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GREEN SUSTAINABLE SUPPLY CHAIN UNDER CAP AND TRADE REGULATION INVOLVING GOVERNMENT INTROSPECTION

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Abstract. This paper investigates Government intervention in a three-echelon supply chain comprising one manufacturer and one retailer. Government is the top level member trying to reduce environmental impacts based on the amount of carbon emission during the production process. Government controls the chain by collecting tax from the retailer which is indirectly paid by the customer and paying subsidy/imposing fine on the manufacturer. Government encourages manufacturer to reduce carbon emission by contributing some subsidy and also makes an effort to generate Government net revenue (GNR) by imposing tax. The GNR is generated by collecting tax from the retailer on the sold product and penalty from the manufacturer at the trading price for the extra amount of emissions. The retail price is decided based on the selling price, tax and greening level. We aim to determine optimal levels of pricing, greening and amount of tax to be levied. The models for both linear and iso-elastic demand patterns are developed. The aim of this piece research is two-fold: (i) review the existent literature on the relationship between environmental collaboration and sustainability performance and (ii) render a tenable prototype of supply chain to illuminate the relationship between sustainability and profitability. According to the aforesaid goals this paper has carried out a detailed empirical research by using advanced structural equation modelling approaches. The research findings will be particularly important for manufacturing companies struggling to find techniques to achieve sustainability performance. Also it will aid the supply chains in developing environmental collaboration with the Govt. in order to attain the targets of GSCM.

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1. Introduction

According to the report of the Intergovernmental Panel on Climate Change (IPCC), the rising rate of global temperature in recent 50 years is approximately twice as fast as that in previous periods. Climate change arising due to anthropogenic activities has been identified as one of the greatest threats to the mankind. Carbon emission is held responsible for the majority of this threat. Reducing carbon emissions is urgently needed otherwise the existence of the whole civilization will come at stake. Therefore, the issue of environmentally

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conscious supply chain or green supply chain management has come up as a new research paradigm in operations management [7,11,15,30,32,41,49]. Eventually the concept of sustainable development and green supply chain management (GSCM) has become a research hotspot. In this paper, we look at an important research area on conflict and cooperation between supply chain partners when they undertake greening initiatives. In this process, Government is the most powerful decision maker who can make rules to reduce pollution and increase the sustainability of products. Governments in many countries have implemented policy instruments to regulate carbon emissions. Two typical polices among them are very effective. These are the cap-and-trade and the carbon tax regulation, in which "cap" indicates that government sets and limits the total amount of carbon emissions and "trade" indicates that firms can buy/sell permits in carbon trading market if their permits are short/surplus [53]. The impacts of these two regulations are different. Carbon tax regulation guides the manufacturers to adjust price while cap-and-trade regulation guides to adjust the quantity to reduce the total emission. In the cap-and-trade system, emission limit (cap) is imposed by the Government. If the emission limit is insufficient to produce target production, extra permits should be purchased *via* trading [14]. Since the European Union Emissions Trading Scheme (EU ETS) was established in 2005, the movement has spread rapidly to Europe, America and Asia [9]. The Government of the developed countries in America and Europe have implemented regulations to reduce carbon emissions and imposed strict financial instructions to the manufacturers producing products causing carbon emission. The Government has also cautioned consumers about the environmental damages as consumer awareness concerning the environmental impact associated to green product choices have huge impact in sustainability.

This research considers different aspects based on consumer behaviours, the product's impact on the environment, SC members' greening efforts and Government policies. We assume that the demand of the consumers depends on the retail price, greening effort and tax. Then we consider the cap-and-trade and tax policies in the SC members. The Government is the top-level decision maker in the integrated system, who announces in advance the rate at which the tax is to be collected from the customers through the retailer. The amount of tax is dependent on the retail price of the green product. This is done with the aim to make the consumers green conscious and the cap and trade policy is imposed to minimize the carbon emission, which is the part of the Government's sustainable development activities. The taxes paid by the customers are transferred to the Government in toto by the retailer. This is a well established practice because the sustainable and development activities of the Government are executed by tax payers money only. Government collects taxes from consumers through retailer in different forms,such as GST, VAT, etc. in India [19] from the customers through the retailer. Government uses that money collected as tax to pay the subsidy to the green conscious manufacturer as and when necessary to encourage minimizing carbon emission.

In this paper we consider a three-echelon supply chain with Government, a single manufacturer and a single retailer. The manufacturer produces new products from the fresh raw materials and sells the products to the retailer who is the extreme downstream chain member. The manufacturer is green conscious and environment friendly and therefore invests in the greening of the product. Government interacts with manufacturer paying subsidy/penalized fine to reduce environmental impacts of carbon emission and interacts with retailer by collecting tax on the products sold. We propose the model where the market demand is assumed to be dependent on the greening innovation of manufacturer, amount of tax imposed on the green product and retail price of the product. Both linear and non-linear kind of demands have been considered in this work. We consider the different policies of game theory and different SC structures by developing interactive models between the Government and SC members. We have analysed four interactive models namely centralized, decentralized and two Stackelberg games.

The rest of the paper is organized as follows: Section 2 provides brief literature review along with the motivation of our research. Section 3 explains the fundamental assumptions and notations used for developing the proposed models. Section 4 deals with mathematical formulation and analysis of the model. Some important results and discussions on our findings are given in Section 5. Section 6 provides numerical results. Sensitivity analysis is performed in Section 7, and finally Section 8 draws conclusions on the findings of the paper.

2. Literature review

In recent years, the global climate change problem caused by carbon emissions has become an important environmental issue and has severely affected sustainable development. Anthropogenic activities hold the lions share of the responsibility. In this section, we will review the relevant literature considering three different streams of researches: SC (supply chain) coordination, PC (pollution control) mechanism and Government intervention in GSCM.

SC coordination: SC coordination between the members of the chain is the most important aspect behind a successful supply chain. The cooperation and competition between the SC members in the integrated business is to be improved as it can enhance the whole performance of the SC. In the late of nineteenth century Choi [10] did some pioneer work in the field of SC coordination. He formulated Supply chain models for substitutable products and solved using game theory framework. The outcome of his work showed retail price is lowest under cooperation and leader is beneficial in non cooperative decision structure. Ghosh and Shah [21,22] investigated green channel under competition of a green Supply chain and discussed different cost sharing contracts which showed that the coordination leads to improvement of the profit of the chain. Giri *et al.* [17] studied two substitutable and one complementary products in two-echelon Supply chain. Li *et al.* [35] analysed the pricing strategies of a dual channel Supply chain in which environmental conscious manufacturers produce green products. Wei *et al.* [54], Giri *et al.* [20] studied the pricing competition problems of two complementary products in two-echelon Supply chain. Giri *et al.* [18] analysed a closed-loop supply chain with selling price, warranty period and green sensitive consumer demand under revenue sharing contract. Competitions between a supplier and a manufacturer in a green supply chain was investigated by Sheu [45]. Li and Li [36] developed game theoretic model for sustainable supply chain under competition in product sustainability. Dong *et al.* [13] discussed about investment on sustainability of a product under the centralized and decentralized scenarios.

PC mechanism: scientists and researchers are engrossed in finding out useful mechanisms to control the environmental pollution in and out for past few decades. In a supply chain pollution control includes many activities such as green innovation, green manufacturing, green conscious promotional activities and etc. One can refer Tseng *et al.* [51,52] for the same. Green manufacturing, green environment designing and green purchasing have been discussed by Arnette *et al.* [3], Kurk and Eagan [32], Diabat and Govindan [12], Green *et al.* [23], Tian *et al.* [50]. Aramyan *et al.* [2] and Sheu and Chen [46] have worked on pollution control and investigated the governmental financial intervention. Bai *et al.* [4], Xu *et al.* [57] also studied green SC system under two-part tariffs contracts and carbon cap-and-trade regulation. Basiri and Heydari [6] studied a collaboration model of a tradition non-green and newly launched green products through one manufacturer and one retailer. Madani and Rasti-Barzoki [38], Zhang and Wang [60] formulated a mathematical model on green innovation.

Recycling of products plays a very important role in pollution control. Recycling with environmental consideration was discussed by Yu and Solvang [59]. Krikke *et al.* [34] analysed decisions concerning the recyclability of a product in detail. Jafari *et al.* [27] studied waste recycling in a three-echelon supply chain model and reverse logistics in dual channel model. Re-manufacturing Seitz, [43], Zhu *et al.* [62] and recycling Chen *et al.* [8] has been discussed in different time frames as different mechanisms of pollution control in the supply chain. Nagurney and Wooliey [40] developed a multi-criteria network model for a sustainable supply chain. Alhaj *et al.* [1] delivered a carbon-sensitive study very effectively. Another very effective mechanism to control pollution in a supply chain are cap-and-trade and carbon tax regulations. Under carbon cap policy, Qi *et al.* [42] studied one supplier and two retailers and provided the range of carbon cap to the policy maker for effectively reduced carbon emissions. Ji *et al.* [28] analysed a model using the Stackelberg game elaborately and Ji *et al* [29] further investigated on-line to off-line supply chain under cap-and-trade regulation fruitfully. Zhang *et al.* [61] discussed an evolutionary game analysis for portfolio policies on green innovation mode under carbon tax and innovation subsidy.

Government intervention in GSCM: government intervention plays the most important role while controlling the damages occurred to the climate due to carbon emission. Government has implemented polices for the supply chains to regulate carbon emissions. The two most effective polices are the cap-and-trade and carbon tax regulation, in which "cap" indicates Government sets and limits the total amount of carbon emissions and "trade" indicates firms can buy/sell permits in carbon trading market if their permits are short/surplus. Krass *et al.* [33] investigated profit maximization problem under carbon tax regulation under cap-and-trade policy and found that the increased tax rate does not always influence the firms to adopt cleaner technology. Yang *et al.* [58] have discussed cap-and-trade scheme where two competing supply chains successfully reduce carbon emission rate and lower retail price, which increases consumers' welfare. Xu *et al.* [56] studied the production and pricing decisions under cap-and-trade and carbon tax regulations.

