufacturer are transformed into $q_i^{(7)} = m_{R_i}^{(7)}$, $u_R^{(7)} = \sum_{i=1}^{2}\left(m_{R_i}^{(7)}\right)^2 - f_R - \eta(1-\tau)(s^{(7)})^2 + \rho_R s^{(7)}$, and $u_M^{(7)} = \sum_{i=1}^{2}m_{R_i}^{(7)}m_{M_i}^{(7)} - f_M - \eta\tau(s^{(7)})^2 + \rho_M s^{(7)}$, after some mathematical simplifications.

In Scenario 8, the sustainability limitations $\boldsymbol{s}_L = (s_{L_1}, s_{L_2})$ are imposed on two competitive SSCs in an oligopoly market. Therefore, the game model between SSC participants can be formulated as follows:

$$\max_{p} u_{R_i}^{(8)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{s}_L) = \left\{ \begin{array}{c} (p_i - w_i)\left[\alpha_i - p_i + dp_j + \beta(s_i - \theta s_j)\right] \\ -f_{R_i} - (1-\tau_i)\eta_i s_i^2 + \rho_{R_i}s_i \end{array} \right\}, \; i = 1,2; \; j = 3 - i; \tag{51}$$

$$\max_{w,s} u_{M_i}^{(8)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{s}_L) = \left\{ \begin{array}{c} (w_i - c_i)\left[\alpha_i - p_i + dp_j + \beta(s_i - \theta s_j)\right] \\ -f_{M_i} - \tau_i\eta_i s_i^2 + \rho_{M_i}s_i \end{array} \right\}, \; i = 1,2; \; j = 3 - i. \tag{52}$$

$$s_i \geqslant s_{L_i}, \; i = 1,2; \; j = 3 - i. \tag{53}$$

Proposition 8 characterizes equilibrium decisions of the competitive SSCs for given thresholds for sustainability level $\boldsymbol{s}_L = (s_{L_1}, s_{L_2})$.

Proposition 8. *Under DLS $\boldsymbol{s}_L = (s_{L_1}, s_{L_2})$ in Scenario 10, if $\eta_i \geqslant \beta^2(2 - d\theta)^2/4(2 - d^2)$, the optimal values for $p_i^{(8)}$, $w_i^{(8)}$ and $s_i^{(8)}$ for SSC i are given by.*

$$p_i^{(8)} = w_i^{(8)} + m_{R_i}^{(8)}, \tag{54}$$

$$w_i^{(8)} = c_i + m_{M_i}^{(8)}, \tag{55}$$

$$\begin{aligned} m_{M_i}^{(8)} = m_{M_i}^{(2)} + \frac{\beta}{2\eta_i\tau_i}\frac{(2-d\theta)B_j^{(2)}-(d-2\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)}-B_i^{(2)}B_j^{(2)}}\lambda_i \\ +\frac{\beta}{2\eta_j\tau_j}\frac{(d-2\theta)B_j^{(2)}-(2-d\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)}-B_i^{(2)}B_j^{(2)}}\lambda_j, \end{aligned} \tag{56}$$

$$s_i^{(8)} = \left[\beta(2-d\theta)m_{M_i}^{(8)} + (\rho_{M_i}+\lambda_i)V\right]\Big/2\eta_i\tau_i V, \tag{57}$$

$$\lambda_i(s_i^{(8)} - s_{L_i}) = 0, \tag{58}$$

$$\lambda_i \geqslant 0, \tag{59}$$

$$\begin{aligned} m_{R_i}^{(8)} = \Big[2(\alpha_i - w_i^{(8)} + dw_j^{(8)} + \beta(s_i^{(8)} - \theta s_j^{(8)})) + d(\alpha_j - w_j^{(8)} + dw_i^{(8)} + \beta(s_j^{(8)} \\ - \theta s_i^{(8)}))\Big]\Big/V, \end{aligned} \tag{60}$$

Propositions 7 and 8 present the results of the Stackelberg game model under the DLS policy, which aim to investigate the effect of the RA's direct limitations on the optimal retailer price, wholesale price, and sustainability level.

Substituting $m_{R_i}^{(8)}$ and $m_{M_i}^{(8)}$ into Equations (1), (51), and (52) yields $q_i^{(8)} = m_{R_i}^{(8)}$, $u_{M_i}^{(8)} = m_{R_i}^{(8)} m_{M_i}^{(8)} - f_{M_i} - \eta_i\tau_i\left(s_i^{(8)}\right)^2 + \rho_{M_i}s_i^{(8)}$, and $u_{R_i}^{(8)} = \left(m_{R_i}^{(8)}\right)^2 - f_{R_i} - \eta_i(1-\tau_i)\left(s_i^{(8)}\right)^2 + \rho_{R_i}s_i^{(8)}$, after some mathematical simplifications. From Propositions 7 and 8, we know that for given sustainability level limitation(s) placed by the RA in oligopoly and monopoly markets, a unique equilibrium for price and sustainability level(s) of SSC (s) can be found. This leads to the following corollary.

Corollary 4. *Under a DLS policy, sustainability limitations directly influence the sustainability levels of SSCs in both oligopoly and monopoly markets. The product price, market demand, and utility function of SSC participants are changed correspondingly. Understanding these effects enables the RA to orchestrate SSCs to fulfill the CSR objectives through an appropriate DLS policy.*

3.2.5. GCSE policy (Scenarios 9–10)

Collaboration between supply chains and governments has become crucial in achieving their respective objectives. Both entities engage in a recursive process to achieve mutual goals, making collaboration a necessary tactic (Sudusinghe and Seuring, 2022). In such scenarios, RAs propose sustainability levels to support SSCs. The GCSE policy is a sustainability-based regulation that the RA supports SSCs by exerting cooperative sustainability improvement efforts. In Scenario 9, the RA takes cooperative sustainability improvement s_G along with the SSC. Therefore, the utility functions of SSC participants can be formulated as

$$\begin{aligned} \max_{p}\ u_R^{(9)}(\boldsymbol{p}, s, \boldsymbol{w}, s_G) = \sum_{i=1}^{2}(p_i - w_i)\left[\alpha_i - p_i + dp_j\right. \\ \left. + \beta(s+s_G)\right] - f_R - (1-\tau)\eta s^2 + \rho_R s; \end{aligned} \tag{61}$$

$$\begin{aligned} \max_{w,s}\ u_M^{(9)}(\boldsymbol{p}, s, \boldsymbol{w}, s_G) = \sum_{i=1}^{2}(w_i - c_i)\left[\alpha_i - p_i + dp_j\right. \\ \left. + \beta(s+s_G)\right] - f_M - \tau\eta s^2 + \rho_M s. \end{aligned} \tag{62}$$

The best response strategies for SSC members regarding the cooperative sustainability effort s_g can be categorized by the following Proposition.

Proposition 9. *When the RA pursues GCSE policy according to Scenario 9; if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right)-d\right]$, then the equilibrium $p_i^{(9)}$, $w_i^{(9)}$ and $s_i^{(9)}$ retail prices, for an SSC in a monopoly market are.*

$$p_i^{(9)} = w_i^{(9)} + m_{R_i}^{(9)}, \tag{63}$$

$$w_i^{(9)} = c_i + m_{M_i}^{(9)}, \tag{64}$$

$$s^{(9)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(9)} + \rho_M V\right]\Big/2\eta\tau V \tag{65}$$

In which $m_{M_i}^{(9)} = m_{M_i}^{(1)} - \frac{\beta(2+d)}{A^{(1)}+B^{(1)}}s_G$, $m_{R_i}^{(9)} = \left\{2(\alpha_i - w_i^{(9)} + dw_j^{(9)}) + d(\alpha_j - w_j^{(9)} + dw_i^{(9)}) + \beta(2+d)(s^{(9)} + s_G)\right\}\Big/V$, and $j = 3-i$

Substituting $m_{R_i}^{(9)}, m_{M_i}^{(9)}$, and s into Eqs. (2), (61), and (62), the demand quantity, utility of retailer and manufacturer are simplified into $q_i^{(9)} = m_{R_i}^{(9)}$, $u_M^{(9)} = \sum_{i=1}^{2} m_{R_i}^{(9)} m_{M_i}^{(9)} - f_M - \eta\tau\left(s^{(9)}\right)^2 + \rho_M(s^{(9)} + s_G)$, and $u_R^{(9)} = \sum_{i=1}^{2}\left(m_{R_i}^{(9)}\right)^2 - f_R - \eta(1-\tau)\left(s^{(9)}\right)^2 + \rho_R(s^{(9)} + s_G)$.

In an oligopoly market, the RA exerts cooperative sustainability efforts $s_G = (s_{G_1}, s_{G_2})$ for competitive SSCs. Hence, the game model between SSC members can be formulated as follows:

$$\max_{p}\ u_{R_i}^{(10)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{s_G}) = \left\{\begin{array}{c}(p_i - w_i)\left[\alpha_i - p_i + dp_j + \beta((s_i + s_{G_i}) - \theta(s_j + s_{G_j}))\right] \\ -f_{R_i} - (1-\tau_i)\eta_i s_i^2 + \rho_{R_i}s_i\end{array}\right\},\ i = 1,2;\ j = 3-i; \tag{66}$$

$$\max_{w,s}\ u_{M_i}^{(10)}(\boldsymbol{p}, \boldsymbol{s}, \boldsymbol{w}, \boldsymbol{s_G}) = \left\{\begin{array}{c}(w_i - c_i)\left[\alpha_i - p_i + dp_j + \beta((s_i + s_{G_i}) - \theta(s_j + s_{G_j}))\right] \\ -f_{M_i} - \tau_i\eta_i s_i^2 + \rho_{M_i}s_i\end{array}\right\},\ i = 1,2;\ j = 3-i. \tag{67}$$

The best SSC member response strategies regarding the cooperative sustainability efforts $s_G = (s_{G_1}, s_{G_2})$ can be categorized by the following Proposition.

Proposition 10. *When the RA establishes GCSE according to Scenario 10, if $\eta_i \geqslant \beta^2(2-d\theta)^2/4(2-d^2)$, the unique equilibrium $p_i^{(10)}$, $w_i^{(10)}$ and $s_i^{(10)}$ of SSCs are as follows:*

$$p_i^{(10)} = w_i^{(10)} + m_{R_i}^{(10)}, \tag{68}$$

$$w_i^{(10)} = c_i + m_{M_i}^{(10)}, \tag{69}$$

$$s_i^{(10)} = \left[\beta(2-d\theta)m_{M_i}^{(10)} + \rho_{M_i}V\right]\Big/2\eta_i\tau_i V \tag{70}$$

In which $m_{R_i}^{(10)} = \left\{2(\alpha_i - w_i^{(10)} + dw_j^{(10)} + \beta(s_i^{(10)} - \theta s_j^{(10)})) + d(\alpha_j - w_j^{(10)} + dw_i^{(10)} + \beta(s_j^{(10)} - \theta s_i^{(10)})) + \beta(2-d\theta)s_{G_i} + \beta(d-2\theta)s_{G_j}\right\}\Big/V$, $m_{M_i}^{(10)} = m_{M_i}^{(2)} + \frac{\beta\left[\left(2-d\theta)B_j^{(2)} - (d-2\theta)A_j^{(2)}\right)\right]}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}s_{G_i} + \frac{\beta\left[\left(d-2\theta)B_j^{(2)} - (2-d\theta)A_j^{(2)}\right)\right]}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}s_{G_j}$, $i = 1,2$, and $j = 3-i$

Substituting $m_{R_i}^{(10)}, m_{M_i}^{(10)}$, and $s_i^{(10)}$ into Eqs. (1), (66) and (67), the demand quantity, utility of retailer and manufacturer in SSC i are simplified into $q_i^{(10)} = m_{R_i}^{(10)}$, $u_{M_i}^{(10)} = m_{R_i}^{(10)} m_{M_i}^{(10)} - f_{M_i} - \eta_i\tau_i\left(s_i^{(10)}\right)^2 + \rho_{M_i}(s_i^{(10)} + s_{G_i})$, and $u_{R_i}^{(10)} = \left(m_{R_i}^{(10)}\right)^2 - f_{R_i} - \eta_i(1-\tau_i)\left(s_i^{(10)}\right)^2 + \rho_{R_i}(s_i^{(10)} + s_{G_i})$.

Propositions 9 and 10 reveal the outcome of the Stackelberg game model when the GCSE policy is in place. The results of both propositions allow for an examination of the impact of cooperative sustainability improvement efforts on the retailer's price, wholesale price, and sustainability level.

Corollary 5. *Under GCSE, the cooperative sustainability improvement efforts of the government increase marginal profit and sustainability level of the smart manufacturer in the corresponding SSC. Recognizing these effects, the RA may orchestrate the equilibrium in markets to meet CSR objectives through an appropriate GCSE policy.*

Table 1 summarizes the optimal values of SSCs under different CSR regulatory policies. Note that the number of scenarios is in accordance with Fig. 1. Moreover, Drg. policy is considered as a benchmark scenario, and the optimal values for $m_{M_i}^{(k)}$ under other policies are computed regarding this benchmark scenario.

In Propositions 3–10, we characterized the equilibrium for sustainability level and price of the product under different government regulatory policies. Moreover, in Corollary 2-5 we conclude that the RA may orchestrate the SSCs to meet its sustainability (CSR) objective(s). In the next section, we investigate the optimum decisions of a government regarding its regulatory objectives.

3.3. Government regulatory mathematical models

In the previous section, we computed the best response strategies of SSCs under each of five regulatory policies. Now, we concentrate on finding the optimum regulatory strategy in each policy. The main aim of the government in CSR policymaking is to improve social utility regarding economic, environmental, and social considerations of businesses. In considering regulatory policy impact on SCs, previous researchers have considered social welfare or utility as the satisfaction of consumers, producers, and the population as a whole (Hafezalkotob, 2018, 2017a, 2017b; Sheu, 2011; Sheu and Chen, 2012; Xie, 2015). We assume that total utility maximization is the primary objective of an RA, which includes both government-based utility (*GBU*) and chain-based utility (*CBU*). Here *GBU* denotes the utility function of government under each CSR policy, defined as $GBU = GNI + \rho_G TSE$ where *GNI* represents the total net income obtained by the government under each CSR policy, which may be negative (expenditure) or positive (revenue) and *TSE* implies the total sustainability efforts in markets (exerted by SSCs or government).

Similarly, Assumption 5, *GBU* implies that the RA can also make a trade-off between profit (the economic aspect of a policy) and the sustainability level (the CSR aspect of a policy) by the coefficient ρ_G. Such that $\rho_G = 0$ indicates a pronounced profit-seeking tendency of government market intervention; however, the higher the coefficient ρ_G, the more government CSR behavior there will be. *CBU* represents the utility of whole SSC(s); therefore, in monopoly and oligopoly markets, we have $CBU = \sum_{i=1}^{2}(u_{M_i} + u_{R_i})$ *and* $CBU = u_M + u_R$, respectively.

A regulatory policy should be designed in consideration of the satisfaction of all system stakeholders. *Total Utility (TU)* of all stakeholders can be a combination of *GBU* and *CBU*, which can be mathematically expressed as $TU = \Omega \cdot GBU + (1-\Omega)\cdot CBU$. In an oligopoly market of SSCs, the general model for the RA can be expressed as

$$
\begin{aligned}
&\max\ TU = \Omega\cdot GBU + (1-\Omega)\cdot CBU,\\
&\text{subject to: } u_{M_i} \geqslant \underline{u}_{M_i},\ u_{R_i} \geqslant \underline{u}_{R_i},\ i = 1,2,\\
&\qquad \sum_i q_i \geqslant D,\\
&\qquad \max_{p_i, s_i} u_{M_i}(\boldsymbol{p}, s, \boldsymbol{w}),\quad i = 1,2,\\
&\qquad \text{subject to: } \max_{p_i} u_{R_i}(\boldsymbol{p}, s, \boldsymbol{w}),\quad i,j = 1,2.
\end{aligned}
\tag{71}
$$

In a monopoly market of an SSC, the general model for the RA can be formulated as:

$$
\begin{aligned}
&\max\ TU = \Omega\cdot GBU + (1-\Omega)\cdot CBU,\\
&\text{subject to: } u_M \geqslant \underline{u}_M,\ u_R \geqslant \underline{u}_R,\\
&\qquad \sum_i q_i \geqslant D,\\
&\qquad \max_{w,s} u_M(\boldsymbol{p}, s, \boldsymbol{w})\\
&\qquad \text{subject to: } \max_{p} u_R(\boldsymbol{p}, s, \boldsymbol{w}).
\end{aligned}
\tag{72}
$$

For each policy adopted by the RA (see Fig. 2), the models (71) or (72) can be adjusted correspondingly. The parameter $\Omega(0 \leqslant \Omega \leqslant 1)$ represents the importance coefficient of the government utility function and it enables the RA to perform a trade-off between *GBU* and *CBU*. The constraints in the models of (71) and (72) are Individual Rationality (IR) constraints and require that the RA (as leader player) should satisfy the minimum requirements of SSC members (as follower players) as well as consumers. Otherwise, the CSR regulatory policy may not be supported by stakeholders and is therefore unlikely to be successful in the long term. Using optimal values for SSC members in Propositions (3)-(10), the multi-level programming problems (71)-(72) can be transformed into single-level programming problems. Table 2 presents the equivalent single-level programming problem of the RA according to each of the CSR regulatory policies presented in Fig. 2.