Researchers are mainly focused on environmental protection in green supply chain under the circumstances of the Government tariffs (tax and/or subsidy). Bansal and Gangopadhyay [5] demonstrated that an approach of discriminatory subsidy is welfare enhancing but mitigates total pollution. Xiangnan Song *et al.* [48] have discussed how to effectively guide carbon reduction behaviour of building owners under emission trading scheme through an evolutionary game-based study. Shen Neng *et al.* [44] prepared a review of carbon trading based on an evolutionary perspective. Mahmoudi and Rasti-Barzoki [39] showed that impose tariffs are most effective Government activity to reduce environmental impacts. Hafezalkotob [24–26] has considered the Govt. environmental protection policies on green and non-green supply chains. Further Sinayi and Rasti-Barzoki [47] considered the Government intervention on a supply chain in which sustainability and integration of greening product is considered. Xiao *et al.* [55] formulated a sustainable supply chain model in which the Government taxes the supplier for the carbon footprint. Liu *et al.* [37] introduced Government subsidies to the firms such that SC members adopt low-carbon strategy. Their analysis showed that leader is beneficial but after emission reduction, it may not happen. Xu *et al.* [57] derived the optimal pollution reduction and production decision for a cost-sharing contract with two-part tariffs agreement under cap-and-trade regulation.

3. Notations and assumptions

The following notations are used to develop the proposed model:

3.1. Notations

D_l: Market demand (linear pattern) of the product in the retail channel
D_i: Market demand (iso-elastic pattern) of the product in the retail channel
p: Unit retail price
c: Unit production cost
w: Unit wholesale price
m: Retailer's margin on the product ($p = w + m$)
A: Basic market potential
θ: Greening effort of the manufacturer (a continuous variable)
t: Government tax vector (*e.g.* Goods and services tax or GST)
a: Carbon emission per unit when greening effort is zero, $a > 0$
b: Coefficient of greening effort on reducing the carbon emission, $b > 0$
s: Unit carbon emission trading price
K: Carbon emission cap
α: Price sensitivity of demand
β: Sensitivity of greening effort
γ: Sensitivity of the tax vector
λ: Greening investment cost
δ: Fraction of retail price used as Government tax ($0 < \delta < 1$)
PIC_l: Profit of the integrated channel for linear demand
PIC_i: Profit of the integrated channel for iso-elastic demand
PM_l: Profit of the manufacturer for linear demand

PM_i: Profit of the manufacturer for iso-elastic demand
PR_l: Profit of the retailer for linear demand
PR_i: Profit of the retailer for iso-elastic demand
PG_l: Net revenue of Government for linear demand
PG_i: Net revenue of Government for iso-elastic demand

3.2. Assumptions

The following assumptions are made to develop the proposed model:

(i) The supply chain has a vertical structure with three levels. The Government is the top-level decision maker. One green conscious manufacturer and a retailer are the bottom level members. Government interacts with the manufacturer by paying subsidy/collecting penalized fine to reduce environmental impacts of carbon emission and interacts with retailer by collecting tax on the products sold.

(ii) Government provides a cap-and-trade regulation for emissions. If the total carbon emissions exceeds the cap K, the manufacturer pays fine for excess emissions by trading price s. Conversely, if the total carbon emissions are less than K, the manufacturer gets the subsidy for a deficient amount of emissions at the same trading price s. Again the Government collects tax such as goods and services tax (GST) t per unit item sold from the retailer.

(iii) The retailer faces completely deterministic demand which is dependent on price (p), greening level (θ) and Government tax (GST) (t). We consider two types of demand pattern, *viz.* linear and iso-elastic. Considering today's market trend towards the use of green products (products that are less harmful to the environment and society), demand is assumed to be increasing on the eco-friendliness of the product; the more eco-friendly the product, the higher the demand will be. On the other hand, demand is assumed to be decreasing on the tax vector (t) of the product. As a result, the demand function decreases with respect to its own price, tax and increases with respect to greening level. Thus, the demand functions are assumed as

$$D_l = A - \alpha p + \beta\theta - \gamma t$$
$$D_i = \frac{A\theta^\beta}{p^\alpha t^\gamma}.$$

(iv) Internally Government fixes the amount of tax and intimates the retailer. It is logical to fix the amount of tax of the product depending on its retail price. Here we take the tax vector t as fraction of the retail price p ($t = \delta p$) where $0 < \delta < 1$. Therefore, we maximize the profit function of the integrated chain with respect to two decision variables-retail price (p) and greening investment level (θ).
As we have assumed the tax vector as $t = \delta p$, the demand functions in linear and iso-elastic patterns take the form

$$D_l = A - \alpha p + \beta\theta - \gamma\delta p = A - (\alpha + \delta\gamma)p + \beta\theta$$
$$D_i = \frac{A\theta^\beta}{p^\alpha(\delta p)^\gamma} = \frac{A\theta^\beta}{p^{\alpha+\gamma}\delta^\gamma}.$$

(v) The greening effort is initiated by the manufacturer in order to reduce carbon emission. The manufacturer produces products inducing carbon emissions of amount $(a - b\theta)$. But even putting greening effort by advanced technology. Carbon emission cannot be completely eliminated. So we assume that $0 < \theta < \frac{a}{b}$. In order to model the cost of greening effort, we assume that unit cost to add eco-friendliness to the product is $\lambda\theta^2$. The quadratic form indicates that expenditure on eco-friendliness has a diminishing return on demand. Therefore, the total cost of production of one unit green product is considered as $c + \lambda\theta^2$.

4. Model formulation and analysis

We consider a three-layer green supply chain which consists of Government as upstream player,and a manufacturer and a retailer as downstream players. The manufacturer produces and sells the green product through the retail channel. The net revenue of Government (PG) is accumulated by collecting tax from the retailer and paying subsidy/collecting penalized fine to reduce environmental impacts of carbon emission to/from the manufacturer. The profit of the manufacturer (PM) is calculated from the total sales revenue, total production cost including greening investment, subsidy/fine for slack/surplus amount of carbon emissions and greening investment cost. The profit of the retailer (PR) is calculated from the products sold solely in the retail channel and the amount of tax paid to the Government Therefore, the profit functions are given by

$$\mathrm{PG}(t) = s[(a-b\theta)D - K]^{+} + tD \tag{4.1}$$

$$\mathrm{PM}(w,\theta) = \big(w - c - \lambda\theta^2\big)D - s[(a-b\theta)D - K]^{+} \tag{4.2}$$

$$\mathrm{PR}(p) = (p - w - t)D \tag{4.3}$$

where D denotes the demand of the chain. The profit of the integrated channel is therefore,

$$\mathrm{PIC}(p,\theta) = \mathrm{PG} + \mathrm{PM} + \mathrm{PR}. \tag{4.4}$$

The profit functions for linear demand are

$$\mathrm{PG}_l(t) = s[(a-b\theta)\{A - (\alpha+\delta\gamma)p + \beta\theta\} - K]^{+} + t[A - (\alpha+\delta\gamma)p + \beta\theta] \tag{4.5}$$

$$\mathrm{PM}_l(w,\theta) = \big(w - c - \lambda\theta^2\big)[A - (\alpha+\delta\gamma)p + \beta\theta] - s[(a-b\theta)\{A - (\alpha+\delta\gamma)p + \beta\theta\} - K]^{+} \tag{4.6}$$

$$\mathrm{PR}_l(p) = (p - w - t)[A - (\alpha+\delta\gamma)p + \beta\theta] \tag{4.7}$$

and the profit functions for iso-elastic demand are

$$\mathrm{PG}_i(t) = s\left[(a-b\theta)\frac{A\theta^{\beta}}{p^{\alpha+\gamma}\delta^{\gamma}} - K\right]^{+} + t\frac{A\theta^{\beta}}{p^{\alpha+\gamma}\delta^{\gamma}} \tag{4.8}$$

$$\mathrm{PM}_i(w,\theta) = \big(w - c - \lambda\theta^2\big)\frac{A\theta^{\beta}}{p^{\alpha+\gamma}\delta^{\gamma}} - s\left[(a-b\theta)\frac{A\theta^{\beta}}{p^{\alpha+\gamma}\delta^{\gamma}} - K\right]^{+} \tag{4.9}$$

$$\mathrm{PR}_i(p) = (p - w - t)\frac{A\theta^{\beta}}{p^{\alpha+\gamma}\delta^{\gamma}}\cdot \tag{4.10}$$

We now optimize the profit functions with respect to the decision variables for integrated/centralized and decentralized policies.

4.1. Integrated/Centralized policy

In this policy, all players cooperatively decide the optimum values of the key decision variables. Since there is a single decision maker, the internal credit transfer parameters (wholesale price w) do not play any role. The optimal decisions are to be obtained from the following:

$$\max_{(p,\theta)} \mathrm{PIC}(p,\theta) = \arg\max_{(p,\theta)} \big(p - c - \lambda\theta^2\big)D.$$

In order to guarantee that the profit function in integrated policy is strictly concave *i.e.* it has a unique maximum value, we derive the following propositions:

4.1.1. Linear demand

The profit of the integrated channel for linear demand is

$$\mathrm{PIC}_l(p,\theta) = \mathrm{PG}_l + \mathrm{PM}_l + \mathrm{PR}_l = \left(p - c - \lambda\theta^2\right) D_l = \left(p - c - \lambda\theta^2\right)[A - (\alpha + \delta\gamma)p + \beta\theta]. \tag{4.11}$$

Now to find the optimum values of the variables p and θ for which the profit PIC_l of the integrated policy is maximum, we differentiate equation (4.11) with respect to p and θ. We obtain the optimal results as given in Proposition 4.1.

Proposition 4.1. *The profit function* PIC_l *is jointly concave in* p *and* θ *and the centralized policy gives a unique solution provided that* $A + \beta\theta > p\phi_1$ *and* $A + 4\beta\theta > \frac{\beta^2}{4\lambda\phi_1} + \phi_1(p + \theta^2\lambda)$ *and the optimal decisions are*

$$p^* = \frac{3\beta^2 + 4\phi_1\lambda(A + c\phi_1)}{8\phi_1^2\lambda}$$
$$\theta^* = \frac{\beta}{2\lambda\phi_1} \text{ where } \phi_1 = (\alpha + \gamma\delta).$$

Proof. Proof of Proposition 4.1 is given in Appendix A. □

4.1.2. Iso-elastic demand

The profit of the integrated channel for Iso-elastic demand is

$$\mathrm{PIC}_i(p,\theta) = \mathrm{PG}_i + \mathrm{PM}_i + \mathrm{PR}_i = \left(p - c - \lambda\theta^2\right) D_i = \left(p - c - \lambda\theta^2\right)\left(\frac{A\theta^\beta}{p^{\alpha+\gamma}\delta^\gamma}\right)\cdot \tag{4.12}$$

Now, to find the optimum values of the variables p and θ for which the profit PIC_i of the integrated policy is maximum we differentiate equation (4.12) with respect to p and θ. We obtain the optimal results as given in Proposition 4.2.

Proposition 4.2. *The profit function* PIC_i *is jointly concave in* p *and* θ *and the centralized policy gives a unique solution provided that* $p(\phi_2 - 1) < (\phi_2 + 1)(c + \theta^2\lambda)$, $(p - c)\beta(\beta - 1) < (\beta + 1)(\beta + 2)\theta^2\lambda$ *and* $2p\lambda\theta^2(\beta - 1)\phi_2(\phi_4 - 1) + \lambda^2\theta^4(\beta + 2)\phi_2(1 - \phi_4) + 2c\phi_2\left[p\beta\phi_4 + \lambda\theta^2(1 - \beta\phi_4 + \phi_3)\right] > \beta\left[p^2(\phi_2 - 1)\phi_4 + c^2\phi_2(\phi_4 + 1)\right]$, *where*

$$\phi_2 = \alpha + \gamma,$$
$$\phi_3 = \alpha + \beta + \gamma,$$
$$\phi_4 = \alpha - \beta + \gamma,$$

and the optimal decisions are

$$p^* = \frac{2c\phi_3}{2\phi_3 - (\beta + 2)}$$
$$\theta^* = \sqrt{\frac{c\beta}{\lambda\{2\phi_3 - (\beta + 2)\}}}.$$

Proof. Proof of Proposition 4.2 is given in Appendix B. □

4.2. Decentralized policy (Nash Game)

In this game, the Government, the manufacturer and the retailer make their decisions simultaneously and non-cooperatively. At the Nash equilibrium, all members maximize their own profits. The Government optimizes its own profit PG*, the manufacturer finds the optimum wholesale price w^* and the optimum level of greening θ^* to achieve the maximum profit PM* and the retailer chooses over the margin on the product m^* to find optimum retail price p^* which maximizes profit PR*.

Now as we have assumed the marginal profit of the retailer as m where $p = w + m$, therefore the demand functions for linear and iso-elastic patterns take the form

$$D_l = A - \alpha p + \beta\theta - \gamma\delta p = A - (\alpha + \delta\gamma)(w + m) + \beta\theta$$
$$D_i = \frac{A\theta^{\beta}}{p^{\alpha}(\delta p)^{\gamma}} = \frac{A\theta^{\beta}}{(w+m)^{\alpha+\gamma}\delta^{\gamma}}.$$

Hence, the optimal decisions are to be obtained from the following:

$$\max_{(w,\theta)} \mathrm{PM}(w,\theta) = \arg\max_{(w,\theta)} \left(w - c - \lambda\theta^2\right) D - s[(a - b\theta)D - K]^+$$
$$\max_{(m)} \mathrm{PR}(m) = \arg\max_{(m)} (p - w - t)D = \arg\max_{(m)} (m - t)D$$

where $[(a - b\theta)D - K]^+ = \begin{cases} (a - b\theta)D - K, & \text{if } (a - b\theta)D > K \\ 0, & \text{if } (a - b\theta)D = K \\ K - (a - b\theta)D, & \text{if } K > (a - b\theta)D \end{cases}.$

In the Vertical Nash game structure the Government, the manufacturer and the retailer maximize their profits individually and simultaneously. In order to guarantee that profit functions of all the chain members both in linear and iso-elastic demand patterns are strictly concave, we derive the following proposition:

4.2.1. Linear demand

The profit functions for linear demand are as follows:

$$\mathrm{PG}_l(t) = s[(a - b\theta)\{A - (\alpha + \delta\gamma)(w + m) + \beta\theta\} - K]^+ + t[A - (\alpha + \delta\gamma)(w + m) + \beta\theta] \tag{4.13}$$
$$\mathrm{PM}_l(w,\theta) = \left(w - c - \lambda\theta^2\right)[A - (\alpha + \delta\gamma)(w + m) + \beta\theta] - s[(a - b\theta)\{A - (\alpha + \delta\gamma)(w + m) + \beta\theta\} - K]^+ \tag{4.14}$$
$$\mathrm{PR}_l(m) = (m - t)[A - (\alpha + \delta\gamma)(w + m) + \beta\theta]. \tag{4.15}$$

Now, to find the optimum values of the variables w, θ and m and further the values of p and t for which the profits of the manufacturer and retailer are maximum, we differentiate equations (4.14) and (4.15) with respect to w, θ and m respectively and simultaneously solve the necessary conditions for optimality. After getting the values of w^*, θ^*, m^*, p^* and t^* we obtain the optimal values of the profit functions PG*, PM* and PR*. The conditions for concavity of the profit functions and the optimal values of the decision variables are given in Proposition 4.3.

Proposition 4.3. *The profit functions for linear demand* PM_l *and* PR_l *are concave functions of the decision variables* w, θ *and* m *in Vertical Nash game provided that* $bs\beta + \lambda(m+w)\phi_1 < \lambda(A + 3\beta\theta)$ *and* $4\phi_1\lambda(A + 3\beta\theta) > 4\phi_1[bs\beta + \phi_1\lambda(m + w)] + [\beta - \phi_1(bs - 2\theta\lambda)]^2$ *and the optimal decisions are*

$$w^* = \frac{(\delta - 1)\{bs\beta\phi_1 - b^2s^2\phi_1^2 + 2\beta^2 + 2\phi_1\lambda(A + 2\phi_1(c + as))\}}{4\lambda\phi_1^2(2\delta - 3)}$$
$$\theta^* = \frac{bs\phi_1 + \beta}{2\phi_1\lambda}$$

$$m^* = \frac{b^2s^2(2\delta-1)\phi_1^2 - \beta^2(2\delta+1) - 2bs\beta\phi_1 - 4\lambda\phi_1(A+(c+as)(2\delta-1)\phi_1)}{4\phi_1^2\lambda(2\delta-3)}$$
$$p^* = \frac{\beta^2(2\delta-5) + 2bs\beta(\delta-2)\phi_1 + b^2s^2\phi_1^2 - 4\phi_1\lambda(\phi_1(c+as) - A(\delta-2))}{2\lambda\phi_1^2(2\delta-3)}$$
$$t^* = \delta\frac{\beta^2(2\delta-5) + 2bs\beta(\delta-2)\phi_1 + b^2s^2\phi_1^2 - 4\phi_1\lambda(\phi_1(c+as) - A(\delta-2))}{2\lambda\phi_1^2(2\delta-3)}\cdot$$

Proof. Proof of Proposition 4.3 is given in Appendix C. □

4.2.2. Iso-elastic demand

The profit functions for iso-elastic demand are as follows:

$$\mathrm{PG}_i(t) = s\left[(a-b\theta)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - K\right]^+ + t\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} \tag{4.16}$$

$$\mathrm{PM}_i(w,\theta) = \left(w-c-\lambda\theta^2\right)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - s\left[(a-b\theta)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - K\right]^+ \tag{4.17}$$

$$\mathrm{PR}_i(m) = (m-t)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma}\cdot \tag{4.18}$$

Now, to find the optimum values of the variables w, θ and m and further the values of p and t for which the profits of the manufacturer and retailer are maximum, we differentiate equations (4.17) and (4.18) with respect to w, θ and m respectively and simultaneously solve the necessary conditions for optimality. After getting the values of w^*, θ^*, m^*, p^* and t^* we obtain the optimal values of the profit functions PG^*, PM^* and PR^*. The conditions for concavity of the profit functions and the optimal values of the decision variables are given in Proposition 4.4.

Proposition 4.4. *The profit functions PM_i and PR_i for iso-elastic demand are concave functions of the decision variables w, θ and m in Vertical Nash game provided that $2m + w + \left(c+as+\theta^2\lambda\right)(\phi_2+1) > bs\theta(\phi_2+1) + \phi_2 w$, $\beta(\beta-1)(c+as-w) + (\beta+1)(\beta+2)\theta^2\lambda > \beta(\beta+1)bs\theta$, $\phi_2[\beta(\beta-1)(c+as-w) - \beta(\beta+1)bs\theta + (\beta+1)(\beta+2)\theta^2\lambda][2m - w(\phi_2-1) + (c+as+\theta^2\lambda-bs\theta)(\phi_2+1)] > \left[\beta\{m-w(\phi_2-1)\} + \phi_2\{\beta(c+as-bs\theta) - bs\theta + (\beta+2)\theta^2\lambda\}\right]^2$ and $2w + (m+w)\delta(\phi_2-1) > m(\phi_2-1)$ and the optimal decisions are*

$$w^* = \frac{\phi_6 - \phi_7}{2\lambda\phi_5^2}$$
$$\theta^* = \frac{2bs\beta(c+as)}{\phi_8 + \frac{\phi_6}{(\phi_2-1)(\delta-1)}}$$
$$m^* = \frac{\{((\phi_2-1)\delta+1)\phi_7 - \phi_6\}}{2\lambda(\phi_2-1)(\delta-1)\phi_5^2}$$
$$p^* = \frac{\phi_2\left\{\phi_8 - \frac{\phi_6}{(\phi_2-1)(\delta-1)}\right\}}{2\lambda\phi_5^2}$$
$$t^* = \delta\frac{\phi_2\left\{\phi_8 - \frac{\phi_6}{(\phi_2-1)(\delta-1)}\right\}}{2\lambda\phi_5^2}$$

where

$$\phi_5 = 4 - 2\delta + \beta + 2\phi_2(\delta-1)$$

$$\phi_6 = bs(\phi_2 - 1)(\delta - 1)\sqrt{b^2s^2[\delta - \beta - 2 - \phi_2(\delta - 1)]^2 - 4\phi_5(c + as)}$$
$$\phi_7 = b^2s^2(\phi_2 - 1)(\delta - 1)[\beta + 2 - \delta - \phi_2(\delta - 1)] + 4\lambda\phi_5(\phi_2 - 1)(\delta - 1)(c + as)$$
$$\phi_8 = b^2s^2[\beta + 2 - \delta - \phi_2(\delta - 1)]^2 - 4\phi_5(c + as).$$