By solving the mathematical models summarized in Table 2, the optimal decisions for each CSR regulatory policy are obtained. The decision variables of each policy are specified in the corresponding objective function. Note that all objective and constraint functions are linear or quadratic functions on decision variables of the RA; consequently, all models in Table 2 are quadratically constrained quadratic problems (QCQP). Since there are many efficient solution methods devised for QCQPs (e.g. barrier penalty function algorithm, gradient projection, complementary pivoting, Wolfe's Methods, active set, interior point (refer to Bazarra (2013) for detailed information), the mathematical models of Table 2 can be efficiently solved.

4. Numerical analysis

In this section, we perform numerical analysis to examine the main game players' decisions, recognizing both monopoly and oligopoly markets and RA regulatory policies. To accomplish this goal, we first obtain optimal decisions for five RA policies in the monopoly and oligopoly markets. We then study the impact of the trade-off coefficient of the government tendency towards *GBU* and *CBU* on the market share (*MS*) of a sustainable product and the government's and chain members' total utilities. We next compare the optimal *TSE* values under various regulatory policies, markets, and under different levels of trade-off coefficient of government tendency towards *GNI* and *TSE*.

All calculations, model formulation, and numerical examples presented in this study were performed using MAPLE software. The input values in our experiments are comprised of $\alpha_1 = 18$, $\alpha_2 = 14$, $c_1 = 3$, $c_2 = 2$, $d = 0.4$, $\beta = 0.3$, $\eta_1 = 0.3$, $\eta_2 = 0.35$, $\tau_1 = 0.5$, $\tau_2 = 0.55$, $\theta = 0.1$, $\rho_{M_1} = 0.8$, $\rho_{M_2} = 0.85$, $\rho_{R_1} = 0.9$, $\rho_{R_2} = 0.95$, $f_{M_1} = f_{M_2} = f_{R_1} = f_{R_2} = 0$, $u_{M_1} = u_{M_2} = u_{R_1} = u_{R_2} = 0$, which are used to solve the QCQPs presented in Table 2 by employing Maple nonlinear solver.

Tables 3-5 present the optimal values under various RA policies in monopoly and oligopoly markets. Table 3 demonstrates and compares the optimal margins in both markets. From Table 3, we find that the government's DTM policy (i.e., Scenarios 3 and 4) is the superior strategy from the viewpoints of SSCs' optimal margins. Among markets, we also find that the DTM policy in the monopoly market yields higher margins.

Optimal values obtained for monopoly market in Table 4, illustrate that the DTM policy of RA better supports the market demand of two substitutable products, sustainability level determined by the manufacturer, and members' utility. Obtained optimal decisions for oligopoly

Table 1
The best response strategies of SSC(s) regarding different CSR regulation policies.

Policies	Monopoly vs. Oligopoly One SSC	Two SSCs
Drg.	$m_{M_i}^{(1)} = \frac{E_i^{(1)}B_j^{(1)} - E_j^{(1)}A_j^{(1)}}{A_i^{(1)}A_j^{(1)} - B_i^{(1)}B_j^{(1)}},$ $s^{(1)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(1)} + \rho_M V\right] \Big/ 2\eta\tau V,$ $w_i^{(1)} = c_i + m_{M_i}^{(1)},$ $m_{R_i}^{(1)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(1)} + dw_j^{(1)}) + \\ d(\alpha_j - w_j^{(1)} + dw_i^{(1)}) + \beta(2+d)s^{(1)} \end{array}\right\} \Big/ V,$ $p_i^{(1)} = w_i^{(1)} + m_{R_i}^{(1)}.$	$m_{M_i}^{(2)} = \frac{E_i^{(2)}B_j^{(2)} - E_j^{(2)}A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}},$ $s_i^{(2)} = \left[\beta(2-d\theta)m_{M_i}^{(2)} + \rho_{M_i} V\right] \Big/ 2\eta_i\tau_i V,$ $w_i^{(2)} = c_i + m_{M_i}^{(2)},$ $m_{R_i}^{(2)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(2)} + dw_j^{(2)} + \beta(s_i^{(2)} - \theta s_j^{(2)})) + \\ d(\alpha_j - w_j^{(2)} + dw_i^{(2)} + \beta(s_j^{(2)} - \theta s_i^{(2)})) \end{array}\right\} \Big/ V,$ $p_i^{(2)} = w_i^{(2)} + m_{R_i}^{(2)}.$
DTM	$m_{M_i}^{(3)} = m_{M_i}^{(1)} - \frac{(2-d^2)B^{(1)} + dA^{(1)}}{(A^{(1)})^2 - (B^{(1)})^2}t_i + \frac{dB^{(1)} + (2-d^2)A^{(1)}}{(A^{(1)})^2 - (B^{(1)})^2}t_j,$ $s^{(3)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(3)} + \rho_M V\right] \Big/ 2\eta\tau V,$ $w_i^{(3)} = c_i + m_{M_i}^{(3)},$ $m_{R_i}^{(3)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(3)} + dw_j^{(3)}) + \\ d(\alpha_j - w_j^{(3)} + dw_i^{(3)}) + \beta(2+d)s^{(3)} \\ -(2-d^2)t_i + dt_j \end{array}\right\} \Big/ V,$ $p_i^{(3)} = w_i^{(3)} + m_{R_i}^{(3)}.$	$m_{M_i}^{(4)} = m_{M_i}^{(2)} - \frac{(2-d^2)B_j^{(2)} + dA_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}t_i + \frac{dB_j^{(2)} + (2-d^2)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}t_j,$ $s_i^{(4)} = \left[\beta(2-d\theta)m_{M_i}^{(4)} + \rho_{M_i} V\right] \Big/ 2\eta_i\tau_i V,$ $w_i^{(4)} = c_i + m_{M_i}^{(4)},$ $m_{R_i}^{(4)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(4)} + dw_j^{(4)} + \beta(s_i^{(4)} - \theta s_j^{(4)})) \\ +d(\alpha_j - w_j^{(4)} + dw_i^{(4)} + \beta(s_j^{(4)} - \theta s_i^{(4)})) \\ -(2-d^2)t_i + dt_j \end{array}\right\} \Big/ V,$ $p_i^{(4)} = w_i^{(4)} + m_{R_i}^{(4)}.$
SP&SC	$m_{M_i}^{(5)} = m_{M_i}^{(1)} - \frac{\beta(2+d)}{2\eta(A^{(1)} + B^{(1)})}x,$ $s^{(5)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(5)} + (\rho_M + \tau x)V\right] \Big/ 2\eta\tau V,$ $w_i^{(5)} = c_i + m_{M_i}^{(5)},$ $m_{R_i}^{(5)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(5)} + dw_j^{(5)}) + \\ d(\alpha_j - w_j^{(5)} + dw_i^{(5)}) + \beta(2+d)s^{(5)} \end{array}\right\} \Big/ V,$ $p_i^{(5)} = w_i^{(5)} + m_{R_i}^{(5)}.$	$m_{M_i}^{(6)} = m_{M_i}^{(2)} + \frac{\beta}{2\eta_i}\frac{(2-d\theta)B_j^{(2)} - (d-2\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}x_i + \frac{\beta}{2\eta_j}\frac{(d-2\theta)B_j^{(2)} - (2-d\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}x_j,$ $s_i^{(6)} = \left[\beta(2-d\theta)m_{M_i}^{(6)} + (\rho_{M_i} + \tau_i x_i)V\right] \Big/ 2\eta_i\tau_i V,$ $w_i^{(6)} = c_i + m_{M_i}^{(6)},$ $m_{R_i}^{(6)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(6)} + dw_j^{(6)} + \beta(s_i^{(6)} - \theta s_j^{(6)})) \\ +d(\alpha_j - w_j^{(6)} + dw_i^{(6)} + \beta(s_j^{(6)} - \theta s_i^{(6)})) \\ -(2-d^2)t_i + dt_j \end{array}\right\} \Big/ V,$ $p_i^{(6)} = w_i^{(6)} + m_{R_i}^{(6)}.$
DLS	$\left\{\begin{array}{l} m_{M_i}^{(7)} = m_{M_i}^{(1)} - \frac{\beta(2+d)}{2\eta\tau(A^{(1)} + B^{(1)})}\lambda, \\ s^{(7)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(7)} + (\rho_M + \lambda)V\right] \Big/ 2\eta\tau V, \\ \lambda(s^{(7)} - s_L) = 0, \\ \lambda \geqslant 0, \end{array}\right.$ $w_i^{(7)} = c_i + m_{M_i}^{(7)},$ $m_{R_i}^{(7)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(7)} + dw_j^{(7)}) + \\ d(\alpha_j - w_j^{(7)} + dw_i^{(7)}) + \beta(2+d)s^{(7)} \end{array}\right\} \Big/ V,$ $p_i^{(7)} = w_i^{(7)} + m_{R_i}^{(7)}.$	$\left\{\begin{array}{l} m_{M_i}^{(8)} = m_{M_i}^{(2)} + \frac{\beta}{2\eta_i\tau_i}\frac{(2-d\theta)B_j^{(2)} - (d-2\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}\lambda_i \\ \quad + \frac{\beta}{2\eta_j\tau_j}\frac{(d-2\theta)B_j^{(2)} - (2-d\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}\lambda_j, \\ s_i^{(8)} = \left[\beta(2-d\theta)m_{M_i}^{(8)} + (\rho_{M_i} + \lambda_i)V\right] \Big/ 2\eta_i\tau_i V, \\ \lambda_i(s^{(8)} - s_{L_i}) = 0, \\ \lambda_i \geqslant 0, \end{array}\right.$ $w_i^{(8)} = c_i + m_{M_i}^{(8)},$ $m_{R_i}^{(8)} = \left\{\begin{array}{c} 2(\alpha_i - w_i^{(8)} + dw_j^{(8)} + \beta(s_i^{(8)} - \theta s_j^{(8)})) \\ +d(\alpha_j - w_j^{(8)} + dw_i^{(8)} + \beta(s_j^{(8)} - \theta s_i^{(8)})) \end{array}\right\} \Big/ V,$ $p_i^{(8)} = w_i^{(8)} + m_{R_i}^{(8)}.$

(*continued on next page*)

market in Table 5, show that the DTM policy benefits the manufacturers, while the retailers are better advantaged by sustainability penalty and credits (i.e. SP&SC policy). From the viewpoints of sustainability and market demand, SP&SC policy is the superior strategy.

Tables 5 and 6 display data that was computed using Propositions 1–10. Making a comparison between Tables 5 and 6 demonstrates that the manufacturers are more benefited in monopoly market under government regulatory policies. Wherein, the oligopoly market better

Table 1 (*continued*)

Policies	Monopoly vs. Oligopoly One SSC	Two SSCs
GCSE	$m_{M_i}^{(9)} = m_{M_i}^{(1)} - \frac{\beta(2+d)}{A^{(1)}+B^{(1)}} s_G,$ $s^{(9)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(9)} + \rho_M V\right] \Big/ 2\eta\tau V,$ $w_i^{(9)} = c_i + m_{M_i}^{(9)},$ $m_{R_i}^{(9)} = \left\{\begin{matrix} 2(\alpha_i - w_i^{(9)} + dw_j^{(9)}) + \\ d(\alpha_j - w_j^{(9)} + dw_i^{(9)}) + \\ \beta(2+d)(s^{(9)} + s_G) \end{matrix}\right\} \Big/ V,$ $p_i^{(9)} = w_i^{(9)} + m_{R_i}^{(9)}.$	$m_{M_i}^{(10)} = m_{M_i}^{(2)} + \frac{\beta\left[\left(2-d\theta\right)B_j^{(2)} - (d-2\theta)A_j^{(2)}\right]}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} s_{G_i}$ $+ \frac{\beta\left[\left(d-2\theta\right)B_j^{(2)} - (2-d\theta)A_j^{(2)}\right]}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} s_{G_j},$ $s_i^{(10)} = \left[\beta(2-d\theta)m_{M_i}^{(10)} + \rho_{M_i} V\right] \Big/ 2\eta_i\tau_i V,$ $w_i^{(10)} = c_i + m_{M_i}^{(10)},$ $m_{R_i}^{(10)} = \left\{\begin{matrix} 2(\alpha_i - w_i^{(10)} + dw_j^{(10)} + \beta(s_i^{(10)} - \theta s_j^{(10)})) \\ +d(\alpha_j - w_j^{(10)} + dw_i^{(10)} + \beta(s_j^{(10)} - \theta s_i^{(10)})) \\ \beta(2-d\theta)s_{G_i} + \beta(d-2\theta)s_{G_j} \end{matrix}\right\} \Big/ V,$ $p_i^{(10)} = w_i^{(10)} + m_{R_i}^{(10)}.$

Note that $m_{R_i}^{(k)}$ and $m_{M_i}^{(k)}$, and $m_i^{(k)}$ are indicated by Proposition k.

supports the retailers. It is worth noting that the managerial insights derived from comparing monopoly and oligopoly markets can be attributed to the aforementioned propositions.

We next concentrate on how the *MS* of a product and total utilities of government and chain members vary when the trade-off coefficient of the government tendency towards *GBU* and *CBU* changes. To do this, *MS* of a sustainable product, i.e., $q_1/(q_1 + q_2)$, is considered through various scenarios under government regulatory policies. Fig. 3 demonstrates that the *MS* of the product in Scenarios 3, 4, and 10 is a decreasing function of the trade-off coefficient of the government tendency towards *GBU* and *CBU*. Under the DTM, DLS, and GCSE policies of the RA, the oligopoly market provides higher *MS* of sustainable products, while the DTM policy in providing higher *MS* in the oligopoly market is the superior strategy. In the context of a monopoly market, the DLS policy is observed to result in a higher *MS* of sustainable products. Therefore, it can be concluded that the DLS policy is an effective regulatory strategy for achieving sustainability goals in such markets. On the other hand, in an oligopoly market, the DTM policy may be deemed as the most effective and beneficial policy for the RA.

Fig. 4 represents the optimal total utilities of the chain members and government under various degrees of trade-off coefficient of the government's tendency towards *GBU* and *CBU*. As shown in Fig. (4.a) and (4.b), under RA DTM policy, we obtain two regions for the utilities of the chain members and government. When $\Omega \leq 0.8$, in both monopoly and oligopoly markets, chain members are benefited under the DTM policy rather than the government, wherein for the higher tendency of the government towards its incomes, i.e., $\Omega > 0.8$, the government's total utility is higher than SSCs. As illustrated in Fig. 4, under SP&SC, DLS, and GCSE policies of RA in monopoly and oligopoly markets, the optimal utility of the chain members is higher than the utility of the RA except the oligopoly market under SP&SC policy. Under the DTM policy, it can be inferred that $\Omega \leq 0.8$ would be the optimal range to ensure the benefits of the chain members. Nevertheless, if the government intends to maximize the overall utility, it would be advisable to keep Ω in the RA region ($\Omega > 0.8$). However, it is worth noting that under other policies, the chain members' utility surpasses that of the RA region.

Making a comparison between the optimal *CBU* and *TU* under the various degrees of government tendency towards its revenue in monopoly and oligopoly markets reveals that the monopoly market provides higher amounts of total utilities for the chain members and government in DTM, DLS, and GCSE policies of RA (see Fig. 4). We also find that the DTM policy of RA is the superior strategy among all other RA policies in the monopoly market, wherein the SP&SC policy in an oligopoly market is preferable from the viewpoints of the players' total utilities when the government has a higher tendency towards its incomes, i.e., $\Omega > 0.5$. In an oligopoly market, the highest TU of 470 is observed when the government enforces the SP&SC policy. Thus, implementing the SP&SC policy would enable the government to attain the maximum TU level.

Fig. 5 compares the optimal *TSE* values under various regulatory policies, monopoly, and oligopoly markets, and under different degrees of trade-off coefficient of government tendency towards *GNI* and *TSE*. As shown in Fig. (5.a), (5.c), and (5.d), under DTM, DLS, and GCSE policies, the optimal *TSE* values in the monopoly market are higher, while the DTM strategy is the superior policy. From the perspective of the optimal *TSE* in the oligopoly market, the SP&SC policy is a superior strategy. The increasing value of the optimal *TSE* versus the trade-off coefficient of the government tendencies towards sustainability efforts demonstrates that the lower inclination of the government to its incomes, the higher sustainability efforts will be. The monopoly market with DTM implementation yields the highest TSE level.

4.1. Analysis on product substitutability coefficient (d)

We next investigate the impact of the degree of product substitutability on the MS of sustainable products and the total utilities of the government and supply chain members (see Fig. 6). When the degree of substitutability is relatively low ($d \leq 0.6$), the oligopoly market offers a higher MS of sustainable products under the DTM, DLS, and GCSE policies of RA. Among these, the GCSE policy is the preferable policy for providing higher MS of sustainable products in both oligopoly and monopoly markets. However, when the degree of substitutability is relatively high ($d > 0.6$), the DTM policy in the oligopoly market and the SP&SC policy in the monopoly market are identified as the superior strategies for providing a higher MS of sustainable products. Furthermore, the Fig. 6 illustrates that the MS of sustainable products is a decreasing function of the degree of substitutability in scenarios 4 (when $d \leq 0.6$), 7, 8, 9, and 10.