Proof. Proof of Proposition 4.4 is given in Appendix D. □

4.3. Manufacturer Stackelberg game

In manufacturer Stackelberg game, the market is controlled by the manufacturer who plays the role of the leader whereas other player *viz.* retailer is the follower. In such scenario, the manufacturer asks the retailer to first choose the value of the margin on the product *i.e.* m^* which is the optimal decision variable of the retailer. Here the manufacturer chooses his wholesale price w^* and the level of greening effort θ^*, and the retailer chooses his retail price p^* optimizing his/her own profit first. After receiving their optimal reactions, the Government decides the optimal value of decision variable t^* (which depends on the value of p) to maximize its own profit. The optimal decisions are to be obtained from the following:

$$\max_{(w,\theta)} \mathrm{PM}(w,\theta) = \arg\max_{(w,\theta)} \big(w - c - \lambda\theta^2\big)D - s[(a - b\theta)D - K]^+$$

such that

$$\max_{(m)} \mathrm{PR}(m) = \arg\max_{(m)} (m - t)D.$$

In order to guarantee that profit functions of all the chain members both in linear and iso-elastic demand pattern are strictly concave, we derive the following proposition:

4.3.1. Linear demand

The profit functions for linear demand are as follows:

$$\mathrm{PG}_l(t) = s[(a - b\theta)\{A - (\alpha + \delta\gamma)(w + m) + \beta\theta\} - K]^+ + t[A - (\alpha + \delta\gamma)(w + m) + \beta\theta] \tag{4.19}$$
$$\mathrm{PM}_l(w,\theta) = \big(w - c - \lambda\theta^2\big)[A - (\alpha + \delta\gamma)(w + m) + \beta\theta] - s[(a - b\theta)\{A - (\alpha + \delta\gamma)(w + m) + \beta\theta\} - K]^+ \tag{4.20}$$
$$\mathrm{PR}_l(m) = (m - t)[A - (\alpha + \delta\gamma)(w + m) + \beta\theta]. \tag{4.21}$$

In manufacturer led Stackelberg game the retailer chooses the values of his/her decision variables and provides the reaction to the manufacturer. To find the optimum values of the variables w, θ and m, we first differentiate equation (4.21) with respect to m and determine the optimal value of m *i.e.* m^*. The manufacturer then determines the optimal values of w^* and θ^* using the reaction of the retailer and the necessary conditions for optimality of PM. We get the conditions for concavity of the profit functions and optimal decisions as given in Proposition 4.5.

Proposition 4.5. *The profit functions* PM_l *and* PR_l *for linear demand are concave functions of the decision variables* w, θ *and* m *in manufacturer led Stackelberg game provided that* $\beta(bs - 3\theta\lambda)(\delta - 1) < \lambda[A(\delta - 1) + w\phi_1]$ *and* $4\phi_1^2\theta^2\lambda^2 + 4\phi_1\lambda[A(\delta - 1) + 2\beta\theta(\delta - 1) + \phi_1(w - bs\theta)] > [bs\phi_1 - \beta(\delta - 1)]^2$ *and the optimal decisions are*

$$w^* = \frac{3\beta^2(\delta - 1)^2 - 2bs\beta(\delta - 1)\phi_1 - b^2s^2\phi_1^2 + 4\phi_1\lambda\{A(1 - \delta) + (c + as)\phi_1\}}{8\phi_1^2\lambda}$$
$$\theta^* = \frac{bs\phi_1 + \beta(1 - \delta)}{2\phi_1\lambda}$$
$$m^* = \frac{2bs\beta(\delta - 1)(2\delta + 1)\phi_1 - \beta^2(\delta - 1)^2(6\delta + 1) + b^2s^2\phi_1^2(2\delta - 1) - 4\phi_1\lambda\{(c + as)(2\delta - 1)\phi_1 + A(\delta - 1)^2\}}{16\lambda(\delta - 1)\phi_1^2}$$

$$p^* = \frac{6bs\beta\phi_1(\delta-1) - 7\beta^2(\delta-1)^2 + b^2s^2\phi_{15}^2 - 4\phi_1\lambda\{(c+as)\phi_1 - 3A(\delta-1)\}}{16\lambda\phi_1^2(\delta-1)}$$
$$t^* = \delta\frac{6bs\beta\phi_1(\delta-1) - 7\beta^2(\delta-1)^2 + b^2s^2\phi_1^2 - 4\phi_1\lambda\{(c+as)\phi_1 - 3A(\delta-1)\}}{16\lambda\phi_1^2(\delta-1)}.$$

Proof. Proof of Proposition 4.5 is given in Appendix E. □

4.3.2. Iso-elastic demand

The profit functions for iso-elastic demand are as follows:

$$\mathrm{PG}_i(t) = s\left[(a-b\theta)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - K\right]^+ + t\frac{A\theta^\beta}{p^\alpha t^\gamma} \tag{4.22}$$
$$\mathrm{PM}_i(w,\theta) = \left(w - c - \lambda\theta^2\right)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - s\left[(a-b\theta)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - K\right]^+ \tag{4.23}$$
$$\mathrm{PR}_i(m) = (m-t)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma}. \tag{4.24}$$

In manufacturer led Stackelberg game, the retailer chooses the value of m and provides the reaction to the manufacturer. Now, to find the optimum values of the variables m we first differentiate equation (4.24) with respect to m and determine the optimal value from the necessary condition. The manufacturer then determines the optimal values of w^* and θ^* using the reactions of the retailer and necessary conditions for optimality of PM. Finally, the Government determines the optimal value of t using the retail price p. We get the conditions for concavity of the profit functions and the optimal decisions as given in Proposition 4.6.

Proposition 4.6. *The profit functions* PM_i *and* PR_i *for iso-elastic demand are concave functions of the decision variables* w*,* θ *and* m *in manufacturer led Stackelberg game provided that* $2m+w+(c+as+\theta^2\lambda)(\phi_2+1) > bs\theta(\phi_2+1)+\phi_2 w$, $w+(c+as+\theta^2\lambda)(\phi_2+1) > bs\theta+\phi_2(w+bs\theta)$, $\beta(\beta+1)bs\theta < \beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda$, *and* $\phi_2[w+(c+as+\theta^2\lambda)(\phi_2+1)-bs\theta-\phi_2(w+bs\theta)][\beta(\beta+1)bs\theta < \beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda] > [w\beta(\phi_2-1)-\phi_2\{\beta(c+as)-(\beta+1)bs\theta+(\beta+2)\theta^2\lambda\}]^2$ *and the optimal decisions are*

$$w^* = \frac{\phi_2(bs\phi_{11}-\phi_{10})}{2\lambda\phi_{12}^2}$$
$$\theta^* = \frac{bs(\phi_2-\beta-1)-\phi_{11}}{2\lambda\phi_{12}}$$
$$m^* = \frac{\phi_2\{(\phi_2-1)\delta+1\}(\phi_{10}-bs\phi_{11})}{2\lambda\phi_{12}^2(\phi_2-1)(\delta-1)}$$
$$p^* = \frac{\phi_2^2(\phi_{10}-bs\phi_{11})}{2\lambda\phi_{12}^2(\phi_2-1)(\delta-1)}$$
$$t^* = \delta\frac{\phi_2^2(\phi_{10}-bs\phi_{11})}{2\lambda\phi_{12}^2(\phi_2-1)(\delta-1)}$$

where

$$\phi_{10} = b^2s^2(\phi_2-\beta-1)+4\lambda(c+as)\phi_{12},$$
$$\phi_{11} = \sqrt{b^2s^2(\phi_2-\beta-1)^2-4\lambda\beta(c+as)\phi_{12}},$$
$$\phi_{12} = (2+\beta-2\phi_2).$$

Proof. Proof of Proposition 4.6 is given in Appendix F. □

4.4. Retailer Stackelberg game

In retailer Stackelberg game, the market is controlled by the retailer who plays the role of the leader whereas other player *viz.* the manufacturer is the follower. This kind of situation arises generally when the manufacturer is outsider and does not have proper idea about the nature of the local market. In such scenario, the retailer asks the manufacturer to first choose the his optimal decisions. The manufacturer will choose his wholesale price w^* and the level of greening effort θ^* and provide the retailer. The retailer then will choose his/her optimal margin on product *i.e.* m^* and the optimal retail price *i.e.* p^*. After receiving these reactions, the Government will decide the optimal value of t^* (which depends on the value of p) to maximize its profit. The optimal decisions are to be obtained from the following:

$$\max_{(m)} \mathrm{PR}(m) = \arg\max_{(m)} (m-t)D$$

such that

$$\max_{(w,\theta)} \mathrm{PM}(w,\theta) = \arg\max_{(w,\theta)} \big(w-c-\lambda\theta^2\big)D - s[(a-b\theta)D-K]^+.$$

In order to guarantee that profit functions of all the chain members both in linear and iso-elastic demand pattern are strictly concave, we derive the following proposition.

4.4.1. Linear demand

The profit functions for linear demand are as follows:

$$\mathrm{PG}_l(t) = s[(a-b\theta)[A-(\alpha+\delta\gamma)(w+m)+\beta\theta]-K]^+ + t[A-(\alpha+\delta\gamma)(w+m)+\beta\theta] \tag{4.25}$$

$$\mathrm{PM}_l(w,\theta) = \big(w-c-\lambda\theta^2\big)[A-(\alpha+\delta\gamma)(w+m)+\beta\theta] - s[(a-b\theta)[A-(\alpha+\delta\gamma)p+\beta\theta]-K]^+ \tag{4.26}$$

$$\mathrm{PR}_l(m) = (m-t)[A-(\alpha+\delta\gamma)(w+m)+\beta\theta]. \tag{4.27}$$

In retailer led Stackelberg game the retailer optimizes his profit after getting reactions from the manufacturer. To find the optimum values of w and θ we use the necessary conditions. The retailer then determines the optimal value of m^* from equation (4.27) using the reactions of the manufacturer. We get the conditions for concavity of the profit functions and optimal decisions as given in Proposition 4.7.

Proposition 4.7. *The profit functions for linear demand* PM_l *and* PR_l *are concave functions of the decision variables* w, θ *and* m *respectively in Vertical Nash game provided that* $bs\beta+\lambda(m+w)\phi_1 < \lambda(A+3\beta\theta)$, $4\phi_1\lambda(A+3\beta\theta) > 4\phi_1[bs\beta+\phi_1\lambda(m+w)]+[\beta-\phi_1(bs-2\theta\lambda)]^2$, *and* $\phi_1[6\beta\theta\lambda-bs\beta+A\lambda-\lambda(m+w)\phi_1] > [\beta+(2\theta\lambda-bs)\phi_1]$ *and the optimal decisions are*

$$w^* = \frac{2bs\beta\phi_1(\delta-1)+\beta^2(4\delta-5)-b^2s^2\phi_1^2(2\delta-3)+4\phi_1\lambda\{A(\delta-1)+(c+as)\phi_1(2\delta-3)\}}{8\lambda\phi_1^2(\delta-2)}$$

$$\theta^* = \frac{bs}{2\lambda}$$

$$m^* = \frac{2bs\beta\phi_1-\beta^2(\delta+1)-b^2s^2\phi_1^2(\delta-1)+4\phi_1\lambda\{A+(c+as)\phi_1(\delta-1)\}}{4\lambda\phi_1^2(\delta-2)}$$

$$p^* = \frac{2bs\beta\phi_1(\delta-3)+\beta^2(2\delta-7)+b^2s^2\phi_1^2-4\phi_1\lambda\{(c+as)\phi_1-A(\delta-3)\}}{4\lambda\phi_1^2(\delta-2)}$$

$$t^* = \delta\frac{2bs\beta\phi_1(\delta-3)+\beta^2(2\delta-7)+b^2s^2\phi_1^2-4\phi_1\lambda\{(c+as)\phi_1-A(\delta-3)\}}{4\lambda\phi_1^2(\delta-2)}.$$

Proof. Proof of Proposition 4.7 is same as Proposition 4.5. Hence we omit the proof. □

4.4.2. Iso-elastic demand

The profit functions for iso-elastic demand are as follows:

$$\mathrm{PG}_i(t) = s\left[(a-b\theta)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - K\right]^+ + t\frac{A\theta^\beta}{p^\alpha t^\gamma} \tag{4.28}$$

$$\mathrm{PM}_i(w,\theta) = \left(w-c-\lambda\theta^2\right)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - s\left[(a-b\theta)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma} - K\right]^+ \tag{4.29}$$

$$\mathrm{PR}_i(m) = (m-t)\frac{A\theta^\beta}{(w+m)^{\alpha+\gamma}\delta^\gamma}\cdot \tag{4.30}$$

Proceeding similarly as in Section 4.4.1 we derive the conditions for the concavity of the profit functions PM_i and PR_i, and optimal decisions of the supply chain members as given in Proposition 4.8.

Proposition 4.8. *The profit functions* PM_i *and* PR_i *for iso-elastic demand are concave functions of the decision variables* w, θ *and* m *in Retailer Stackelberg game provided that* $\beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda > \beta(\beta+1)bs\theta$, $\phi_2[\beta(\beta-1)(c+as-w)-\beta(\beta+1)bs\theta+(\beta+1)(\beta+2)\theta^2\lambda][2m-w(\phi_2-1)+(c+as+\theta^2\lambda-bs\theta)(\phi_2+1)] > [\beta\{m-w(\phi_2-1)\}+\phi_2\{\beta(c+as-bs\theta)-bs\theta+(\beta+2)\theta^2\lambda\}]^2$ *and* $\phi_{13}[\beta(\beta-1)\phi_{14}-bs\theta\beta(\beta+1)]+\phi_2(c+as) > (m+w)\beta+\phi_{13}\phi_2\beta+\phi_{14}(\beta+1)$ *where* $\phi_{13} = \sqrt{b^2s^2(\phi_2-\beta-1)^2 - 4\lambda\beta\left[c+as+w+\frac{\delta(1-\phi_2)-1}{(1-\phi_2)(1-\delta)}\phi_{12}\right]}$, $\phi_{14} = 2\lambda(2\phi_2-\beta-2)[(\beta+2)\frac{\delta(1-\phi_2)-1}{(1-\phi_2)-1}(1-\phi_2)+2(c+as+w)\phi_2]$ *and the optimal decisions are*

$$w^* = \frac{\left(bs\phi_2\phi_{13} - b^2s^2\phi_2(\phi_2-\beta-1)+\phi_{20}\right)}{2\lambda(\beta+2-2\phi_{12})^2}$$

$$\theta^* = \frac{bs(\phi_2-\beta-1)-\phi_{13}}{2\lambda\phi_{12}}$$

$$m^* = \frac{1-\delta(\phi_2-1)}{2\lambda(\phi_2-1)(\delta-1)}$$

$$p^* = \frac{\left(bs\phi_2\phi_{13} - b^2s^2\phi_2(\phi_2-\beta-1)+\phi_{14}\right)}{2\lambda(\beta+2-2\phi_{12})^2}\left\{\frac{\lambda(\phi_2-1)(\delta-1)+1}{\lambda(\phi_2-1)(\delta-1)}\right\}$$

$$t^* = \delta\frac{\left(bs\phi_2\phi_{13} - b^2s^2\phi_2(\phi_2-\beta-1)+\phi_{14}\right)}{2\lambda(\beta+2-2\phi_{12})^2}\left\{\frac{\lambda(\phi_2-1)(\delta-1)+1}{\lambda(\phi_2-1)(\delta-1)}\right\}.$$

Proof. Proof of Proposition 4.8 is similar as Proposition 4.6. Hence the proof is omitted. □

5. Results and discussion

This section discusses several implications of the results derived in the previous sections. The equilibrium values of wholesale price, retail price and level of green innovation are compared across all the models for linear demand. The same exercise can also be carried out for iso-elastic demand. The comparison of results will help to understand how different policies *viz.* integrated, vertical Nash and Stackelberg policies affect the various prime variables of the supply chain. A comparative analysis can be performed Tables 1 and 2.

We now compare the optimal values of the pricing variables namely, wholesale price, retail price and the greening strategy in the following two propositions.

Proposition 5.1. *The wholesale price and retail price for linear demand follow the sequences* $w_{\mathrm{ms}} > w_{\mathrm{dc}} > w_{\mathrm{rs}}$ *and* $p_{\mathrm{rs}} > p_{\mathrm{dc}} > p_{\mathrm{ms}} > p_{\mathrm{c}}$ *respectively where* c, dc, ms *and* rs *stand for centralized, decentralized, manufacturer and retailer Stackelberg policies, respectively.*

TABLE 1. Comparative analysis of equilibrium values in integrated and decentralized policies.

Equilibrium results for linear demand		
Variables	Centralized policy	Decentralized policy
w^*	–	$\frac{(\delta-1)\{bs\beta\phi_1 - b^2s^2\phi_1^2 + 2\beta^2 + 2\phi_1\lambda(A+2\phi_1(c+as))\}}{4\lambda\phi_1^2(2\delta-3)}$
θ^*	$\frac{\beta}{2\lambda\phi_1}$	$\frac{bs\phi_1+\beta}{2\lambda\phi_1}$
p^*	$\frac{3\beta^2+4\phi_1\lambda(A+c\phi_1)}{8\lambda\phi_1^2}$	$\frac{\beta^2(2\delta-5)+2bs\beta(\delta-2)\phi_1+b^2s^2\phi_1^2-4\phi_1\lambda(\phi_1(c+as)-A(\delta-2))}{2\lambda\phi_1^2(2\delta-3)}$

TABLE 2. Comparative analysis of equilibrium values in manufacturer and retailer Stackleberg games.

Equilibrium results for linear demand		
Variables	Manufacturer Stackelberg	Retailer Stackelberg
w^*	$\frac{3\beta^2(\delta-1)^2-2bs\beta(\delta-1)\phi_1-b^2s^2\phi_1^2+4\phi_1\lambda\{A(1-\delta)+(c+as)\phi_1\}}{8\lambda\phi_1^2}$	$\frac{2bs\beta\phi_1(\delta-1)+\beta^2(4\delta-5)-b^2s^2\phi_1^2(2\delta-3)+4\phi_1\lambda\{A(\delta-1)+(c+as)\phi_1(2\delta-3)\}}{8\lambda\phi_1^2(\delta-2)}$
θ^*	$\frac{bs\phi_1+\beta(1-\delta)}{2\lambda\phi_1}$	$\frac{bs}{2\lambda}$
p^*	$\frac{6bs\beta\phi_1(\delta-1)-7\beta^2(\delta-1)^2+b^2s^2\phi_{15}^2-4\phi_1\lambda\{(c+as)\phi_1-3A(\delta-1)\}}{16\lambda\phi_1^2(\delta-1)}$	$\frac{2bs\beta\phi_1(\delta-3)+\beta^2(2\delta-7)+b^2s^2\phi_1^2-4\phi_1\lambda\{(c+as)\phi_1-A(\delta-3)\}}{4\lambda\phi_1^2(\delta-2)}$

Proof. The wholesale price in the manufacturer Stackelberg game has the highest value because the manufacturer bears the greening cost and also he plays the leading role in the pricing of the product. Further, it is observed that the wholesale price in the decentralized policy is higher than the wholesale price in the retailer Stackelberg policy. This is due to the pricing strategy of the rational manufacturer who charges higher price in vertical Nash structure to meet the greening investment that he had to do.