Fig. 7 depicts the optimal total utilities of chain members and the government under varying degrees of product substitutability. As shown in the figure, when the degree of substitutability among products is low ($d \leq 0.4$) in a monopoly market, all regulatory policies, including DTM, SP&SC, DLS, and GCSE, provide higher utilities for chain members than the government. Among these policies, the DTM strategy is identified as the superior strategy, offering higher optimal utilities for both chain members and the government. Therefore, firms in a monopolistic market can benefit by adopting these regulatory policies, especially when the degree of substitutability among their products is low. However, in an oligopoly market, the DLS and GCSE policies secure higher utility for chain members under all degrees of substitutability, while the SP&SC

Table 2
The single-level mathematical models for CSR regulatory polices of RA.

	Monopoly vs. Oligopoly	
Policies	One SSC	Two SSCs
DTM	max $TU(t) = \Omega(\sum_i t_i q_i^{(3)} + \rho_G s^{(3)}) + (1-\Omega)(u_M^{(3)} + u_R^{(3)})$ subject to: $p_i^{(3)} = w_i^{(3)} + m_{R_i}^{(3)}, \quad w_i^{(3)} = c_i + m_{M_i}^{(3)}, \quad i,j = 1,2,$ $s^{(3)} = \left[\beta(2+d)\sum_{i=1}^2 m_{M_i}^{(3)} + \rho_M V\right] \Big/ 2\eta\tau V,$ $q_i^{(3)} = m_{R_i}^{(3)}, \quad i,j=1,2,$ $u_M^{(3)} = \sum_{i=1}^2 m_{R_i}^{(3)} m_{M_i}^{(3)} - f_M - \tau\eta(s^{(3)})^2 + \rho_M s^{(3)} \geqslant \underline{u}_M,$ $u_R^{(3)} = \sum_{i=1}^2 (m_{R_i}^{(3)})^2 - f_R - (1-\tau)\eta(s^{(3)})^2 + \rho_R s^{(3)} \geqslant \underline{u}_R,$ $\sum_i q_i^{(3)} \geqslant D.$	max $TU(t) = \Omega(\sum_i t_i q_i^{(4)} + \rho_G s_i^{(4)}) + (1-\Omega)\sum_i (u_{M_i}^{(4)} + u_{R_i}^{(4)})$ subject to: $p_i^{(4)} = w_i^{(4)} + m_{R_i}^{(4)}, \quad w_i^{(4)} = c_i + m_{M_i}^{(4)}, \quad i=1,2,$ $s_i^{(4)} = \left[\beta(2-d\theta)m_{M_i}^{(4)} + \rho_{M_i} V\right] \Big/ 2\eta_i\tau_i V, \quad i=1,2,$ $q_i^{(4)} = m_{R_i}^{(4)}, \quad i=1,2,$ $u_{M_i}^{(4)} = m_{R_i}^{(4)} m_{M_i}^{(4)} - f_{M_i} - \eta_i\tau_i (s_i^{(4)})^2 + \rho_{M_i} s_i^{(4)} \geqslant \underline{u}_{M_i}, \ i=1,2,$ $u_{R_i}^{(4)} = (m_{R_i}^{(4)})^2 - f_{R_i} - \eta_i(1-\tau_i)(s_i^{(4)})^2 + \rho_{R_i} s_i^{(4)} \geqslant \underline{u}_{R_i}, \ i=1,2,$ $\sum_i q_i^{(4)} \geqslant D.$
SP&SC	max $TU(x, s_T) = \Omega(\sum_i x(s^{(5)} - s_T) + \rho_G s^{(5)}) + (1-\Omega)(u_M^{(5)} + u_R^{(5)})$ subject to: $p_i^{(5)} = w_i^{(5)} + m_{R_i}^{(5)}, \quad w_i^{(5)} = c_i + m_{M_i}^{(5)}, \quad i,j=1,2,$ $s^{(5)} = \left[\beta(2+d)\sum_{i=1}^2 m_{M_i}^{(5)} + (\rho_M + \tau x)V\right] \Big/ 2\eta\tau V,$ $q_i^{(5)} = m_{R_i}^{(5)}, \quad i,j=1,2,$ $u_M^{(5)} = \left\{\sum_{i=1}^2 m_{R_i}^{(5)} m_{M_i}^{(5)} - f_M + \tau x(s^{(5)} - s_T) - \eta\tau(s^{(5)})^2 + \rho_M s^{(5)}\right\} \geqslant \underline{u}_M,$ $u_R^{(5)} = \left\{\begin{array}{c} \sum_{i=1}^2 (m_{R_i}^{(5)})^2 - f_R + (1-\tau)x(s^{(5)} - s_T) \\ -\eta(1-\tau)(s^{(5)})^2 + \rho_R s^{(5)} \end{array}\right\} \geqslant \underline{u}_R,$ $\sum_i q_i^{(5)} \geqslant D.$	max $TU(x, s_T) = \Omega(\sum_i x_i(s_i^{(6)} - s_{T_i}) + \rho_G s_i^{(6)})$ $+(1-\Omega)\sum_i (u_{M_i}^{(6)} + u_{R_i}^{(6)})$ subject to: $p_i^{(6)} = w_i^{(6)} + m_{R_i}^{(6)}, \quad w_i^{(6)} = c_i + m_{M_i}^{(6)}, \quad i=1,2,$ $s_i^{(6)} = \left[\beta(2-d\theta)m_{M_i}^{(6)} + (\rho_{M_i} + \tau_i x_i)V\right] \Big/ 2\eta_i\tau_i V, \quad i=1,2,$ $q_i^{(6)} = m_{R_i}^{(6)}, \quad i=1,2,$ $u_{M_i}^{(6)} = \left\{\begin{array}{c} m_{R_i}^{(6)} m_{M_i}^{(6)} - f_{M_i} + \tau_i x_i(s_i^{(6)} - s_{T_i}) \\ -\eta_i\tau_i(s_i^{(6)})^2 + \rho_{M_i} s_i^{(6)} \end{array}\right\} \geqslant \underline{u}_{M_i}, \ i=1,2,$ $u_{R_i}^{(6)} = \left\{\begin{array}{c} (m_{R_i}^{(6)})^2 - f_{R_i} + (1-\tau_i)x_i(s_i^{(6)} - s_{T_i}) \\ -\eta_i(1-\tau_i)(s_i^{(6)})^2 + \rho_{R_i} s_i^{(6)} \end{array}\right\} \geqslant \underline{u}_{R_i}, \ i=1,2,$ $\sum_i q_i^{(6)} \geqslant D.$
DLS	max $TU(s_L) = \Omega(\rho_G s^{(7)}) + (1-\Omega)(u_M^{(7)} + u_R^{(7)})$ subject to: $p_i^{(7)} = w_i^{(7)} + m_{R_i}^{(7)}, \quad w_i^{(7)} = c_i + m_{M_i}^{(7)}, \quad i,j=1,2,$ $s^{(7)} = \left[\beta(2+d)\sum_{i=1}^2 m_{M_i}^{(7)} + (\rho_M + \lambda)V\right] \Big/ 2\eta\tau V,$ $\lambda(s^{(7)} - s_L) = 0,$ $\lambda \geqslant 0,$ $u_M^{(7)} = \sum_{i=1}^2 m_{R_i}^{(7)} m_{M_i}^{(7)} - f_M - \eta\tau(s^{(7)})^2 + \rho_M s^{(7)} \geqslant \underline{u}_M,$ $u_R^{(7)} = \sum_{i=1}^2 (m_{R_i}^{(7)})^2 - f_R - \eta(1-\tau)(s^{(7)})^2 + \rho_R s^{(7)} \geqslant \underline{u}_R,$ $\sum_i q_i^{(7)} \geqslant D.$	max $TU(s_L) = \Omega(\sum_i \rho_G s_i^{(8)}) + (1-\Omega)\sum_i (u_{M_i}^{(8)} + u_{R_i}^{(8)})$ subject to: $p_i^{(8)} = w_i^{(8)} + m_{R_i}^{(8)}, \quad w_i^{(8)} = c_i + m_{M_i}^{(8)}, \quad i=1,2,$ $s_i^{(8)} = \left[\beta(2-d\theta)m_{M_i}^{(8)} + (\rho_{M_i} + \lambda_i)V\right] \Big/ 2\eta_i\tau_i V, \quad i=1,2,$ $\lambda_i(s_i^{(8)} - s_{L_i}) = 0,$ $q_i^{(8)} = m_{R_i}^{(8)}, \quad i=1,2,$ $u_{M_i}^{(8)} = m_{R_i}^{(8)} m_{M_i}^{(8)} - f_{M_i} - \eta_i\tau_i(s_i^{(8)})^2 + \rho_{M_i} s_i^{(8)} \geqslant \underline{u}_{M_i}, \ i=1,2,$ $u_{R_i}^{(8)} = (m_{R_i}^{(8)})^2 - f_{R_i} - \eta_i(1-\tau_i)(s_i^{(8)})^2 + \rho_{R_i} s_i^{(8)} \geqslant \underline{u}_{R_i}, \ i=1,2,$ $\sum_i q_i^{(8)} \geqslant D.$
GCSE	max $TU(s_G) = \Omega\rho_G(s^{(9)} + s_G) + (1-\Omega)(u_M^{(9)} + u_R^{(9)})$ subject to: $p_i^{(9)} = w_i^{(9)} + m_{R_i}^{(9)}, \quad w_i^{(9)} = c_i + m_{M_i}^{(9)}, \quad i,j=1,2,$ $s^{(9)} = \left[\beta(2+d)\sum_{i=1}^2 m_{M_i}^{(9)} + \rho_M V\right] \Big/ 2\eta\tau V,$ $u_M^{(9)} = \left\{\sum_{i=1}^2 m_{R_i}^{(9)} m_{M_i}^{(9)} - f_M - \eta\tau(s^{(9)})^2 + \rho_M(s^{(9)} + s_G)\right\} \geqslant \underline{u}_M,$ $u_R^{(9)} = \left\{\begin{array}{c} \sum_{i=1}^2 (m_{R_i}^{(9)})^2 - f_R - \eta(1-\tau)(s^{(9)})^2 + \\ \rho_R(s^{(9)} + s_G) \end{array}\right\} \geqslant \underline{u}_R,$ $\sum_i q_i^{(9)} \geqslant D.$	max $TU(s_G) = \Omega\sum_i \rho_G(s_i^{(10)} + s_{G_i}) + (1-\Omega)\sum_i (u_{M_i}^{(10)} + u_{R_i}^{(10)})$ subject to: $p_i^{(10)} = w_i^{(10)} + m_{R_i}^{(10)}, \quad w_i^{(10)} = c_i + m_{M_i}^{(10)}, \quad i=1,2,$ $s_i^{(10)} = \left[\beta(2-d\theta)m_{M_i}^{(10)} + \rho_{M_i} V\right] \Big/ 2\eta_i\tau_i V, \quad i=1,2,$ $u_{M_i}^{(10)} = \left\{\begin{array}{c} m_{R_i}^{(10)} m_{M_i}^{(10)} - f_{M_i} - \eta_i\tau_i(s_i^{(10)})^2 + \\ \rho_{M_i}(s_i^{(10)} + s_{G_i}) \end{array}\right\} \geqslant \underline{u}_{M_i}, \ i=1,2,$ $u_{R_i}^{(10)} = \left\{\begin{array}{c} (m_{R_i}^{(10)})^2 - f_{R_i} - \eta_i(1-\tau_i)(s_i^{(10)})^2 + \\ \rho_{R_i}(s_i^{(10)} + s_{G_i}) \end{array}\right\} \geqslant \underline{u}_{R_i}, \ i=1,2,$ $\sum_i q_i^{(10)} \geqslant D.$

Note that $m_{R_i}^{(k)}$ and $m_{M_i}^{(k)}$, and $m_i^{(k)}$ are indicated by Proposition k.

Table 3
The optimal margins in both monopoly and oligopoly markets..($\Omega = 0.5, \rho_G = 0.5$)

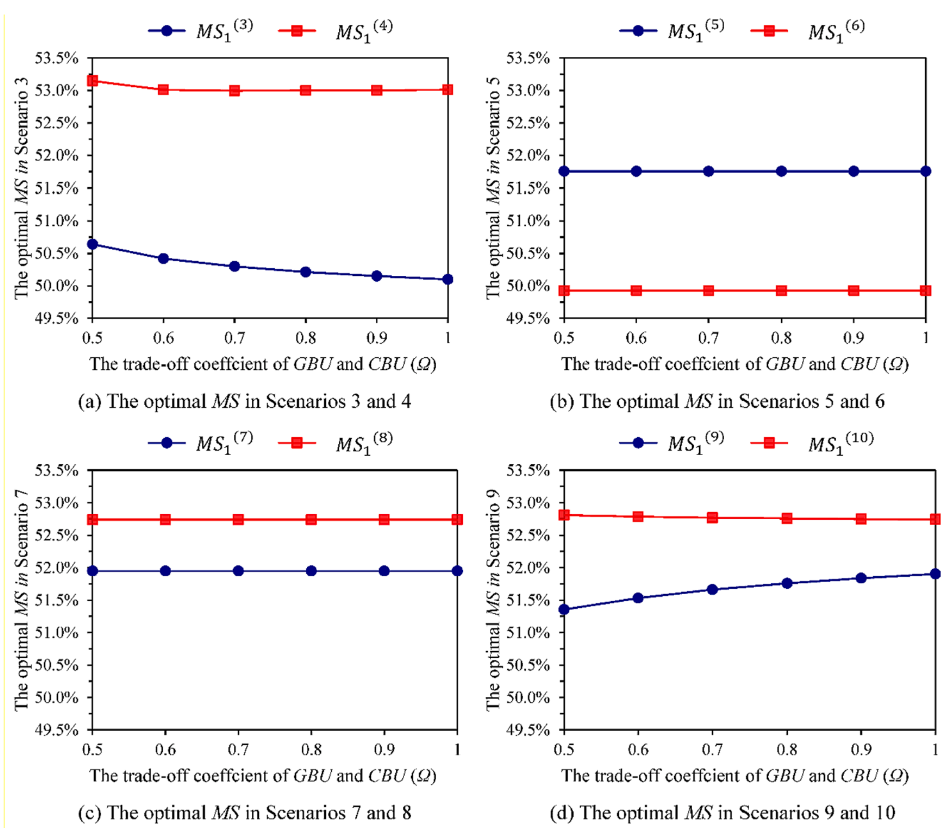
Policy	Monopoly					Oligopoly				
	Sce.	m_{M_1}	m_{M_2}	m_{R_1}	m_{R_2}	Sce.	m_{M_1}	m_{M_2}	m_{R_1}	m_{R_2}
Drg.	1	19.010	18.081	7.225	6.684	2	12.860	11.525	6.162	5.522
DTM	3	**59.806**	**57.529**	**36.783**	**35.853**	4	**18.753**	**16.533**	**8.986**	**7.922**
SP&SC	5	21.053	20.125	7.992	7.450	6	16.563	14.926	13.226	13.26
DLS	7	19.010	18.081	7.225	6.684	8	12.860	11.525	6.162	5.522
GSCE	9	27.116	26.188	10.265	9.724	10	15.117	13.509	7.243	6.473

Table 4
The optimal values in the monopoly market ($\Omega = 0.5, \rho_G = 0.5$)

Sce.	p_1	p_2	s	w_1	w_2	q_1	q_2	u_R	u_M	RA's optimal decisions
1	29.235	26.765	25.848	22.010	20.081	7.225	6.684	19.920	178.659	–
3	99.589	95.381	**76.001**	62.806	59.529	**36.783**	**35.853**	**1840.4**	**3456.81**	$t_1 = 56.516$, t_2=53.818
5	32.045	29.575	34.023	24.053	22.125	7.992	7.450	0.000	195.411	$x = 3.372$, $s_T = 20.000$
7	29.235	26.765	25.848	22.010	20.081	7.225	6.684	19.920	178.659	$s_L = 0.547$
9	40.382	37.911	35.982	30.116	28.188	10.265	9.724	58.172	385.416	$s_G = 22.293$

Table 5
The optimal values in the oligopoly market..($\Omega = 0.5, \rho_G = 0.5$)

Sce.	p_1	p_2	s_1	s_2	w_1	w_2	q_1	q_2	u_{R_1}	u_{R_2}	u_{M_1}	u_{M_2}	RAs optimal decisions
2	22.022	19.047	9.231	6.792	15.860	13.525	6.162	5.522	33.498	29.683	73.849	60.537	–
4	30.739	26.455	12.24	8.783	21.753	18.533	8.986	7.922	69.293	58.953	**155.84**	**123.59**	$t_1 = 11.97$, t_2=10.60
6	32.789	30.192	**28.37**	**23.61**	19.563	16.926	**13.23**	**13.27**	**200.68**	**201.27**	0.000	0.000	$x_1 = 10.35$, x_2=10.82, $s_{T_1} = 5.0$, s_{T_2}=5.0
8	22.022	19.047	9.231	6.792	15.860	13.525	6.162	5.522	33.498	29.683	73.849	60.537	$s_{L_1} = 0.86$, s_{L_2}=1.03
10	25.360	21.982	10.38	7.581	18.117	15.509	7.243	6.473	55.214	48.496	110.14	90.380	$s_{G_1} = 10.63$, s_{G_2}=8.89