On the other hand, the retailer maintains higher margins in the decentralized policy than the centralized policy by charging higher retail price. Clearly bargaining process is advantageous for the retailer. Further, the margin of the retailer is lower in the manufacturer Stackelberg policy in comparison to the other policies because being the follower the retailer has to accept the decision taken by the manufacturer and let go the high share on his part. For obvious reasons, the highest value of retail price is achieved in the retailer Stackelberg policy. □

Proposition 5.2. *The level of greening effort for linear demand follows the sequence* $\theta_{\rm dc} > \theta_{\rm rs} > \theta_{\rm c} > \theta_{\rm ms}$ *where* c*,* dc*,* ms *and* rs *stand for centralized, decentralized, manufacturer and retailer Stackelberg policies, respectively.*

6. Numerical example

In this section, we perform numerical study for our proposed model. As it is difficult to access the actual industry data, we generate the data in numerical examples to closely comply with certain assumptions of our study. We have checked that all the conditions for the existence and uniqueness of optimal solutions given in Propositions 4.1–4.8 are fully satisfied for the chosen data sets. We take the values of the parameters for linear

TABLE 3. Optimal results for the case of linear demand.

Key variables	Centralized policy	Vertical Nash policy	Manufacturer Stackelberg	Retailer Stackelberg
w	–	87.04	**88.00**	78.79
θ	7.14286	8.14286	**6.00**	8.4326
m	–	65.33	61.92	**81.83**
p	106.38	152.37	149.92	**160.62**
t	31.91	45.71	44.98	**48.18**
PIC	**1772.98**	919.49	1003.63	847.45
PG	–	432.05	547.58	457.40
PM	–	295.07	310.70	157.06
PR	–	192.55	145.35	232.99

Notes. These are the optimal values of the parameters.

demand as

$$A = 55, \alpha = 0.2, \beta = 1, \gamma = 0.5, a = 12, b = 0.2, c = 25, \lambda = 0.2, K = 10, \delta = 0.3 \text{ and } s = 2$$

and for iso-elastic demand

$$A = 5000, \alpha = 2, \beta = 0.2, \gamma = 0.6, a = 5, b = 0.2, c = 8, \lambda = 0.2, K = 2, \delta = 0.2 \text{ and } s = 2.$$

In the case of linear demand, with higher price sensitivity b or higher production cost c, the difference of profits under centralized and decentralized policy reduces. On the contrary, change in the greening cost parameter θ has significant effect on this profit difference. For iso-elastic demand, the profit difference between the centralized and decentralized channels gets diminished with increased price dependency α. We also observe that, with higher production cost c and greening cost factor θ, the profit difference decreases. The more the difference between the total profits under two different scenarios (centralized and decentralized) is, the more the necessity for coordination arises. We study the impacts of the greening cost parameter and promotional cost parameter on the optimal decisions and compare them. The optimal results for different sets of parameter-values are shown in Tables 3 and 4.

Tables 3 and 4 show that the centralized policy is the benchmark case, as expected. Amongst the other decentralized policies, the manufacturer-led policy achieves the best performance in both linear and iso-elastic demands. We observe that both the marginal profit (m) and retail price (p) are maximum in the retailer-led chain in linear demand as well as in iso-elastic demand.

7. Sensitivity analysis

In this section, we discuss the sensitivity analysis. Sensitivity analysis is the study to observe how the optimal solution changes depending upon the changes of some key parameters of the model. We change the value of one parameter at a time and keep all other parameters fixed to investigate the impact of a specific parameter on the optimal solution. Here we choose the sensitivity analysis is to be performed to investigate the profit improvement between centralized and decentralized policies with respect to the parameters α, β and λ where α denotes the prie sensitivity of demand, β denotes sensitivity of greening effort and λ denotes the greening investment cost. Here we denote the profit of the decentralized chain as P_{d}, manufacturer stackelberg policy as P_{ms} and retailer stackelberg policy as P_{rs}. The results of the sensitivity analysis are provided in the Tables 5–10.

Table 4. Optimal results for the case of iso-elastic demand.

Key variables	Centralized policy	Vertical Nash policy	Manufacturer Stackelberg	Retailer Stackelberg
w	–	17.62	**30.17**	23.50
θ	1.63299	7.29678	**1.10211**	3.5088
m	–	6.30	21.12	**38.77**
p	13.87	23.92	51.29	**62.27**
t	2.77	4.77	10.25	**12.45**
PIC	**82.95**	28.22	79.45	74.07
PG	–	3.03	26.66	32.21
PM	–	15.77	33.47	15.87
PR	–	9.42	19.33	25.96

Notes. These are the optimal values of the parameters.

Table 5. Profits *vs.* α in the case of linear demand

Change in α (in %)	Centralized PIC	Decentralized $P_{\rm d}$	MS $P_{\rm ms}$	RS $P_{\rm rs}$	% of improvement $\frac{({\rm PIC}-P_{\rm d})*100}{\rm PIC}$	% of improvement $\frac{({\rm PIC}-P_{\rm ms})*100}{\rm PIC}$	% of improvement $\frac{({\rm PIC}-P_{\rm rs})*100}{\rm PIC}$
0.1(−50%)	2889.06	1119.23	1810.42	1541.11	61%	37%	46%
0.15(−25%)	2224.54	1081.77	1331.07	1128.59	51%	40%	49%
0.25(+25%)	1447.51	857.34	766.79	644.66	40%	47%	55%
0.3(+50%)	1202.69	750.14	588.22	492.24	37%	51%	59%

Table 6. Profits *vs.* α in the case of iso-elastic demand.

Change in α (in %)	Centralized PIC	Decentralized $P_{\rm d}$	MS $P_{\rm ms}$	RS $P_{\rm rs}$	% of improvement $\frac{({\rm PIC}-P_{\rm d})*100}{\rm PIC}$	% of improvement $\frac{({\rm PIC}-P_{\rm ms})*100}{\rm PIC}$	% of improvement $\frac{({\rm PIC}-P_{\rm rs})*100}{\rm PIC}$
1(−50%)	144.10	30.18	83.22	73.21	79%	42%	49%
1.5(−25%)	95.47	24.86	47.11	35.82	73%	50%	62%
2.5(+25%)	22.95	11.67	10.53	10.12	49%	54%	55%
3(+50%)	6.65	4.89	3.63	3.34	36%	45%	46%

7.1. Effect of price sensitivity of demand (α)

We have observed that as α increases both wholesale price and selling price in the retail channel increase for both linear and iso-elastic demand pattern. This is because as α represents the price sensitivity of demand so as it increases the basic market price for the retail channel increases which in turn decreases the demand. On the other hand for lower value of α basic market price decreases and demand increases. This is the reason why profits in all the four policies centralized, Nash game, manufacturer-led and the retailer-led decentralized policies decrease as α increases. This is invariably true for both the demand patterns linear and iso-elastic. The selling price becomes lower than the retail prices in the Nash game and the centralized policy when α exceeds the values 0.2 in linear demand and 2 in iso-elastic demand. This is due to the price sensitivity level of the product which, in the centralized policy, is much more than that of the Nash game policy. From the Tables 5 and 6 it is clear that in order to increase profit, α must be set less than 0.2 for linear demand and 2 for iso-elastic demand.

TABLE 7. Profits *vs.* β in the case of linear demand.

Change in β (in %)	Centralized PIC	Decentralized P_{d}	MS P_{ms}	RS P_{rs}	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{d}})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{ms}})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{rs}})*100}{\mathrm{PIC}}$
0.5(−50%)	1587.46	727.54	888.55	754.27	54%	44%	52%
0.75(−25%)	1663.52	896.30	936.92	793.39	46%	43%	52%
1.25(+25%)	1918.85	1212.80	1190.41	918.15	36%	37%	52%
1.5(+50%)	2104.96	1430.03	1390.42	1007.12	32%	33%	52%

TABLE 8. Profits *vs.* β in the case of iso-elastic demand.

Change in β (in %)	Centralized PIC	Decentralized P_{d}	MS P_{ms}	RS P_{rs}	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{d}})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{ms}})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{rs}})*100}{\mathrm{PIC}}$
0.1(−50%)	80.27	31.76	73.21	75.32	60%	8%	6%
0.15(−25%)	81.23	30.07	45.82	54.21	62%	44%	33%
0.25(+25%)	85.27	26.08	25.12	30.35	69%	70%	64%
0.3(+50%)	88.14	23.55	11.29	10.55	73%	87%	88%

TABLE 9. Profits *vs.* λ in the case of linear demand.

Change in λ (in %)	Centralized PIC	Decentralized P_{d}	MS P_{ms}	RS P_{rs}	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{d}})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{ms}})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_{\mathrm{rs}})*100}{\mathrm{PIC}}$
0.1(−50%)	2036.28	1303.45	1179.07	988.34	36%	42%	51%
0.15(−25%)	1858.72	1179.42	1060.64	893.25	37%	43%	52%
0.25(+25%)	1722.51	1084.53	970.14	820.54	37%	44%	52%
0.3(+50%)	1689.26	1061.41	948.10	802.84	37%	44%	52%

7.2. Effect of greening sensitivity (β)

Now let us observe the changes of the greening level β in all the four policies considered for both models linear and iso-elastic. From the Tables 7 and 8 it is clearly evident that if β increases the profit also increases. Greening level takes the highest value in the centralized policy and the least value in the decentralized policy. The greening level takes the least value in manufacturer and retailer led stackleberg games. Greening level thus plays as a very crucial parameter in the sensitivity analysis. The profits in all the four policies centralized, Nash game, manufacturer-led and the retailer-led decentralized policies increase as β increases. This is invariably true for both the demand patterns linear and iso-elastic. From the Tables 7 and 8 it is clear that in order to increase profit, β must be set greater than 1 for linear demand and 0.1 for iso-elastic demand.

7.3. Effect of greening investment cost (λ)

Now, we illustrate how the green innovation investment cost λ influences the green supply chain. In Tables 9 and 10, we represent the effect of λ on the profit for the centralized policy and the Nash game, the manufacturer-led decentralized and the retailer-led decentralized policy, respectively. Commonly, all these variables decrease very fast until λ crosses a certain level, but after that, they decrease slowly for all the four policies. In case of centralized policy, initially for smaller value of λ , the selling price is higher than the selling price in all the other policies.

Table 10. Profits *vs.* λ in the case of iso-elastic demand.