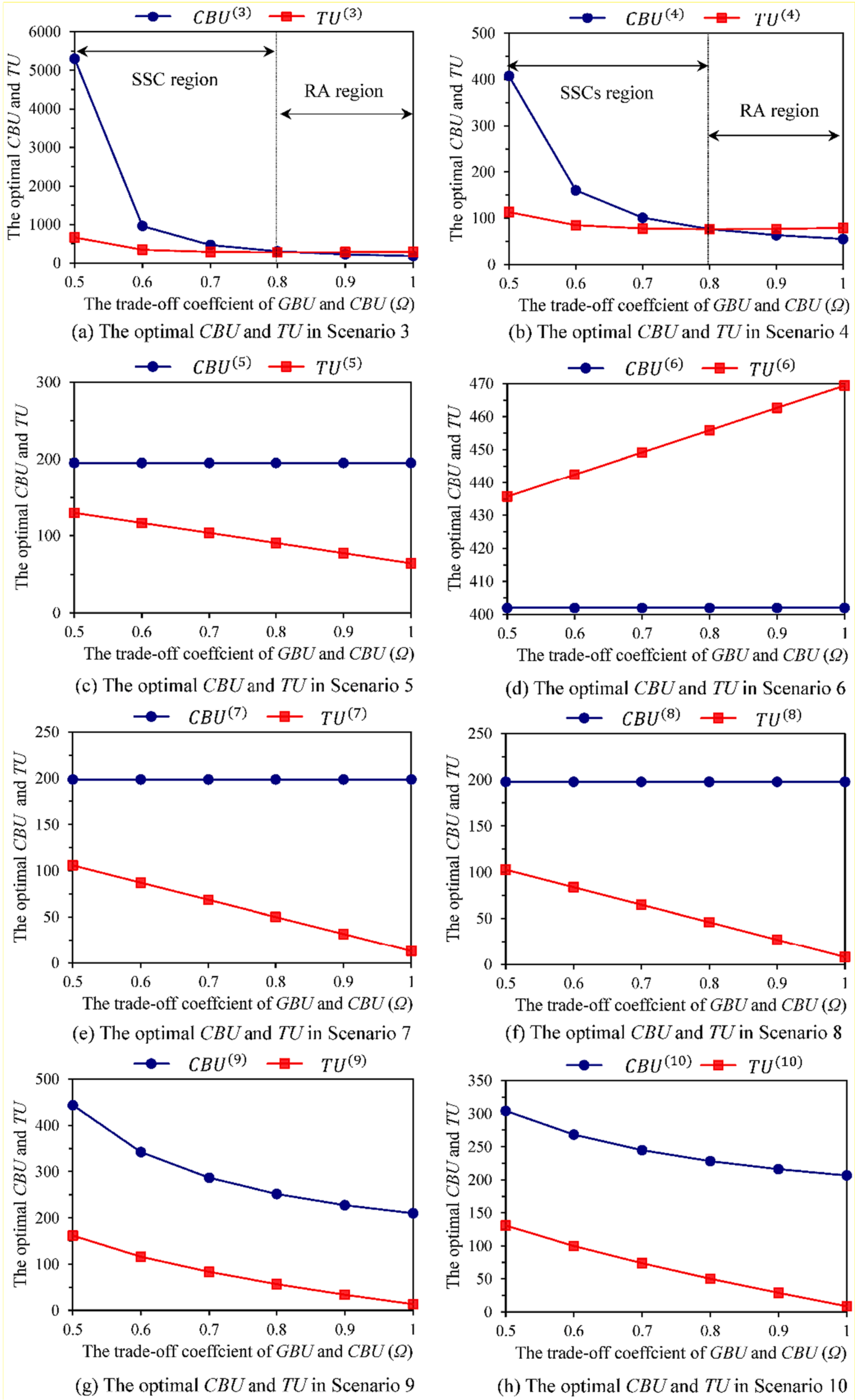
(a) The optimal *MS* in Scenarios 3 and 4

(b) The optimal *MS* in Scenarios 5 and 6

(c) The optimal *MS* in Scenarios 7 and 8

(d) The optimal *MS* in Scenarios 9 and 10

Fig. 3. The *MS* of the sustainable products under various trade-off coefficients of *GBU* and *CBU*.



(a) The optimal *CBU* and *TU* in Scenario 3
(b) The optimal *CBU* and *TU* in Scenario 4
(c) The optimal *CBU* and *TU* in Scenario 5
(d) The optimal *CBU* and *TU* in Scenario 6
(e) The optimal *CBU* and *TU* in Scenario 7
(f) The optimal *CBU* and *TU* in Scenario 8
(g) The optimal *CBU* and *TU* in Scenario 9
(h) The optimal *CBU* and *TU* in Scenario 10

Fig. 4. The optimal *CBU* and *TU* under various trade-off coefficient of *GBU* and *CBU*.

policy secures higher utility for the government. Therefore, firms in an oligopolistic market can maximize their utility by adopting these policies.

Fig. 8 presents a comparison of optimal TSE values under various regulatory policies of the RA for different degrees of substitutability in both monopoly and oligopoly markets. Results shown in Fig. 8.a, 8.c, and 8.d indicate that the degree of product substitutability significantly affects the choice of regulatory policies and optimal TSE values. Specifically, in a monopoly market, when the degree of substitutability is low ($d \leq 0.4$), the DTM, DLS, and GCSE policies lead to higher optimal TSE values. Among these policies, the DTM strategy is found to be the most effective. Therefore, monopolistic firms can benefit from adopting these regulatory policies, especially when the degree of substitutability among their products is low. In contrast, in an oligopoly market, the

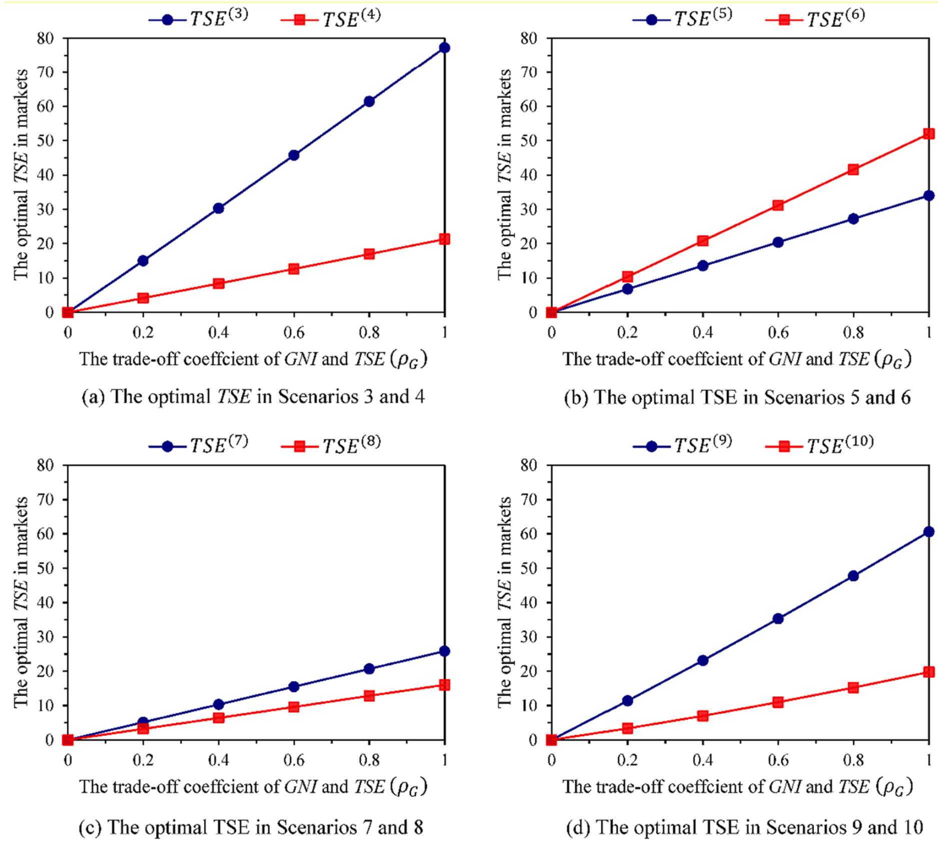


Fig. 5. The optimal TSE under various trade-off coefficient of *GNI* and *TSE*.

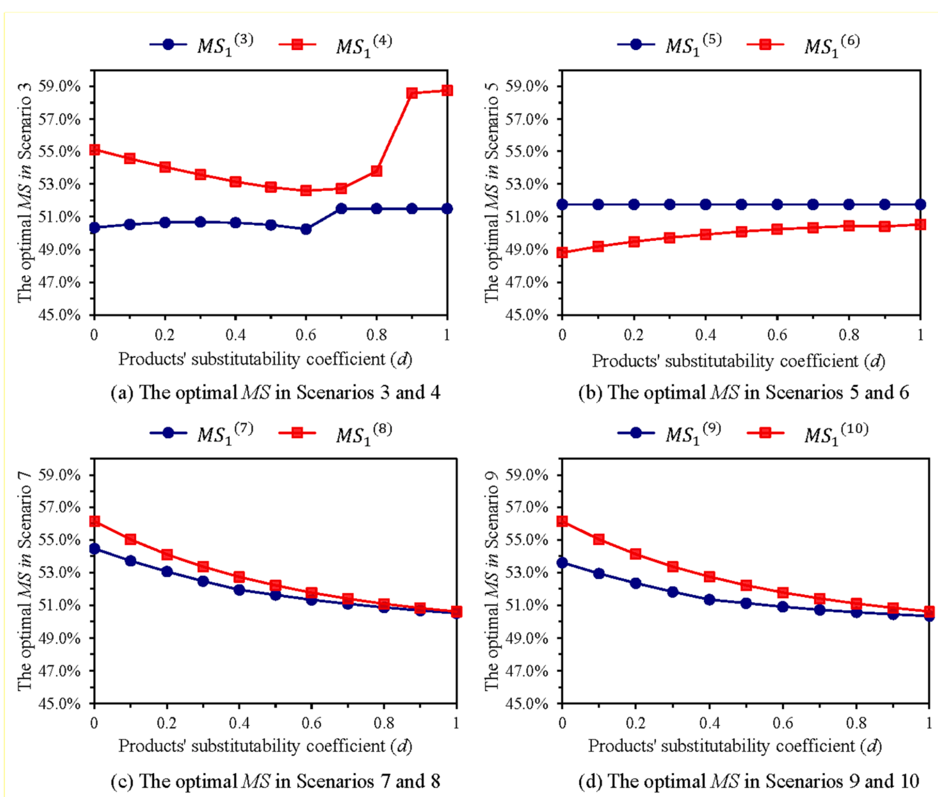


Fig. 6. The *MS* of the sustainable products under different substitutability degrees of products.

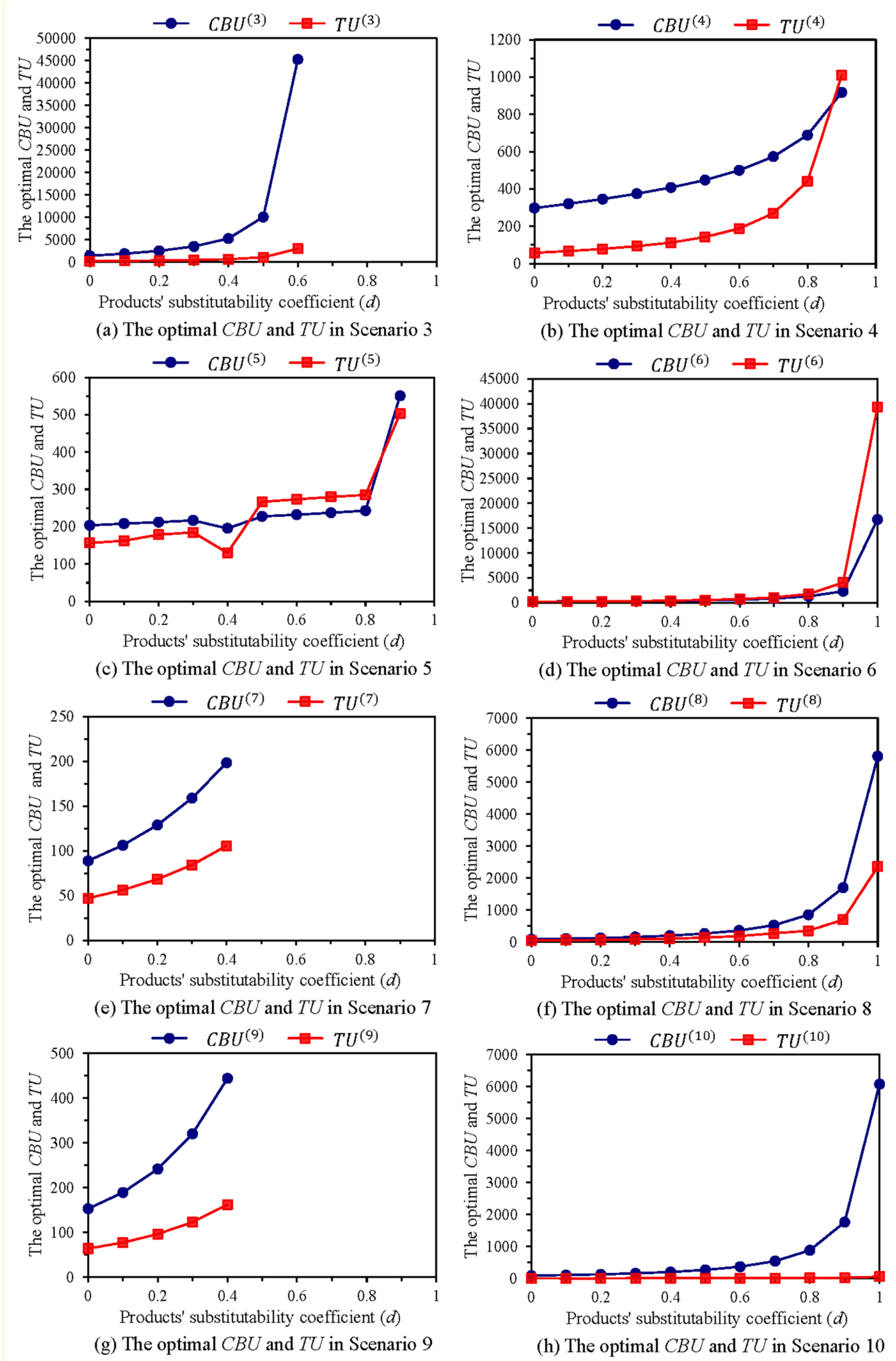


Fig. 7. The optimal *CBU* and *TU* under different substitutability degrees between products.

SP&SC policy is identified as the superior strategy for maximizing the optimal TSE value, regardless of the degree of substitutability among their products. Additionally, the figure suggests that higher degrees of substitutability among products lead to increased substitutability efforts in the market.

5. Conclusion

This study has provided a thorough examination of the interplay between CSR and SM within the context of SSCM. We have proposed five CSR regulatory policies and applied a Stackelberg game theoretical framework to analyze their impact on the performance of SSCs that sell substitutable products under monopoly and oligopoly market structures. We highlighted the crucial role that governments play in selecting the appropriate policy as the basis for effective regulations. We introduced and evaluated the impacts of different CSR regulatory policies, namely Deregulation, Direct Tariff on Market, Sustainability Penalty & Sustainability Credits, Direct Limitation on Sustainability, and Government Cooperative Sustainability Efforts, on the performance of SSCs in both monopoly and oligopoly markets. We found that members of an SSC may not simply be profit-seeking, instead, they may increase their sustainability levels based on ethical and CSR strategy considerations.

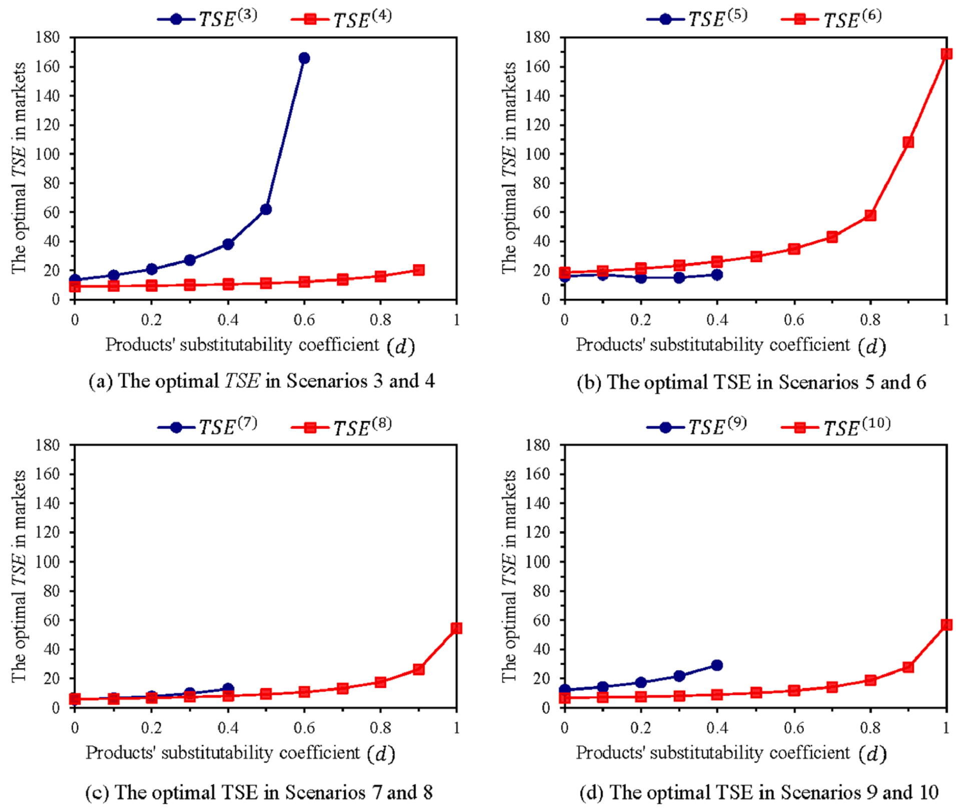


Fig. 8. The optimal TSE under different substitutability degrees between products.

Through a numerical example and a comprehensive sensitivity analysis, important managerial insights were provided to SSCs on how to effectively adopt CSR and SM principles to promote decarbonization and other environmental benefits. Numerical analysis suggested that the DTM policy of the RA in the monopoly market is the superior strategy from the perspectives of chain members' and government's total utilities and optimal sustainability efforts. We also find that the DTM policy in the oligopoly market and DLS policy in the monopoly market yield a higher market share of the sustainable product, which the DTM in the superior policy. From the viewpoints of the market demand and sustainability level in monopoly market the DTM policy is the best, wherein the SP&SC policy is superior in the oligopoly market. Our findings have uncovered the connection between government CSR regulations, market structure, and environmental sustainability, providing valuable insights for SSC managers. The successful implementation of CSR and SM approaches can lead to economic, social, and environmental well-being for all stakeholders involved. As such, it is of paramount importance for governments to implement appropriate policies and regulations to promote the principles of CSR and SM, particularly with regards to environmental sustainability.

There are several interesting and challenging future research directions that can be considered. For example, examining the impact of asymmetric information sharing in real-world scenarios, as many enterprises may be hesitant to share necessary information. Another suggestion is to investigate alternative governmental policies for CSR, such as mandatory CSR information disclosure (see Liu et al., 2023). Additionally, incorporating green and smart manufacturing parameters into the model at the same time and examining the joint effects of governmental smart-green policies would provide valuable insights.

CRediT authorship contribution statement

Ashkan Hafezalkotob: Investigation, Validation, Writing – original draft, Formal analysis, Writing – review & editing, Project administration. **Sobhan Arisian:** Investigation, Validation, Writing – original draft, Formal analysis, Writing – review & editing, Project administration. **Raziyeh Reza-Gharehbagh:** Investigation, Validation, Writing – original draft, Formal analysis, Writing – review & editing. **Lia Nersesian:** Investigation, Validation, Writing – original draft, Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix:. Mathematical proofs

Proposition 1 proof

In a Stackelberg game model under Drg. policy in Scenario 1, to obtain the value of $p_i^{(1)}$, $\frac{\partial U_{R_i}^{(1)}}{\partial m_{R_i}^{(1)}}$ and $\frac{\partial U_{R_j}^{(1)}}{\partial m_{R_j}^{(1)}}$ must be obtained (m_{R_i} represents the retailer's unit marginal profit). In addition, with considering $\frac{\partial U_{R_i}^{(1)}}{\partial m_{R_i}^{(1)}} = 0$ and $\frac{\partial U_{R_j}^{(1)}}{\partial m_{R_j}^{(1)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(1)}}{\partial m_{R_i}^{(1)}} = \alpha_i - w_i^{(1)} + dw_j^{(1)} - 2m_{R_i}^{(1)} + dm_{R_j}^{(1)} + \beta s^{(1)} = 0; i = 1,2 j = 3-i, \tag{A.1}$$

$$\frac{\partial U_{R_j}^{(1)}}{\partial m_{R_j}^{(1)}} = \alpha_j - w_j^{(1)} + dw_i^{(1)} - 2m_{R_j}^{(1)} + dm_{R_i}^{(1)} + \beta s^{(1)} = 0; j = 1,2 i = 3-j, \tag{A.2}$$

$$m_{R_i}^{(1)} = \left[2(\alpha_i - w_i^{(1)} + dw_j^{(1)}) + d(\alpha_j - w_j^{(1)} + dw_i^{(1)}) + \beta(2+d)s^{(1)}\right] \Big/ V; i = 1,2 j = 3-i. \tag{A.3}$$

By substituting $m_{R_i}^{(1)}$ into following equation the optimal retailer's price will be obtained:

$$p_i^{(1)} = w_i^{(1)} + m_{R_i}^{(1)}; i = 1,2 j = 3-i. \tag{A.4}$$

To obtain optimal manufacturer's prices according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(1)}}{\partial w_i^{(1)}}=0$ and $\frac{\partial U_{M_j}^{(1)}}{\partial w_j^{(1)}} = 0$ must be solved. With considering $w_i^{(1)} - c_i^{(1)} = m_{M_i}^{(1)}$ and $w_j^{(1)} - c_j^{(1)} = m_{M_j}^{(1)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(1)}}{\partial m_{M_i}^{(1)}} = 0$ and $\frac{\partial U_{M_j}^{(1)}}{\partial m_{M_j}^{(1)}}$ are as follows:

$$\frac{\partial U_{M_i}^{(1)}}{\partial m_{M_i}^{(1)}} = 2(\alpha_i - c_i + dc_j) + d(\alpha_j - c_j + dc_i) + \frac{\beta(2+d)\rho_M}{2\eta\tau V} + [2(d^2-2) + \frac{\beta^2(2+d)^2}{2\eta\tau V}]m_{M_i}^{(1)} + [2d + \frac{\beta^2(2+d)^2}{2\eta\tau V}]m_{M_j}^{(1)} = 0, \tag{A.5}$$

where $i = 1,2$ and $j = 3-i$.

$$\frac{\partial U_{M_j}^{(1)}}{\partial m_{M_j}^{(1)}} = 2(\alpha_j - c_j + dc_i) + d(\alpha_i - c_i + dc_j) + \frac{\beta(2+d)\rho_M}{2\eta\tau V} + [2(d^2-2) + \frac{\beta^2(2+d)^2}{2\eta\tau V}]m_{M_j}^{(1)} + [2d + \frac{\beta^2(2+d)^2}{2\eta\tau V}]m_{M_i}^{(1)} = 0, \tag{A.6}$$

where $j = 1,2$ and $i = 3-j$.

By solving the equations above the optimal $m_{M_i}^{(1)}$ is achieved:

$$m_{M_i}^{(1)} = \left[E_i^{(1)}B^{(1)} - E_j^{(1)}A^{(1)}\right] \Big/ \left[\left(A^{(1)}\right)^2 - \left(B^{(1)}\right)^2\right]; i = 1,2, j = 3-i \tag{A.7}$$

To simplify the model, it is considered:

$$A^{(1)} = 2d + \beta^2(2+d)^2/2\eta\tau V, \tag{A.8}$$

$$B^{(1)} = -2(2-d^2) + \beta^2(2+d)^2/2\eta\tau V, \tag{A.9}$$

$$E_i^{(1)} = 2(\alpha_i - c_i + dc_j) + d(\alpha_j - c_j + dc_i) + \beta(2+d)\rho_M/2\eta\tau; i = 1,2 j = 3-i, \tag{A.10}$$

$$E_j^{(1)} = 2(\alpha_j - c_j + dc_i) + d(\alpha_i - c_i + dc_j) + \beta(2+d)\rho_M/2\eta\tau; j = 1,2 i = 3-j, \tag{A.11}$$

$$V = 4 - d^2. \tag{A.12}$$

By substituting $m_{M_i}^{(1)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(1)} = c_i + m_{M_i}^{(1)}; i = 1,2 j = 3-i. \tag{A.13}$$

$\frac{\partial U_{M_i}^{(1)}}{\partial s^{(1)}} = \sum_{i=1}^{2} m_{M_i}^{(1)} \frac{\beta(2+d)}{V} - 2\eta\tau s + \rho_M = 0$, By calculating $\frac{\partial U_{M_i}^{(1)}}{\partial s_i^{(1)}} = 0$, the optimal amount of $s_i^{(1)}$ is achieved:

$$\frac{\partial U_{M_i}^{(1)}}{\partial s_i^{(1)}} = \sum_{i=1}^{2} m_{M_i}^{(1)} \frac{\beta(2+d)}{V} - 2\eta\tau s + \rho_M = 0 \tag{A.15}$$

$$s^{(1)} = \frac{\sum_{i=1}^{2} m_{M_i}^{(1)}\beta(2+d)}{2\eta\tau V} + \frac{\rho_M}{2\eta\tau}, \tag{A.16}$$

where $i = 1,2$ and $j = 3-i$.

$$H(U_{M_i}^{1}) = \begin{bmatrix} \frac{-2+d^2+(d^2-2)}{4-d^2} & \frac{2\beta - d\beta\theta}{4-d^2} \\ \frac{2\beta - d\beta\theta}{4-d^2} & -2\eta \end{bmatrix}$$

Considering $H(U_{M_i}^{(1)}) = \begin{bmatrix} \frac{-2+d^2+(d^2-2)}{4-d^2} & \frac{2\beta - d\beta\theta}{4-d^2} \\ \frac{2\beta - d\beta\theta}{4-d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U^{(1)}_{M_i})$ is negatively defined. It is necessary to mention that if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right)-d\right]$ the determinant of Hessian matrix takes a positive amount $\det(H(U^1_{M_i}))>0$, the concavity of the profit function holds. □.

Proposition 2 proof

To obtain the retailer price Under Drg. policy in Scenario 2 $\frac{\partial U^{(2)}_{R_i}}{\partial m^{(2)}_{R_i}}$ and $\frac{\partial U^{(2)}_{R_j}}{\partial m^{(2)}_{R_j}}$ must be obtained. In addition, with considering $\frac{\partial U^{(2)}_{R_i}}{\partial m^{(2)}_{R_i}}=0$ and $\frac{\partial U^{(2)}_{R_j}}{\partial m^{(2)}_{R_j}}=0$ the optimal retailer's price will be calculated:

$$\frac{\partial U^{(2)}_{R_i}}{\partial m^{(2)}_{R_i}}=\alpha_i-w^{(2)}_i+dw^{(2)}_j-2m^{(2)}_{R_i}+dm^{(2)}_{R_j}+\beta(s^{(2)}_i-\theta s^{(2)}_j)=0; i=1,2 j=3-i, \tag{A.17}$$

$$\frac{\partial U^{(2)}_{R_j}}{\partial m^{(2)}_{R_j}}=\alpha_j-w^{(2)}_j+dw^{(2)}_i-2m^{(2)}_{R_j}+dm^{(2)}_{R_i}+\beta(s^{(2)}_j-\theta s^{(2)}_i)=0; j=1,2 i=3-j, \tag{A.18}$$

$$m^{(2)}_{R_i}=\left\{\begin{array}{c}2(\alpha_i-w^{(2)}_i+dw^{(2)}_j+\beta(s^{(2)}_i-\theta s^{(2)}_j))+\\ d(\alpha_j-w^{(2)}_j+dw^{(2)}_i+\beta(s^{(2)}_j-\theta s^{(2)}_i))\end{array}\right\}\Big/V; i=1,2 j=3-i. \tag{A.19}$$

By substituting $m^{(2)}_{R_i}$ into the following equation the optimal retailer's price will be obtained:

$$p^{(2)}_i=w^{(2)}_i+m^{(2)}_{R_i}; i=1,2. \tag{A.20}$$

To obtain optimal manufacturer's prices according to the Stackelberg game model, $\frac{\partial U^{(2)}_{M_i}}{\partial w^{(2)}_i}=0$ and $\frac{\partial U^{(2)}_{M_j}}{\partial w^{(2)}_j}=0$ must be solved. With considering $w^{(2)}_i-c^{(2)}_i=m_{M_i}$ and $w^{(2)}_j-c^{(2)}_j=m_{M_j}$ as the manufacturer's unit marginal profit $\frac{\partial U^{(2)}_{M_i}}{\partial m_{M_i}}=0$ and $\frac{\partial U^{(2)}_{M_j}}{\partial m_{M_j}}$ are as follows:

$$\begin{aligned}\frac{\partial U^{(2)}_{M_i}}{\partial m_{M_i}}&=[2(\alpha_i-c_i+dc_j+\frac{\rho_{M_i}\beta}{2\eta_i\tau_i}-\theta\frac{\rho_{M_j}\beta}{2\eta_j\tau_j})+d(\alpha_j-c_j+dc_i+\frac{\rho_{M_j}\beta}{2\eta_j\tau_j}-\theta\frac{\rho_{M_i}\beta}{2\eta_i\tau_i})]\\ &+[\frac{2\beta^2(2-d\theta)}{2\eta_i\tau_iV}-\theta\frac{d\beta^2(2-d\theta)}{2\eta_i\tau_iV}-2(2-d^2)]m^{(2)}_{M_i}+[\frac{d\beta^2(2-d\theta)}{2\eta_j\tau_jV}-\theta\frac{2\beta^2(2-d\theta)}{2\eta_j\tau_jV}+d]m^{(2)}_{M_j}=0,\end{aligned} \tag{A.21}$$

where $i=1,2$ and $j=3-i$.

$$\begin{aligned}\frac{\partial U^{(2)}_{M_j}}{\partial m_{M_j}}&=[2(\alpha_j-c_j+dc_i+\frac{\rho_{M_j}\beta}{2\eta_j\tau_j}-\theta\frac{\rho_{M_i}\beta}{2\eta_i\tau_i})+d(\alpha_i-c_i+dc_j+\frac{\rho_{M_i}\beta}{2\eta_i\tau_i}-\theta\frac{\rho_{M_j}\beta}{2\eta_j\tau_j})]\\ &+[\frac{2\beta^2(2-d\theta)}{2\eta_j\tau_jV}-\theta\frac{d\beta^2(2-d\theta)}{2\eta_j\tau_jV}-2(2-d^2)]m^{(2)}_{M_j}+[\frac{d\beta^2(2-d\theta)}{2\eta_i\tau_iV}-\theta\frac{2\beta^2(2-d\theta)}{2\eta_i\tau_iV}+d]m^{(2)}_{M_i}=0,\end{aligned} \tag{A.22}$$

where $j=1,2$ and $i=3-j$.

By solving the equations above the optimal $m^{(2)}_{M_i}$ is achieved:

$$m^{(2)}_{M_i}=\left[E^{(2)}_iB^{(2)}_j-E^{(2)}_jA^{(2)}_i\right]\Big/\left[A^{(2)}_iA^{(2)}_j-B^{(2)}_iB^{(2)}_j\right]; i=1,2 j=3-i. \tag{A.23}$$

To simplify the model, it is considered:

$$E^{(2)}_i=2(\alpha_i-c_i+dc_j)+d(\alpha_j-c_j+dc_i)+\frac{\beta(2-d\theta)\rho_{M_i}}{2\eta_i\tau_i}+\frac{\beta(d-2\theta)\rho_{M_j}}{2\eta_j\tau_j}, \tag{A.24}$$

$$A^{(2)}_i=d+\beta^2(2-d\theta)(d-2\theta)/2\eta_i\tau_iV, \tag{A.25}$$

$$B^{(2)}_i=\beta^2(2-d\theta)^2/2\eta_i\tau_iV-2(2-d^2), \tag{A.26}$$

where $i=1,2$ and $j=3-i$..

$$E^{(2)}_j=2(\alpha_j-c_j+dc_i)+d(\alpha_i-c_i+dc_j)+\frac{\beta(2-d\theta)\rho_{M_j}}{2\eta_j\tau_j}+\frac{\beta(d-2\theta)\rho_{M_i}}{2\eta_i\tau_i}, \tag{A.27}$$

$$A^{(2)}_j=d+\beta^2(2-d\theta)(d-2\theta)/2\eta_j\tau_jV, \tag{A.28}$$

$$B^{(2)}_j=\beta^2(2-d\theta)^2/2\eta_j\tau_jV-2(2-d^2), \tag{A.29}$$

where $j=1,2$ and $i=3-j$. By substituting $m^{(2)}_{M_i}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(2)} = c_i + m_{M_i}^{(2)}; i = 1, 2 j = 3 - i. \tag{A.30}$$

By calculating $\frac{\partial U_{M_i}^{(2)}}{\partial s_i^{(2)}} = 0$, the optimal amount of $s_i^{(2)}$ is achieved:

$$\frac{\partial U_{M_i}^{(2)}}{\partial s_i^{(2)}} = (w_i^{(2)} - c_i^{(2)})\frac{2\beta - d\beta\theta}{V} - 2\eta_i\tau_i s_i^{(2)} + \rho_{M_i} = 0, \tag{A.31}$$

$$s_i^{(2)} = \left[\beta(2 - d\theta)m_{M_i}^{(2)} + \rho_{M_i}V\right]\Big/2\eta_i\tau_i V, \tag{A.32}$$

where $i = 1, 2$ and $j = 3 - i$.