Change in λ (in %)	Centralized PIC	Decentralized P_d	MS P_ms	RS P_rs	% of improvement $\frac{(\mathrm{PIC}-P_\mathrm{d})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_\mathrm{ms})*100}{\mathrm{PIC}}$	% of improvement $\frac{(\mathrm{PIC}-P_\mathrm{rs})*100}{\mathrm{PIC}}$
0.1(−50%)	88.90	32.11	21.03	23.21	63%	76%	73%
0.15(−25%)	65.47	24.35	17.51	15.22	62%	73%	76%
0.25(+25%)	42.95	14.45	10.23	10.12	66%	76%	76%
0.3(+50%)	26.65	9.69	7.31	7.54	63%	72%	75%

From Tables 9 and 10 we note that greening level decreases when λ increases and the profit also decreases. This is obvious. The higher greening cost not only discourages the manufacturer to produce the green product, but also forces them to charge a higher selling price. So, to produce the green product, the government should encourage the manufacturer by reducing taxes and other governmental issues.

As λ increases, the selling price decreases faster than the retail price. For higher value of λ retail price becomes higher than the selling price. The reason is that, when the greening cost is minimum, the manufacturer can produce higher greening product. At the same time, he can charge higher price in direct channel for higher green product. When the greening cost becomes higher, the greening level of the product becomes lower and it forces the manufacturer to set lower price. However, for the manufacturer-led decentralized policy, the retailer-led decentralized policy and the Nash game, the profit decreases as λ increases for both linear and iso-elastic demand pattern. From the Tables 9 and 10 it is clear that in order to increase profit, λ must be set lower than 0.1 for linear demand and 0.1 for iso-elastic demand.

8. Conclusion

This piece of research considers a three-layer supply chain with Government, a manufacturer and a retailer as participating entities. The environment-conscious Government encourages the manufacturer to produce green product by contributing some subsidy for saved carbon or penalizes for an extra amount of emissions as per trading price. The manufacturer produces green product from fresh raw materials and sells to retailer. Three basic supply chain policies namely integrated, decentralized and vertical Nash policies are discussed. Optimal results are derived under different game structures analytically as well as numerically. Some useful managerial insights are presented and some effects of some key parameters on the optimal decisions are investigated through sensitivity analysis.

This paper aims on the review of the research on the green supply chain design. The review reflects that research on green consciousness and sustainability consciousness has increased during past decade due to growing worldwide environmental concerns and the enforcement of carbon policies in many countries. Various quantitative models can be cogitated for the sustainability matter. However, the choice of a quantitative model depends mainly on the members involved in the supply chain, followed by the strategic and the operational decisions to be made solely on the carbon policies.

However advancements are made in optimization algorithms, it not easy to solve some supply chain models having limited capability for integrating the strategic and multi objective operations. From the perspective of carbon policy, most studies focus on cap-and-trade and carbon tax. The carbon policy with a mandatory cap is more effective for sustainability. The carbon tax policy may be better but the cost of executing it might be too high. Our study reveals that with a lower carbon tax, it is difficult to achieve higher emission reduction. With the cap-and-trade, however, carbon credits available in the market and the supply chain members can help in achieving more economic benefits as well as emissions reductions. Some studies on subsidy and carbon policies are also available. It is worthy to note that, the integration of different carbon policies as subsidy and tax or like cap and tax may be a better option for the cost and emissions efficiency. Hence, the industry should reciprocate in a particular manner to a specific carbon policy by optimizing its specific supply chains. In short few techniques must be customized for necessary actions to take so that the supply chains can pursue low-carbon operations less expensively.

In spite of significant contribution, the paper has some limitations. In our study, we have assumed deterministic pattern of demand which has limited scope of application. Further research can consider stochastic demand. It would be interesting to investigate how the randomness in demand affects the chain members' decisions and performance. Another interesting extension would be to consider the quality level of produced green product. The manufacturer may allow those products which have a certain level of quality. He/she can also be involved in a closed-loop supply chain where the under-quality product can be returned to the manufacturer for re-manufacturing. Lastly, in this paper, we have considered only one retailer. One can consider multiple retailers competing among themselves. It will be an interesting extension to investigate how the manufacturer and the retailer make their decisions when there is a competition between green and non-green products. Our proposed model can also be extended for other demand structures involving quality of the product, promotional effort, etc.

Appendix A.

Proof of Proposition 4.1. The profit function PIC_l given in the equation (4.11) has two key decision variables p and θ. For concavity of the profit function given in equation (4.11), all the second order partial derivatives with respect to the decision variables must be negative and the associated Hessian matrix must be negative definite. We have, $\frac{\partial^2\mathrm{PIC}}{\partial p^2} = -2\phi_1$, $\frac{\partial^2\mathrm{PIC}}{\partial\theta^2} = -8\beta\theta\lambda - 2A\lambda + 2p\lambda\phi_1$, which is negative if $A + 4\beta > p\phi_1$.

The associated Hessian matrix is given by $H = \begin{bmatrix} \frac{\partial^2\mathrm{PIC}}{\partial p^2} & \frac{\partial^2\mathrm{PIC}}{\partial p\partial\theta} \\ \frac{\partial^2\mathrm{PIC}}{\partial\theta\partial p} & \frac{\partial^2\mathrm{PIC}}{\partial\theta^2} \end{bmatrix}$. Here $\mid H \mid = 4A\lambda\phi_1 + 8\beta\theta\lambda\phi_1^2 - 4\lambda\phi_1^2(p+\theta^2\lambda)$ where $\phi_1 = (\alpha+\gamma\delta)$, Therefore, $\mid H \mid > 0$ if $A + 4\beta\theta > \frac{\beta^2}{4\lambda\phi_1} + \phi_1(p+\theta^2\lambda)$.

If the Hessian matrix is negative definite then there exists a unique optimal solution which can be obtained from the first order necessary conditions $\frac{\partial\mathrm{PIC}}{\partial p} = 0$, $\frac{\partial\mathrm{PIC}}{\partial\theta} = 0$, as

$$p^* = \frac{3\beta^2 + 4\phi_1\lambda(A + c\phi_1)}{8\phi_1^2\lambda}$$

$$\theta^* = \frac{\beta}{2\lambda\phi_1}\cdot$$

□

Appendix B.

Proof of Proposition 4.2. The profit function PIC_l given in the equation (4.12) has two key decision variables p and θ. For concavity of the profit function given in equation (4.12), all the second order partial derivatives with respect to the decision variables must be negative and the associated Hessian matrix must be negative definite. We have, $\frac{\partial^2\mathrm{PIC}}{\partial p^2} = \frac{A\phi_2\theta^\beta}{p^{\phi_2+2}\delta^\gamma}[p(\phi_2-1) - (c+\theta^2\lambda)(\phi_2+1)]$, $\frac{\partial^2\mathrm{PIC}}{\partial\theta^2} = \frac{A\theta^{\beta-2}}{p^{\phi_2}\delta^\gamma}[(p-c)\beta(\beta-1) - (\beta+1)(\beta+2)\theta^2\lambda]$, where $\phi_2 = \alpha+\gamma$. Clearly for concavity above two expressions must be negative which leads to the conditions $p(\phi_2-1) < (\phi_2+1)(c+\theta^2\lambda)$ and $(p-c)\beta(\beta-1) < (\beta+1)(\beta+2)\theta^2\lambda$.

The associated Hessian matrix is given by $H = \begin{bmatrix} \frac{\partial^2\mathrm{PIC}}{\partial p^2} & \frac{\partial^2\mathrm{PIC}}{\partial p\partial\theta} \\ \frac{\partial^2\mathrm{PIC}}{\partial\theta\partial p} & \frac{\partial^2\mathrm{PIC}}{\partial\theta^2} \end{bmatrix}$, where $\mid H \mid = \frac{A^2\theta^{2(\beta-1)}}{p^{2(\phi_2+1)}\delta^{2\gamma}}[2p\lambda\theta^2(\beta-1)\phi_2(\phi_4-1) + \lambda^2\theta^4(\beta+2)\phi_2(1-\phi_4) + 2c\phi_2\{p\beta\phi_4 + \lambda\theta^2(1-\beta\phi_4+\phi_3)\} - \beta\{p^2(\phi_2-1)\phi_4 + c^2\phi_2(\phi_4+1)\}]$. Now $\mid H \mid > 0$ if $2p\lambda\theta^2(\beta-1)\phi_2(\phi_4-1) + \lambda^2\theta^4(\beta+2)\phi_2(1-\phi_4) + 2c\phi_2\big[p\beta\phi_4 + \lambda\theta^2(1-\beta\phi_4+\phi_3)\big] > \beta\big[p^2(\phi_2-1)\phi_4 + c^2\phi_2(\phi_4+1)\big]$, where

$$\phi_3 = \alpha+\beta+\gamma,$$

$$\phi_4 = \alpha - \beta + \gamma.$$

If the Hessian matrix is negative definite then there exists a unique optimal solution which can be obtained from the first order necessary conditions $\frac{\partial \text{PIC}}{\partial p} = 0$, $\frac{\partial \text{PIC}}{\partial \theta} = 0$ as

$$p^* = \frac{2c\phi_3}{2\phi_3 - (\beta + 2)}$$
$$\theta^* = \sqrt{\frac{c\beta}{\lambda\{2\phi_3 - (\beta + 2)\}}}.$$

□

Appendix C.

Proof of Proposition 4.3. The profit function PM_l given in the equation (4.14) has two key decision variables w and θ. For concavity of the profit function given in equation (4.14), all the second order partial derivatives with respect to the decision variables must be negative and the associated Hessian matrix must be negative definite. We have, $\frac{\partial^2 \text{PM}_l}{\partial w^2} = -2\phi_1$, $\frac{\partial^2 \text{PM}_l}{\partial \theta^2} = 2bs\beta + 2\lambda\phi_1(m + w) - 2\lambda(A + 3\theta\beta)$. Therefore for concavity $bs\beta + \lambda(m + w)\phi_1 < \lambda(A + 3\beta\theta)$.