Considering $H(U_{M_i}^{(2)}) = \begin{bmatrix} \frac{-2 + d^2 + (d^2 - 2)}{4 - d^2} & \frac{2\beta - d\beta\theta}{4 - d^2} \\ \frac{2\beta - d\beta\theta}{4 - d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(2)})$ is negatively defined. It is necessary to mention that if $\eta_i \geqslant \beta^2(2 - d\theta)^2/4(2 - d^2)$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(2)})) > 0$, the concavity of the profit function holds. □.

Proposition 3 proof

To obtain the retailer's price Under DTM policy $t = (t_1, t_2)$ in Scenario 3 $\frac{\partial U_{R_i}^{(3)}}{\partial m_{R_i}^{(3)}}$ and $\frac{\partial U_{R_j}^{(3)}}{\partial m_{R_j}^{(3)}}$ must be obtained. In addition, with considering $\frac{\partial U_{R_i}^{(3)}}{\partial m_{R_i}^{(3)}} = 0$ and $\frac{\partial U_{R_j}^{(3)}}{\partial m_{R_j}^{(3)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(3)}}{\partial m_{R_i}^{(3)}} = \alpha_i - w_i^{(3)} + dw_j^{(3)} - 2m_{R_i}^{(3)} + dm_{R_j}^{(3)} + \beta s^{(3)} - t_i + dt_j = 0; i = 1, 2 j = 3 - i, \tag{A.33}$$

$$\frac{\partial U_{R_j}^{(3)}}{\partial m_{R_j}^{(3)}} = \alpha_j - w_j^{(3)} + dw_i^{(3)} - 2m_{R_j}^{(3)} + dm_{R_i}^{(3)} + \beta s^{(3)} - t_j + dt_i = 0; j = 1, 2 i = 3 - j, \tag{A.34}$$

$$m_{R_i}^{(3)} = \frac{2(\alpha_i - w_i^{(3)} + dw_j^{(3)}) + d(\alpha_j - w_j^{(3)} + dw_i^{(3)}) + \beta(2 + d)s^{(3)} - (2 - d^2)t_i + t_j}{V}; i = 1, 2 j = 3 - i, \tag{A.35}$$

By substituting $m_{R_i}^{(3)}$ into the following equation the optimal retailer's price will be obtained:

$$p_i^{(3)} = w_i^{(3)} + m_{R_i}^{(3)}; i = 1, 2 j = 3 - i. \tag{A.36}$$

To obtain optimal manufacturer's prices according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(3)}}{\partial w_i^{(3)}} = 0$ and $\frac{\partial U_{M_j}^{(3)}}{\partial w_j^{(3)}} = 0$ must be solved. With considering $w_i^{(3)} - c_i^{(3)} = m_{M_i}^{(3)}$ and $w_j^{(3)} - c_j^{(3)} = m_{M_j}^{(3)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(3)}}{\partial m_{M_i}^{(3)}} = 0$ and $\frac{\partial U_{M_j}^{(3)}}{\partial m_{M_j}^{(3)}}$ are as follows:

$$\frac{\partial U_{M_j}^{(3)}}{\partial m_{M_j}} = 2(\alpha_j - c_j + dc_i - m_{M_i} + dm_{M_j} - t_i + dt_j) + d(\alpha_j - c_j + dc_j - m_{M_j} + dm_{M_j} - t_j + dt_i)$$
$$+\left[\frac{\beta^2(2 + d)^2(m_{M_i}^{(3)} + m_{M_j}^{(3)})}{2\eta\tau V} + \frac{\beta(2 + d)\rho_M}{2\eta\tau} + (d - 2)\right]m_{M_j}^{(3)} + \left[2d + \frac{\beta^2(2 + d)^2}{2\eta\tau V} + d\right]m_{M_i}^{(3)} = 0,$$

$$\frac{\partial U_{M_i}^{(3)}}{\partial m_{M_i}^{(3)}} = 2(\alpha_i - c_i + dc_j - m_{M_i} + dm_{M_j} - t_i + dt_j)$$
$$+d(\alpha_j - c_j + dc_i - m_{M_j} + dm_{M_i} - t_j + dt_i) + \left[\frac{\beta^2(2 + d)^2(m_{M_i}^{(3)} + m_{M_j}^{(3)})}{2\eta\tau V} + \frac{\beta(2 + d)\rho_M}{2\eta\tau} + (d - 2)\right]m_{M_i}^{(3)} + \left[2d + \frac{\beta^2(2 + d)^2}{2\eta\tau V} + d\right]m_{M_j}^{(3)} = 0,$$

where $i = 1, 2$ and $j = 3 - i$.

$$\frac{\partial U_{M_j}^{(3)}}{\partial m_{M_j}} = 2(\alpha_j - c_j + dc_i - m_{M_j} + dm_{M_i} - t_j + dt_i) + d(\alpha_i - c_i + dc_j - m_{M_i} + dm_{M_j} - t_i + dt_j)$$
$$+\left[\frac{\beta^2(2 + d)^2(m_{M_j}^{(3)} + m_{M_i}^{(3)})}{2\eta\tau V} + \frac{\beta(2 + d)\rho_M}{2\eta\tau} + (d - 2)\right]m_{M_j}^{(3)} + \left[2d + \frac{\beta^2(2 + d)^2}{2\eta\tau V} + d\right]m_{M_i}^{(3)} = 0, \tag{A.38}$$

where $j = 1, 2$ and $i = 3 - j$. By solving the equations above the optimal $m_{M_i}^{(3)}$ is achieved:

$$m_{M_i}^{(3)} = m_{M_i}^{(1)} - \frac{(2 - d^2)B^{(1)} + dA^{(1)}}{(A^{(1)})^2 - (B^{(1)})^2}t_i + \frac{dB^{(1)} + (2 - d^2)A^{(1)}}{(A^{(1)})^2 - (B^{(1)})^2}t_j; i = 1, 2 j = 3 - i. \tag{A.39}$$

By substituting $m_{M_i}^{(3)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(3)} = c_i + m_{M_i}^{(3)}; i = 1,2 j = 3 - i. \tag{A.40}$$

By calculating $\frac{\partial U_{M_i}^{(3)}}{\partial s_i^{(3)}} = 0$, the optimal amount of $s_i^{(3)}$ is achieved:

$$\frac{\partial U_M^{(3)}}{\partial s^{(3)}} = \sum_{i=1}^{2} m_{M_i} \frac{\beta(2+d)}{V} - 2\eta\,\tau\, s^{(3)} + \rho_M = 0, \tag{A.41}$$

$$s^{(3)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(3)} + \rho_M V\right] \Big/ 2\eta\tau V, \tag{A.42}$$

where $i = 1,2, j = 3 - i$.

Considering $H(U_{M_i}^{(3)}) = \begin{bmatrix} \frac{-2+d^2+(d^2-2)}{4-d^2} & \frac{2\beta - d\beta\theta}{4-d^2} \\ \frac{2\beta - d\beta\theta}{4-d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(3)})$ is negatively defined. It is necessary to mention that if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right) - d\right]$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(3)})) > 0$, the concavity of the profit function holds. □.

Proposition 4 proof

To obtain the retailer price under Drg. policy $\boldsymbol{t} = (t_1, t_2)$ in Scenario 4 $\frac{\partial U_{R_i}^{(4)}}{\partial m_{R_i}^{(4)}}$ and $\frac{\partial U_{R_j}^{(4)}}{\partial m_{R_j}^{(4)}}$ must be obtained. In addition, with considering $\frac{\partial U_{R_i}^{(4)}}{\partial m_{R_i}^{(4)}} = 0$ and $\frac{\partial U_{R_j}^{(4)}}{\partial m_{R_j}^{(4)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(4)}}{\partial m_{R_i}^{(4)}} = \alpha_i - w_i^{(4)} + d w_j^{(4)} - 2 m_{R_i}^{(4)} + d m_{R_j}^{(4)} + \beta(s_i^{(4)} - \theta s_j^{(4)}) - t_i + d t_j = 0; i = 1,2 j = 3 - i, \tag{A.43}$$

$$\frac{\partial U_{R_j}^{(4)}}{\partial m_{R_j}^{(4)}} = \alpha_j - w_j^{(4)} + d w_i^{(4)} - 2 m_{R_j}^{(4)} + d m_{R_i}^{(4)} + \beta(s_j^{(4)} - \theta s_i^{(4)}) - t_j + d t_i = 0; j = 1,2 i = 3 - j, \tag{A.44}$$

$$m_{R_i}^{(4)} = \frac{\left\{ \begin{array}{c} 2(\alpha_i - w_i^{(4)} + d w_j^{(4)} + \beta(s_i^{(4)} - \theta s_j^{(4)})) \\ + d(\alpha_j - w_j^{(4)} + d w_i^{(4)} + \beta(s_j^{(4)} - \theta s_i^{(4)})) - (2-d^2) t_i + d t_j \end{array} \right\}}{V}; i = 1,2 j = 3 - i. \tag{A.45}$$

By substituting $m_{R_i}^{(4)}$ into the following equation the optimal retailer's price will be obtained:

$p_i^{(4)} = w_i^{(4)} + m_{R_i}^{(4)}; i = 1,2 j = 3 - i.$

To obtain optimal manufacturer's price according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(4)}}{\partial w_i^{(4)}} = 0$ and $\frac{\partial U_{M_j}^{(4)}}{\partial w_j^{(4)}} = 0$ must be solved. With considering $w_i^{(4)} - c_i^{(4)} = m_{M_i}^{(4)}$ and $w_j^{(4)} - c_j^{(4)} = m_{M_j}^{(4)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(4)}}{\partial m_{M_i}^{(4)}} = 0$ and $\frac{\partial U_{M_j}^{(4)}}{\partial m_{M_j}^{(4)}} = 0$ are as follows:

$$\begin{aligned} \frac{\partial U_{M_i}^{(4)}}{\partial m_{M_i}} &= 2(a_i - c_i + d c_j - t_i + d t_j) + d(a_j - c_j + d c_i - t_j + d t_i) + (2\beta - d\beta\theta)\frac{\rho_{M_i}}{2\eta_i \tau_i} + (-2\beta\theta + d\beta)\frac{\rho_{M_j}}{2\eta_j \tau_j} + \\ &\left(-2 + d^2 - 2 + \frac{2\beta^2(2-d\theta)}{2\eta_i \tau_i V} + d^2 - \frac{d\beta^2\theta(2-d\theta)}{2\eta_i \tau_i V}\right) m_{M_i}^{(4)} + \left(2d - \frac{2\beta^2\theta(2-d\theta)}{2\eta_j \tau_j V} - d + \frac{d\beta^2(2-d\theta)}{2\eta_j \tau_j V}\right) m_{M_j}^{(4)} = 0, \end{aligned} \tag{A.46}$$

where $i = 1, 2$ and $j = 3 - i$.

$$\begin{aligned} \frac{\partial U_{M_j}^{(4)}}{\partial m_{M_j}} &= 2(a_j - c_j + d c_i - t_j + d t_i) + d(a_i - c_i + d c_j - t_i + d t_j) + (2\beta - d\beta\theta)\frac{\rho_{M_j}}{2\eta_j \tau_j} + (-2\beta\theta + d\beta)\frac{\rho_{M_i}}{2\eta_i \tau_i} + \\ &\left(-2 + d^2 - 2 + \frac{2\beta^2(2-d\theta)}{2\eta_j \tau_j V} + d^2 - \frac{d\beta^2\theta(2-d\theta)}{2\eta_j \tau_j V}\right) m_{M_j}^{(4)} + \left(2d - \frac{2\beta^2\theta(2-d\theta)}{2\eta_i \tau_i V} - d + \frac{d\beta^2(2-d\theta)}{2\eta_i \tau_i V}\right) m_{M_i}^{(4)} = 0, \end{aligned} \tag{A.47}$$

where $j = 1, 2$ and $i = 3 - j$. By solving the equations above the optimal $m_{M_i}^{(4)}$ is achieved:

$$m_{M_i}^{(4)} = m_{M_i}^{(2)} - \frac{(2-d^2)B_j^{(2)} + dA_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} t_i + \frac{dB_j^{(2)} + (2-d^2)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} t_j; i = 1,2 j = 3 - i. \tag{A.48}$$

By substituting $m_{M_i}^{(4)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(4)} = c_i + m_{M_i}^{(4)}; i = 1,2 j = 3 - i. \tag{A.49}$$

By calculating $\frac{\partial U_{M_i}^{(4)}}{\partial s_i^{(4)}} = 0$, the optimal amount of $s_i^{(4)}$ is achieved:

$$\frac{\partial U_M^{(4)}}{\partial s_i^{(4)}} = m_{M_i}^{(4)} \frac{2\beta - d\beta\theta}{V} - 2\eta_i \tau_i s_i^{(4)} + \rho_{M_i} = 0, \tag{A.50}$$

$$s_i^{(4)} = \left[\beta(2 - d\theta) m_{M_i}^{(4)} + \rho_{M_i} V\right] \Big/ 2\eta_i \tau_i V, \tag{A.51}$$

where $i = 1,2$ and $j = 3 - i$.

Considering $H(U_{M_i}^{(4)}) = \begin{bmatrix} \frac{-2 + d^2 + (d^2 - 2)}{4 - d^2} & \frac{2\beta - d\beta\theta}{4 - d^2} \\ \frac{2\beta - d\beta\theta}{4 - d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(4)})$ is negatively defined. It is necessary to mention that if $\eta_i \geqslant \beta^2 (2 - d\theta)^2 / 4(2 - d^2)$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(4)})) > 0$, the concavity of the profit function holds. □.

Proposition 5 proof

To obtain the retailer price Under SP&SC policy (x, s_T) in Scenario 5 $\frac{\partial U_{R_i}^{(5)}}{\partial m_{R_i}^{(5)}}$ and $\frac{\partial U_{R_j}^{(5)}}{\partial m_{R_j}^{(5)}}$ must be obtained. In addition, with considering $\frac{\partial U_{R_i}^{(5)}}{\partial m_{R_i}^{(5)}} = 0$ and $\frac{\partial U_{R_j}^{(5)}}{\partial m_{R_j}^{(5)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(5)}}{\partial m_{R_i}^{(5)}} = \alpha_i - w_i^{(5)} + d w_j^{(5)} - 2 m_{R_i}^{(5)} + d m_{R_j}^{(5)} + \beta s = 0; i = 1,2 j = 3 - i, \tag{A.52}$$

$$\frac{\partial U_{R_j}^{(5)}}{\partial m_{R_j}^{(5)}} = \alpha_j - w_j^{(5)} + d w_i^{(5)} - 2 m_{R_j}^{(5)} + d m_{R_i}^{(5)} + \beta s = 0; j = 1,2 i = 3 - j, \tag{A.53}$$

$$m_{R_i}^{(5)} = \left\{ \begin{array}{c} 2(\alpha_i - w_i^{(5)} + d w_j^{(5)}) + \\ d(\alpha_j - w_j^{(5)} + d w_i^{(5)}) + \beta(2 + d) s^{(5)} \end{array} \right\} \Big/ V; i = 1,2 j = 3 - i. \tag{A.54}$$

By substituting $m_{R_i}^{(5)}$ into the following equation the optimal retailer's price will be obtained:

$$p_i^{(5)} = w_i^{(5)} + m_{R_i}^{(5)}; i = 1,2 j = 3 - i. \tag{A.55}$$

To obtain optimal manufacturer's price according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(5)}}{\partial w_i^{(5)}} = 0$ and $\frac{\partial U_{M_j}^{(5)}}{\partial w_j^{(5)}} = 0$ must be solved. With considering $w_i^{(5)} - c_i^{(5)} = m_{M_i}^{(5)}$ and $w_j^{(5)} - c_j^{(5)} = m_{M_j}^{(5)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(5)}}{\partial m_{M_i}^{(5)}} = 0$ and $\frac{\partial U_{M_j}^{(5)}}{\partial m_{M_j}^{(5)}} = 0$ are as follows:

$$\begin{aligned} \frac{\partial U_{M_i}^{(5)}}{\partial m_{M_i}^{(5)}} &= 2(\alpha_i - c_i + d c_j - m_{M_i}^{(5)} + d m_{M_j}^{(5)}) + d(\alpha_j - c_j + d c_i - m_{M_j}^{(5)} + d m_{M_i}^{(5)}) + \frac{\beta\,(2 + d)}{2\eta\tau} \\ &[\frac{\beta\,(2 + d) \sum_{i=1}^{2} (m_{M_i}^{(5)} + T_i)}{2\eta\tau V} + \rho_M] + (m_{M_i}^{(5)} + T_i)(d^2 - 2) + d(m_{M_j}^{(5)} + T_j) = 0, \end{aligned} \tag{A.56}$$

where $i = 1,2$ and $j = 3 - i$.

$$\begin{aligned} \frac{\partial U_{M_j}^{(5)}}{\partial m_{M_j}^{(5)}} &= 2(\alpha_j - c_j + d c_i - m_{M_j}^{(5)} + d m_{M_i}^{(5)}) + d(\alpha_i - c_i + d c_j - m_{M_i}^{(5)} + d m_{M_j}^{(5)}) + \frac{\beta\,(2 + d)}{2\eta\tau} \\ &[\frac{\beta\,(2 + d) \sum_{j=1}^{2} (m_{M_j}^{(5)} + T_j)}{2\eta\tau V} + \rho_M] + (m_{M_j}^{(5)} + T_j)(d^2 - 2) + d(m_{M_i}^{(5)} + T_i) = 0, \end{aligned} \tag{A.57}$$

where $j = 1,2$ and $i = 3 - j$. By solving the equations above the optimal $m_{M_i}^{(5)}$ is achieved:

$$m_{M_i}^{(5)} = m_{M_i}^{(1)} - \frac{\beta(2 + d)}{2\eta\left(A^{(1)} + B^{(1)}\right)} x i = 1,2 j = 3 - i \tag{A.58}$$

By substituting $m_{M_i}^{(5)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$w_i^{(5)} = c_i + m_{M_i}^{(5)}, i = 1, 2 j = 3 - i$

By calculating $\frac{\partial U_{M_i}^{(5)}}{\partial s_i^{(5)}} = 0$, the optimal amount of $s_i^{(5)}$ is achieved:

$$\frac{\partial U_M^{(5)}}{\partial s^{(5)}} = \sum_{i=1}^{2} (m_{M_i}^{(5)} + T_i) \frac{\beta(2+d)}{2\eta V} - 2\eta\, \tau\, s^{(5)} + \rho_M = 0, \tag{A.59}$$

$$s^{(5)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(5)} + (\rho_M + \tau x)V\right] \Big/ 2\eta\tau V, \tag{A.60}$$

where $i = 1, 2$ and $j = 3 - i$..

Considering $H(U_{M_i}^{(5)}) = \begin{bmatrix} \frac{-2+d^2+(d^2-2)}{4-d^2} & \frac{2\beta - d\beta\theta}{4-d^2} \\ \frac{2\beta - d\beta\theta}{4-d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(5)})$ is negatively defined. It is necessary to mention that if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right) - d\right]$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(5)})) > 0$, the concavity of the profit function holds. □.

Proposition 6 proof

To obtain the retailer price Under SP&SC (x, s_T) in Scenario 6 $\frac{\partial U_{R_i}^{(6)}}{\partial m_{R_i}^{(6)}}$ and $\frac{\partial U_{R_j}^{(6)}}{\partial m_{R_j}^{(6)}}$ must be obtained. In addition with considering $\frac{\partial U_{R_i}^{(6)}}{\partial m_{R_i}^{(6)}} = 0$ and $\frac{\partial U_{R_j}^{(6)}}{\partial m_{R_j}^{(6)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(6)}}{\partial m_{R_i}^{(6)}} = \alpha_i - w_i^{(6)} + dw_j^{(6)} - 2m_{R_i}^{(6)} - dm_{R_j}^{(6)} + \beta(s_i^{(6)} - \theta s_j^{(6)}) = 0; i = 1, 2 j = 3 - i, \tag{A.61}$$

$$\frac{\partial U_{R_j}^{(6)}}{\partial m_{R_j}^{(6)}} = \alpha_j - w_j^{(6)} + dw_i^{(6)} - 2m_{R_j}^{(6)} - dm_{R_i}^{(6)} + \beta(s_j^{(6)} - \theta s_i^{(6)}) = 0; j = 1, 2 i = 3 - j, \tag{A.62}$$

$$m_{R_i}^{(6)} = \left\{ \begin{array}{c} 2(\alpha_i - w_i^{(6)} + dw_j^{(6)} + \beta(s_i^{(6)} - \theta s_j^{(6)})) \\ +d(\alpha_j - w_j^{(6)} + dw_i^{(6)} + \beta(s_j^{(6)} - \theta s_i^{(6)})) \end{array} \right\} \Big/ V; i = 1, 2 j = 3 - i. \tag{A.63}$$

By substituting $m_{R_i}^{(6)}$ into the following equation the optimal retailer's price will be obtained:

$$p_i^{(6)} = w_i^{(6)} + m_{R_i}^{(6)}; i = 1, 2 j = 3 - i. \tag{A.64}$$

To obtain optimal manufacturer's price according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(6)}}{\partial w_i^{(6)}} = 0$ and $\frac{\partial U_{M_j}^{(6)}}{\partial w_j^{(6)}} = 0$ must be solved. With considering $w_i^{(6)} - c_i^{(6)} = m_{M_i}^{(6)}$ and $w_j^{(6)} - c_j^{(6)} = m_{M_j}^{(6)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(6)}}{\partial m_{M_i}^{(6)}} = 0$ and $\frac{\partial U_{M_j}^{(6)}}{\partial m_{M_j}^{(6)}} = 0$ are as follows:

$$\begin{aligned} \frac{\partial U_{M_i}^{(6)}}{\partial m_{M_i}^{(6)}} &= 2(\alpha_i - c_i + dc_j + \frac{\beta\rho_{M_i}}{2\eta_i\tau_i} - \frac{\theta\beta\rho_{M_j}}{2\eta_j\tau_j}) + d(\alpha_j - c_j + dc_i + \frac{\beta\rho_{M_j}}{2\eta_j\tau_j} - \frac{\theta\beta\rho_{M_i}}{2\eta_i\tau_i}) + \\ &T_i[\frac{2\beta^2(2-d\theta)}{2\eta_i\tau_i V} - \frac{\beta^2 d\theta(2-d\theta)}{2\eta_i\tau_i V} + (d^2-2)] - T_j[\frac{2\beta^2\theta(2-d\theta)}{2\eta_j\tau_j V} - \frac{\beta^2 d(2-d\theta)}{2\eta_i\tau_i V}] + \\ &m_{M_i}^{(6)}[d^2 - 2 + \frac{2\beta^2(2-d\theta)}{2\eta_i\tau_i V} - \frac{d\beta^2\theta(2-d\theta)}{2\eta_i\tau_i V} + (d^2-2)] + m_{M_j}^{(6)}[d - \frac{2\beta^2\theta(2-d\theta)}{2\eta_j\tau_j V} + \frac{\beta^2\theta(2-d\theta)}{2\eta_j\tau_j V}] = 0, \end{aligned} \tag{A.65}$$

where $i = 1, 2$ and $j = 3 - i$.

$$\begin{aligned} \frac{\partial U_{M_j}^{(6)}}{\partial m_{M_j}^{(6)}} &= 2(\alpha_j - c_j + dc_i + \frac{\beta\rho_{M_j}}{2\eta_j\tau_j} - \frac{\theta\beta\rho_{M_i}}{2\eta_i\tau_i}) + d(\alpha_i - c_i + dc_j + \frac{\beta\rho_{M_i}}{2\eta_i\tau_i} - \frac{\theta\beta\rho_{M_j}}{2\eta_j\tau_j}) + T_j[\frac{2\beta^2(2-d\theta)}{2\eta_j\tau_j V} - \\ &\frac{\beta^2 d\theta(2-d\theta)}{2\eta_j\tau_j V} + (d^2-2)] - T_i[\frac{2\beta^2\theta(2-d\theta)}{2\eta_i\tau_i V} - \frac{\beta^2 d(2-d\theta)}{2\eta_j\tau_j V}] + m_{M_j}^{(6)}[d^2 - 2 + \frac{2\beta^2(2-d\theta)}{2\eta_j\tau_j V} \\ &- \frac{d\beta^2\theta(2-d\theta)}{2\eta_j\tau_j V} + (d^2-2)] + m_{M_i}^{(6)}[d - \frac{2\beta^2\theta(2-d\theta)}{2\eta_i\tau_i V} + \frac{\beta^2\theta(2-d\theta)}{2\eta_i\tau_i V}] = 0, \end{aligned} \tag{A.66}$$

where $j = 1, 2$ and $i = 3 - j$. By solving the equations above the optimal $m_{M_i}^{(6)}$ is achieved:

$$m_{M_i}^{(6)} = m_{M_i}^{(2)} + \frac{\beta}{2\eta_i}\frac{(2-d\theta)B_j^{(2)} - (d-2\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}x_i + \frac{\beta}{2\eta_j}\frac{(d-2\theta)B_j^{(2)} - (2-d\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}x_j; i = 1,2, j = 3-i. \tag{A.67}$$

By substituting $m_{M_i}^{(6)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(6)} = c_i + m_{M_i}^{(6)}; i = 1,2 j = 3-i. \tag{A.68}$$

By calculating $\frac{\partial U_{M_i}^{(6)}}{\partial s_i^{(6)}} = 0$, the optimal amount of $s_i^{(6)}$ is achieved:

$$\frac{\partial U_M^{(6)}}{\partial s_i^{(6)}} = (m_{M_i}^{(6)} + T_i)\frac{2\beta - d\beta\theta}{V} - 2\eta_i\tau_i s_i^{(6)} + \rho_{M_i} = 0, \tag{A.69}$$

$$s_i^{(6)} = \left[\beta(2-d\theta)m_{M_i}^{(6)} + (\rho_{M_i} + \tau_i x_i)V\right]\Big/2\eta_i\tau_i V, \tag{A.70}$$

where $i = 1,2$ and $j = 3-i$.

Considering $H(U_{M_i}^{(6)}) = \begin{bmatrix} \frac{-2+d^2+(d^2-2)}{4-d^2} & \frac{2\beta - d\beta\theta}{4-d^2} \\ \frac{2\beta - d\beta\theta}{4-d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(6)})$ is negatively defined. It is necessary to mention that if $\eta_i \geqslant \beta^2(2-d\theta)^2/4(2-d^2)$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(6)})) > 0$, the concavity of the profit function holds. □.

Proposition 7 proof

To obtain the retailer price Under DLS policy s_L in Scenario 7 $\frac{\partial U_{R_i}^{(7)}}{\partial m_{R_i}^{(7)}}$ and $\frac{\partial U_{R_j}^{(7)}}{\partial m_{R_j}^{(7)}}$ must be obtained. In addition with considering $\frac{\partial U_{R_i}^{(7)}}{\partial m_{R_i}^{(7)}} = 0$ and $\frac{\partial U_{R_j}^{(7)}}{\partial m_{R_j}^{(7)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(7)}}{\partial m_{R_i}^{(7)}} = \alpha_i - w_i^{(7)} + dw_j^{(7)} - 2m_{R_i}^{(7)} + dm_{R_j}^{(7)} + \beta s^{(7)} = 0; i = 1,2 j = 3-i, \tag{A.71}$$

$$\frac{\partial U_{R_j}^{(7)}}{\partial m_{R_j}^{(7)}} = \alpha_j - w_j^{(7)} + dw_i^{(7)} - 2m_{R_j}^{(7)} + dm_{R_i}^{(7)} + \beta s^{(7)} = 0; j = 1,2 i = 3-j, \tag{A.72}$$

$$m_{R_i}^{(7)} = \left[2(\alpha_i - w_i^{(7)} + dw_j^{(7)}) + d(\alpha_j - w_j^{(7)} + dw_i^{(7)}) + \beta(2+d)s^{(7)}\right]\Big/V; i = 1,2 j = 3-i. \tag{A.73}$$

By substituting $m_{R_i}^{(7)}$ into the following equation the optimal retailer's price will be obtained:

$$p_i^{(7)} = w_i^{(7)} + m_{R_i}^{(7)}; i = 1,2 j = 3-i. \tag{A.74}$$

To obtain optimal manufacturer's price according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(7)}}{\partial w_i^{(7)}} = 0$ and $\frac{\partial U_{M_j}^{(7)}}{\partial w_j^{(7)}} = 0$ must be solved. With considering $w_i^{(7)} - c_i^{(7)} = m_{M_i}^{(7)}$ and $w_j^{(7)} - c_j^{(7)} = m_{M_j}^{(7)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(7)}}{\partial m_{M_i}^{(7)}} = 0$ and $\frac{\partial U_{M_j}^{(7)}}{\partial m_{M_j}^{(7)}} = 0$ are as follows:

$$\begin{aligned} \frac{\partial U_{M_i}^{(7)}}{\partial m_{M_i}^{(7)}} &= 2(\alpha_i - c_i + dc_j - m_{M_i}^{(7)} + dm_{M_j}^{(7)}) + d(\alpha_j - c_j + dc_i - m_{M_j}^{(7)} + dm_{M_i}^{(7)}) + \beta(2+d) \\ &\quad [\frac{\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(7)}}{2\eta\,\tau\,V} + \frac{\rho_M + \tau x}{2\eta\,\tau}] + m_{M_i}(d^2-2) + dm_{M_j}^{(7)} = 0, \end{aligned} \tag{A.75}$$

where $i = 1,2$ and $j = 3-i$.

$$\begin{aligned} \frac{\partial U_{M_j}^{(7)}}{\partial m_{M_j}^{(7)}} &= 2(\alpha_j - c_j + dc_i - m_{M_j}^{(7)} + dm_{M_i}^{(7)}) + d(\alpha_i - c_i + dc_j - m_{M_i}^{(7)} + dm_{M_j}^{(7)}) + \beta(2+d) \\ &\quad [\frac{\beta(2+d)\sum_{j=1}^{2} m_{M_j}^{(7)}}{2\eta\,\tau\,V} + \frac{\rho_M + \tau x}{2\eta\,\tau}] + m_{M_j}(d^2-2) + dm_{M_i}^{(7)} = 0, \end{aligned} \tag{A.76}$$

where $j = 1,2$ and $i = 3-j$. By solving the equations above $m_{M_i}^{(7)}$ is achieved:

$$m_{M_i}^{(7)} = m_{M_i}^{(1)} - \lambda\beta(2+d)/2\eta\tau\left(A^{(1)} + B^{(1)}\right); i = 1,2 j = 3-i. \tag{A.77}$$

By substituting $m_{M_i}^{(7)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(7)} = c_i + m_{M_i}^{(7)}; i = 1,2 j = 3-i. \tag{A.78}$$

By calculating $\frac{\partial U_{M_i}^{(7)}}{\partial s_i^{(7)}} = 0$, the optimal amount of $s_i^{(7)}$ is achieved:

$$\frac{\partial U_M^{(7)}}{\partial s^{(7)}} = \frac{\beta(2+d)}{V}\sum_{i=1}^{2} m_{M_i}^{(7)} + \tau x - -2\eta\,\tau\, s^{(7)} + \rho_M \ = 0, \tag{A.79}$$

$$s^{(7)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(7)} + (\rho_M + \lambda)V\right] \Big/ 2\eta\tau V, \tag{A.80}$$

where $i = 1,2$ and $j\ = 3 - i.$.

Considering $H(U_{M_i}^{(7)}) = \begin{bmatrix} \frac{-2+d^2+(d^2-2)}{4-d^2} & \frac{2\beta-d\beta\theta}{4-d^2} \\ \frac{2\beta-d\beta\theta}{4-d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0\leqslant d\leqslant 1$,

$H(U_{M_i}^{(7)})$ is negatively defined. It is necessary to mention that if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right)-d\right]$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(7)})) > 0$, the concavity of the profit function holds. □.

Proposition 8 proof

To obtain the retailer price Under DLS $s_L = (s_{L_1}, s_{L_2})$ in Scenario 8 $\frac{\partial U_{R_i}^{(8)}}{\partial m_{R_i}^{(8)}}$ and $\frac{\partial U_{R_j}^{(8)}}{\partial m_{R_j}^{(8)}}$ must be obtained. In addition with considering $\frac{\partial U_{R_i}^{(8)}}{\partial m_{R_i}^{(8)}} = 0$ and $\frac{\partial U_{R_j}^{(8)}}{\partial m_{R_j}^{(8)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(8)}}{\partial m_{R_i}^{(8)}} = \alpha_i - w_i^{(8)} + d w_j^{(8)} - 2m_{R_i}^{(8)} + d m_{R_j}^{(8)} + \beta(s_i^{(8)} - \theta s_j^{(8)}) = 0; i = 1,2 j = 3-i, \tag{A.81}$$

$$\frac{\partial U_{R_j}^{(8)}}{\partial m_{R_j}^{(8)}} = \alpha_j - w_j^{(8)} + d w_i^{(8)} - 2m_{R_j}^{(8)} + d m_{R_i}^{(8)} + \beta(s_j^{(8)} - \theta s_i^{(8)})_i = 0; i = 1,2 j = 3-i, \tag{A.82}$$

$$m_{R_i}^{(8)} = \left[2(\alpha_i - w_i^{(8)} + d w_j^{(8)} + \beta(s_i^{(8)} - \theta s_j^{(8)})) + d(\alpha_j - w_j^{(8)} + d w_i^{(8)} + \beta(s_j^{(8)} - \theta s_i^{(8)}))\right] \Big/ V; i = 1,2 j = 3-i. \tag{A.83}$$

By substituting $m_{R_i}^{(8)}$ into following equation the optimal retailer's price will be obtained:

$$p_i^{(8)} = w_i^{(8)} + m_{R_i}^{(8)}; i = 1,2 j = 3-i. \tag{A.84}$$

To obtain optimal manufacturer's price according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(8)}}{\partial w_i^{(8)}}=0$ and $\frac{\partial U_{M_j}^{(8)}}{\partial w_j^{(8)}} = 0$ must be solved. With considering $w_i^{(8)} - c_i^{(8)} = m_{M_i}^{(8)}$ and $w_j^{(8)} - c_j^{(8)} = m_{M_j}^{(8)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(8)}}{\partial m_{M_i}^{(8)}} = 0$ and $\frac{\partial U_{M_j}^{(8)}}{\partial m_{M_j}^{(8)}} = 0$ are as follows:

$$\begin{aligned}\frac{\partial U_{M_i}^{(8)}}{\partial m_{M_i}^{(8)}} &= 2(\alpha_i - c_i + dc_j) + d(\alpha_j - c_j + dc_i) + (2\beta - d\beta\theta)\frac{\rho_{M_i} + \tau_i x_i}{2\eta_i\tau_i} + (-2\beta\theta + d\beta)\frac{\rho_{M_j} + \tau_j x_j}{2\eta_j\tau_j} + \\ &\quad [-2 + d^2 - 2 + \frac{\beta^2(2-d\theta)^2}{2\eta_i\tau_i V} + (d^2-2)]m_{M_i}^{(8)} + (d + \beta^2(d-2\theta)\frac{(2-d\theta)}{2\eta_j\tau_j V})m_{M_j}^{(8)} = 0,\end{aligned} \tag{A.85}$$

where $i = 1,2$ and $j\ = 3 - i$.

$$\begin{aligned}\frac{\partial U_{M_j}^{(8)}}{\partial m_{M_j}^{(8)}} &= 2(\alpha_j - c_j + dc_i) + d(\alpha_i - c_i + dc_j) + (2\beta - d\beta\theta)\frac{\rho_{M_j} + \tau_j x_j}{2\eta_j\tau_j} + (-2\beta\theta + d\beta)\frac{\rho_{M_i} + \tau_i x_i}{2\eta_i\tau_i} + \\ &\quad [-2 + d^2 - 2 + \frac{\beta^2(2-d\theta)^2}{2\eta_j\tau_j V} + (d^2-2)]m_{M_j}^{(8)} + (d + \beta^2(d-2\theta)\frac{(2-d\theta)}{2\eta_i\tau_i V})m_{M_i}^{(8)} = 0,\end{aligned} \tag{A.86}$$

where $j = 1,2$ and $i\ = 3 - j$. By solving the equations above $m_{M_i}^{(8)}$ is achieved:

$$m_{M_i}^{(8)} = m_{M_i}^{(2)} + \frac{\beta}{2\eta_i\tau_i}\frac{(2-d\theta)B_j^{(2)} - (d-2\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}\lambda_i + \frac{\beta}{2\eta_j\tau_j}\frac{(d-2\theta)B_j^{(2)} - (2-d\theta)A_j^{(2)}}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}}\lambda_j; i = 1,2 j = 3-i. \tag{A.87}$$

By substituting $m_{M_i}^{(8)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(8)} = c_i + m_{M_i}^{(8)}; i = 1,2 j = 3 - i. \tag{A.88}$$

By calculating $\frac{\partial U_{M_i}^{(8)}}{\partial s_i^{(8)}} = 0$, the optimal amount of $s_i^{(8)}$ is achieved:

$$\frac{\partial U_M^{(8)}}{\partial s_i^{(8)}} = m_{M_i}^{(8)} \frac{2\beta - d\beta\theta}{V} - 2\eta_i \tau_i s_i^{(8)} + \rho_{M_i} + \tau_i x_i = 0, \tag{A.89}$$

$$s_i^{(8)} = \left[\beta(2 - d\theta) m_{M_i}^{(8)} + (\rho_{M_i} + \lambda_i) V\right] \Big/ 2\eta_i \tau_i V, \tag{A.90}$$

where $i = 1,2$ and $j = 3 - i$.

Considering $H(U_{M_i}^{(8)}) = \begin{bmatrix} \frac{-2 + d^2 + (d^2 - 2)}{4 - d^2} & \frac{2\beta - d\beta\theta}{4 - d^2} \\ \frac{2\beta - d\beta\theta}{4 - d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(8)})$ is negatively defined. It is necessary to mention that if $\eta_i \geqslant \beta^2 (2 - d\theta)^2 / 4(2 - d^2)$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(8)})) > 0$, the concavity of the profit function holds. □.

Proposition 9 proof

To obtain the retailer price Under GCSE policy in scenario 9 $\frac{\partial U_{R_i}^{(9)}}{\partial m_{R_i}^{(9)}}$ and $\frac{\partial U_{R_j}^{(9)}}{\partial m_{R_j}^{(9)}}$ must be obtained. In addition, with considering $\frac{\partial U_{R_i}^{(9)}}{\partial m_{R_i}^{(9)}} = 0$ and $\frac{\partial U_{R_j}^{(9)}}{\partial m_{R_j}^{(9)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(9)}}{\partial m_{R_i}^{(9)}} = \alpha_i - w_i^{(8)} + dw_j^{(8)} - 2m_{R_i}^{(8)} + dm_{R_j}^{(8)} + \beta s^{(8)} = 0; i = 1,2 j = 3 - i, \tag{A.91}$$

$$\frac{\partial U_{R_j}^{(9)}}{\partial m_{R_j}^{(9)}} = \alpha_j - w_j^{(9)} + dw_i^{(9)} - 2m_{R_j}^{(9)} + dm_{R_i}^{(9)} + \beta s^{(9)} = 0; j = 1,2 i = 3 - j, \tag{A.92}$$

$$m_{R_i}^{(9)} = \left\{ \begin{array}{c} 2(\alpha_i - w_i^{(9)} + dw_j^{(9)}) + \\ d(\alpha_j - w_j^{(9)} + dw_i^{(9)}) + \beta(2 + d)(s^{(9)} + s_G) \end{array} \right\} \Big/ V; i = 1,2, j = 3 - i, \tag{A.93}$$

By substituting $m_{R_i}^{(9)}$ into the following equation the optimal retailer's price will be obtained:

$$p_i^{(9)} = w_i^{(9)} + m_{R_i}^{(9)}; i = 1,2 j = 3 - i. \tag{A.94}$$

To obtain optimal manufacturer's price according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(9)}}{\partial w_i^{(9)}}=0$ and $\frac{\partial U_{M_j}^{(9)}}{\partial w_j^{(9)}} = 0$ must be solved. With considering $w_i^{(9)} - c_i^{(9)} = m_{M_i}^{(9)}$ and $w_j^{(9)} - c_j^{(9)} = m_{M_j}^{(9)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(9)}}{\partial m_{M_i}^{(9)}} = 0$ and $\frac{\partial U_{M_j}^{(9)}}{\partial m_{M_j}^{(9)}} = 0$ are as follows:

$$\begin{aligned} \frac{\partial U_{M_i}^{(9)}}{\partial m_{M_i}^{(9)}} &= 2(\alpha_i - c_i + dc_j - m_{M_i}^{(9)} + dm_{M_j}^{(9)}) + d(\alpha_j - c_j + dc_i - m_{M_j}^{(9)} + dm_{M_i}^{(9)}) + \beta(2 + d) \\ &\quad [\frac{\beta(2 + d)\sum_{i=1}^{2} m_{M_i}^{(9)}}{2\eta\, \tau\, V} + \frac{\rho_M + \lambda}{2\eta\, \tau}] + m_{M_i}^{(9)}(d^2 - 2) + dm_{M_j}^{(9)} = 0, \end{aligned} \tag{A.95}$$

where $i = 1,2$ and $j = 3 - i$.

$$\begin{aligned} \frac{\partial U_{M_j}^{(9)}}{\partial m_{M_j}^{(9)}} &= 2(\alpha_j - c_j + dc_i - m_{M_j}^{(9)} + dm_{M_i}^{(9)}) + d(\alpha_i - c_i + dc_j - m_{M_i}^{(9)} + dm_{M_j}^{(9)}) + \beta(2 + d) \\ &\quad [\frac{\beta(2 + d)\sum_{j=1}^{2} m_{M_j}^{(9)}}{2\eta\, \tau\, V} + \frac{\rho_M + \lambda}{2\eta\, \tau}] + m_{M_j}^{(9)}(d^2 - 2) + dm_{M_i}^{(9)} = 0, \end{aligned} \tag{A.96}$$

where $j = 1,2$ and $i = 3 - j$. By solving the equations above $m_{M_i}^{(9)}$ is achieved:

$$m_{M_i}^{(9)} = m_{M_i}^{(1)} - \frac{\beta(2 + d)}{A^{(1)} + B^{(1)}} s_G, i = 1,2. \tag{A.97}$$

By substituting $m_{M_i}^{(9)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(9)} = c_i + m_{M_i}^{(9)}, i = 1,2 j = 3-i \tag{A.98}$$

By calculating $\frac{\partial U_{M_i}^{(9)}}{\partial s_i^{(9)}} = 0$, the optimal amount of $s_i^{(9)}$ is achieved:

$$\frac{\partial U_M^{(9)}}{\partial s^{(9)}} = \frac{\beta(2+d)}{V}\sum_{i=1}^{2} m_{M_i}^{(9)} + \lambda - 2\eta\,\tau\, s^{(9)} + \rho_M = 0, \tag{A.99}$$

$$s^{(9)} = \left[\beta(2+d)\sum_{i=1}^{2} m_{M_i}^{(9)} + \rho_M V\right] \Big/ 2\eta\tau V, \tag{A.100}$$

where $i = 1,2$ and $j = 3-i$.

Considering $H(U_{M_i}^{(9)}) = \begin{bmatrix} \frac{-2+d^2+(d^2-2)}{4-d^2} & \frac{2\beta - d\beta\theta}{4-d^2} \\ \frac{2\beta - d\beta\theta}{4-d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(9)})$ is negatively defined. It is necessary to mention that if $\eta \geqslant \beta^2(2-d)/(2+d)\left[2\left(2-d^2\right)-d\right]$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(9)})) > 0$, the concavity of the profit function holds. □.

Proposition 10 proof

To obtain the retailer price When the RA establishes GCSE according to Scenario 10 $\frac{\partial U_{R_i}^{(10)}}{\partial m_{R_i}^{(10)}}$ and $\frac{\partial U_{R_j}^{(10)}}{\partial m_{R_j}^{(10)}}$ must be obtained. In addition, with considering $\frac{\partial U_{R_i}^{(10)}}{\partial m_{R_i}^{(10)}} = 0$ and $\frac{\partial U_{R_j}^{(10)}}{\partial m_{R_j}^{(10)}} = 0$ the optimal retailer's price will be calculated:

$$\frac{\partial U_{R_i}^{(10)}}{\partial m_{R_i}^{(10)}} = \alpha_i - w_i^{(10)} + dw_j^{(10)} - 2m_{R_i}^{(10)} + dm_{R_j}^{(10)} + \beta(s_i^{(10)} - \theta s_j^{(10)}) = 0; i = 1,2 j = 3-i, \tag{A.101}$$

$$\frac{\partial U_{R_j}^{(10)}}{\partial m_{R_j}^{(10)}} = \alpha_j - w_j^{(10)} + dw_i^{(10)} - 2m_{R_j}^{(10)} + dm_{R_i}^{(10)} + \beta(s_j^{(10)} - \theta s_i^{(10)}) = 0; j = 1,2 i = 3-j, \tag{A.102}$$

$$m_{R_i}^{(10)} = \left\{ \begin{array}{c} 2(\alpha_i - w_i^{(10)} + dw_j^{(10)} + \beta(s_i^{(10)} - \theta s_j^{(10)})) \\ +d(\alpha_j - w_j^{(10)} + dw_i^{(10)} + \beta(s_j^{(10)} - \theta s_i^{(10)})) + \beta(2-d\theta)s_{G_i} + \beta(d-2\theta)s_{G_j} \end{array} \right\} \Big/ V; i = 1,2 j = 3-i. \tag{A.103}$$

By substituting $m_{R_i}^{(10)}$ into following equation the optimal retailer's price will be obtained:

$$p_i^{(10)} = w_i^{(10)} + m_{R_i}^{(10)}; i = 1,2 j = 3-i. \tag{A.104}$$

To obtain optimal manufacturer's price according to the Stackelberg game model, $\frac{\partial U_{M_i}^{(10)}}{\partial w_i^{(10)}}=0$ and $\frac{\partial U_{M_j}^{(10)}}{\partial w_j^{(10)}} = 0$ must be solved. With considering $w_i^{(10)} - c_i^{(10)} = m_{M_i}^{(10)}$ and $w_j^{(10)} - c_j^{(10)} = m_{M_j}^{(10)}$ as the manufacturer's unit marginal profit $\frac{\partial U_{M_i}^{(10)}}{\partial m_{M_i}^{(10)}} = 0$ and $\frac{\partial U_{M_j}^{(10)}}{\partial m_{M_j}^{(10)}} = 0$ are as follows:

$$\begin{aligned} &\frac{\partial U_{M_i}^{(10)}}{\partial m_{M_i}^{(10)}} = 2(\alpha_i - c_i + dc_j) + d(\alpha_j - c_j + dc_i) + \frac{\beta\,(2-d\theta)\rho_{M_i}}{2\eta_i\tau_i V} + \frac{\beta(d-2\theta)\rho_{M_j}}{2\eta_i\tau_i V} + \\ &\frac{\beta\,(2-d\theta)\lambda_i}{2\eta_i\tau_i V} + \frac{\beta(d-2\theta)\lambda_j}{2\eta_i\tau_i V} + [\frac{\beta^2(2-d\theta)^2}{2\eta_i\tau_i V} - 2(2-d^2)]m_{M_i}^{(10)} + [d + \frac{\beta^2(2-d\theta)(d-2\theta)}{2\eta_j\tau_j V}]m_{M_j}^{(10)} = 0, \end{aligned} \tag{A.105}$$

where $i = 1,2$ and $j = 3-i$.

$$\begin{aligned} &\frac{\partial U_{M_j}^{(10)}}{\partial m_{M_j}^{(10)}} = 2(\alpha_j - c_j + dc_i) + d(\alpha_i - c_i + dc_j) + \frac{\beta\,(2-d\theta)\rho_{M_j}}{2\eta_j\tau_j V} + \frac{\beta(d-2\theta)\rho_{M_i}}{2\eta_i\tau_i V} + \\ &\frac{\beta\,(2-d\theta)\lambda_j}{2\eta_j\tau_j V} + \frac{\beta(d-2\theta)\lambda_j}{2\eta_j\tau_j V} + [\frac{\beta^2(2-d\theta)^2}{2\eta_j\tau_j V} - 2(2-d^2)]m_{M_j}^{(10)} + [d + \frac{\beta^2(2-d\theta)(d-2\theta)}{2\eta_i\tau_i V}]m_{M_i}^{(10)} = 0, \end{aligned} \tag{A.106}$$

where $j = 1,2$ and $i = 3-j$. By solving the equations above $m_{M_i}^{(10)}$ is achieved:

$$m_{M_i}^{(10)} = m_{M_i}^{(2)} + \frac{\beta\left[\left(2-d\theta\right)B_j^{(2)} - (d-2\theta)A_j^{(2)}\right]}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} s_{G_i} + \frac{\beta\left[\left(d-2\theta\right)B_j^{(2)} - (2-d\theta)A_j^{(2)}\right]}{A_i^{(2)}A_j^{(2)} - B_i^{(2)}B_j^{(2)}} s_{G_j}; i = 1,2 j = 3-i. \tag{A.107}$$

By substituting $m_{M_i}^{(10)}$ in the following equation the optimal manufacturer's wholesale price will be obtained:

$$w_i^{(10)} = c_i + m_{M_i}^{(10)}; i = 1,2 j = 3 - i. \tag{A.108}$$

By calculating $\frac{\partial U_{M_i}^{(10)}}{\partial s_i^{(10)}} = 0$, the optimal amount of $s_i^{(2)}$ is achieved:

$$\frac{\partial U_{M_i}^{(10)}}{\partial s_i^{(10)}} = m_{M_i}^{(10)} \frac{2\beta - d\beta\theta}{V} - 2\eta_i \tau_i s_i^{(10)} + \rho_{M_i} = 0, \tag{A.109}$$

$$s_i^{(10)} = \left[\beta(2 - d\theta) m_{M_i}^{(10)} + \rho_{M_i} V\right] \Big/ 2\eta_i \tau_i V, \tag{A.110}$$

where $i = 1, 2$ and $j = 3 - i$.

Considering $H(U_{M_i}^{(10)}) = \begin{bmatrix} \frac{-2 + d^2 + (d^2 - 2)}{4 - d^2} & \frac{2\beta - d\beta\theta}{4 - d^2} \\ \frac{2\beta - d\beta\theta}{4 - d^2} & -2\eta \end{bmatrix}$ as the Hessian matrix and $0 \leqslant d \leqslant 1$,

$H(U_{M_i}^{(10)})$ is negatively defined. It is necessary to mention that if $\eta_i \geqslant \beta^2 (2 - d\theta)^2 / 4(2 - d^2)$ the determinant of Hessian matrix takes a positive amount $\det(H(U_{M_i}^{(10)})) > 0$, the concavity of the profit function holds. □.

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