The associated Hessian matrix is given by $H = \begin{bmatrix} \frac{\partial^2 \text{PM}_l}{\partial w^2} & \frac{\partial^2 \text{PM}_l}{\partial w \partial \theta} \\ \frac{\partial^2 \text{PM}_l}{\partial \theta \partial w} & \frac{\partial^2 \text{PM}_l}{\partial \theta^2} \end{bmatrix}$, where $\mid H \mid = 4\phi_1\lambda(A + 3\beta\theta) - 4\phi_1[bs\beta + \phi_1\lambda(m + w)] - [\beta - \phi_1(bs - 2\theta\lambda)]^2$. Now $\mid H \mid > 0$ if $4\phi_1\lambda(A + 3\beta\theta) > 4\phi_1[bs\beta + \phi_1\lambda(m + w)] + [\beta - \phi_1(bs - 2\theta\lambda)]^2$. Again profit function PR_l given in the equation (4.15) has one key decision variable m. For concavity of the profit function given in equation (4.15), the second order partial derivative with respect to the decision variable must be negative. We have, $\frac{\partial^2 \text{PR}_l}{\partial m^2} = -2\phi_1(1 - \delta)$.

There exists a unique optimal solution which can be obtained from the first order necessary conditions $\frac{\partial \text{PM}_l}{\partial w} = 0$, $\frac{\partial \text{PM}_l}{\partial \theta} = 0$, and $\frac{\partial \text{PR}_l}{\partial m} = 0$ as

$$w^* = \frac{(\delta - 1)\{bs\beta\phi_1 - b^2s^2\phi_1^2 + 2\beta^2 + 2\phi_1\lambda(A + 2\phi_1(c + as))\}}{4\lambda\phi_1^2(2\delta - 3)}$$
$$\theta^* = \frac{bs\phi_1 + \beta}{2\phi_1\lambda}$$
$$m^* = \frac{b^2s^2(2\delta - 1)\phi_1^2 - \beta^2(2\delta + 1) - 2bs\beta\phi_1 - 4\lambda\phi_1(A + (c + as)(2\delta - 1)\phi_1)}{4\phi_1^2\lambda(2\delta - 3)}$$
$$p^* = \frac{\beta^2(2\delta - 5) + 2bs\beta(\delta - 2)\phi_1 + b^2s^2\phi_1^2 - 4\phi_1\lambda(\phi_1(c + as) - A(\delta - 2))}{2\lambda\phi_1^2(2\delta - 3)}$$
$$t^* = \delta\frac{\beta^2(2\delta - 5) + 2bs\beta(\delta - 2)\phi_1 + b^2s^2\phi_1^2 - 4\phi_1\lambda(\phi_1(c + as) - A(\delta - 2))}{2\lambda\phi_1^2(2\delta - 3)}.$$

□

Appendix D.

Proof of Proposition 4.4. The profit function PM_i given in the equation (4.17) has two key decision variables w and θ. For concavity of the profit function given in equation (4.17), all the second order partial derivatives with respect to the decision variables must be negative and the associated Hessian matrix must be negative definite. We have, $\frac{\partial^2 \text{PM}_i}{\partial w^2} = \frac{-A\phi_2\theta^\beta}{(m+w)^{\phi_2+2}\delta^\gamma}[2m+w+(c+as+\theta^2\lambda)(\phi_2+1)-bs\theta(\phi_2+1)-\phi_2 w]$, $\frac{\partial^2 \text{PM}_i}{\partial \theta^2} = \frac{-A\theta^{\beta-2}}{(m+w)^{\phi_2}\delta^\gamma}[\beta(\beta-1)(c+$

$as-w)+(\beta+1)(\beta+2)\theta^2\lambda-\beta(\beta+1)bs\theta]$. Therefore for concavity $2m+w+(c+as+\theta^2\lambda)(\phi_2+1) > bs\theta(\phi_2+1)+\phi_2 w$ and $\beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda > \beta(\beta+1)bs\theta$.

The associated Hessian matrix is given by $H = \begin{bmatrix} \frac{\partial^2 \text{PM}_i}{\partial w^2} & \frac{\partial^2 \text{PM}_i}{\partial w \partial \theta} \\ \frac{\partial^2 \text{PM}_i}{\partial \theta \partial w} & \frac{\partial^2 \text{PM}_i}{\partial \theta^2} \end{bmatrix}$, where $|H| = \phi_2[\beta(\beta-1)(c+as-w) - \beta(\beta+1)bs\theta + (\beta+1)(\beta+2)\theta^2\lambda][2m - w(\phi_2-1) + (c+as+\theta^2\lambda - bs\theta)(\phi_2+1)] - [\beta\{m - w(\phi_2-1)\} + \phi_2\{\beta(c+as-bs\theta) - bs\theta + (\beta+2)\theta^2\lambda\}]^2$. Now $|H| > 0$ if $\phi_2[\beta(\beta-1)(c+as-w) - \beta(\beta+1)bs\theta + (\beta+1)(\beta+2)\theta^2\lambda][2m - w(\phi_2-1) + (c+as+\theta^2\lambda - bs\theta)(\phi_2+1)] > [\beta\{m-w(\phi_2-1)\} + \phi_2\{\beta(c+as-bs\theta) - bs\theta + (\beta+2)\theta^2\lambda\}]^2$. Again profit function PR_i given in the equation (4.18) has one key decision variable m. For concavity of the profit function given in equation (4.18), the second order partial derivative with respect to the decision variable must be negative. We have, $\frac{\partial^2 \text{PR}_i}{\partial m^2} = \frac{-A\phi_2\theta^\beta}{(m+w)^{\phi_2+2}\delta^\gamma}[2w + (m+w)\delta(\phi_2-1) - m(\phi_2-1)]$.

Therefore the condition for concavity is $2w + (m+w)\delta(\phi_2-1) > m(\phi_2-1)$. There exists a unique optimal solution which can be obtained from the first order necessary conditions $\frac{\partial \text{PM}_i}{\partial w} = 0$, $\frac{\partial \text{PM}_i}{\partial \theta} = 0$, and $\frac{\partial \text{PR}_i}{\partial m} = 0$ as

$$\begin{aligned}
w^* &= \frac{\phi_6 - \phi_7}{2\lambda\phi_5^2} \\
\theta^* &= \frac{2bs\beta(c+as)}{\phi_8 + \frac{\phi_6}{(\phi_2-1)(\delta-1)}} \\
m^* &= \frac{\{((\phi_2-1)\delta+1)\phi_7 - \phi_6\}}{2\lambda(\phi_2-1)(\delta-1)\phi_5^2} \\
p^* &= \frac{\phi_2\left\{\phi_8 - \frac{\phi_6}{(\phi_2-1)(\delta-1)}\right\}}{2\lambda\phi_5^2} \\
t^* &= \delta\frac{\phi_2\left\{\phi_8 - \frac{\phi_6}{(\phi_2-1)(\delta-1)}\right\}}{2\lambda\phi_5^2}
\end{aligned}$$

where

$$\begin{aligned}
\phi_5 &= 4 - 2\delta + \beta + 2\phi_2(\delta-1) \\
\phi_6 &= bs(\phi_2-1)(\delta-1)\sqrt{b^2s^2[\delta - \beta - 2 - \phi_2(\delta-1)]^2 - 4\phi_5(c+as)} \\
\phi_7 &= b^2s^2(\phi_2-1)(\delta-1)[\beta+2-\delta-\phi_2(\delta-1)] + 4\lambda\phi_5(\phi_2-1)(\delta-1)(c+as) \\
\phi_8 &= b^2s^2[\beta+2-\delta-\phi_2(\delta-1)]^2 - 4\phi_5(c+as).
\end{aligned}$$

□

Appendix E.

Proof of Proposition 4.5. In manufacturer led Stackelberg game the retailer chooses the values of his/her decision variables and provides the reaction to the manufacturer.

Retailer's reaction

The retailer's profit function is given in equation (4.21). As the profit function PR_l given in the equation (4.21) has one key decision variable m, so to find the reaction of the retailer, we first differentiate equation (4.21) with respect to m and determine the optimal value of m.

For concavity of the profit function given in equation (4.21), the second order partial derivative with respect to the decision variable must be negative. We have, $\frac{\partial^2 \text{PR}_l}{\partial m^2} = -2\phi_1(1-\delta)$.

Therefore this gives a unique optimal reaction as

$$m^* = \frac{2bs\beta(\delta-1)(2\delta+1)\phi_1 - \beta^2(\delta-1)^2(6\delta+1) + b^2s^2\phi_1^2(2\delta-1) - 4\phi_1\lambda\{(c+as)(2\delta-1)\phi_1 + A(\delta-1)^2\}}{16\lambda(\delta-1)\phi_1^2}.$$

Manufacturer's reaction

The manufacturer's profit function given in equation (4.20) has two decision variables w and θ. The manufacturer then determines the optimal values of w^* and θ^* using the reaction of the retailer and the necessary conditions for optimality of PM_l. We need to differentiate equation (4.20) with respect to w and θ. For concavity of the profit function given in equation (4.20), all the second order partial derivatives with respect to the decision variables must be negative and the associated Hessian matrix must be negative definite. We have, $\frac{\partial^2 \mathrm{PM}_l}{\partial w^2} = \frac{-\phi_1}{(1-\delta)}$, $\frac{\partial^2 \mathrm{PM}_l}{\partial \theta^2} = \beta(bs - 3\theta\lambda) - \frac{\lambda[A(\delta-1)+w\phi_1]}{(\delta-1)}$.

Therefore for concavity $\beta(bs-3\theta\lambda)(\delta-1) < \lambda[A(\delta-1)+w\phi_2]$. The associated Hessian matrix is given by $H = \begin{bmatrix} \frac{\partial^2 \mathrm{PM}_l}{\partial w^2} & \frac{\partial^2 \mathrm{PM}_l}{\partial w \partial \theta} \\ \frac{\partial^2 \mathrm{PM}_l}{\partial \theta \partial w} & \frac{\partial^2 \mathrm{PM}_l}{\partial \theta^2} \end{bmatrix}$, where $\mid H \mid = \frac{4\phi_1^2\theta^2\lambda^2 + 4\phi_1\lambda[A(\delta-1)+2\beta\theta(\delta-1)+\phi_1(w-bs\theta)] - [bs\phi_1 - \beta(\delta-1)]^2}{4(\delta-1)^2}$. Now $\mid H \mid > 0$ if $4\phi_1^2\theta^2\lambda^2 + 4\phi_1\lambda[A(\delta-1)+2\beta\theta(\delta-1)+\phi_1(w-bs\theta)] > [bs\phi_1 - \beta(\delta-1)]^2$.

There exists a unique optimal solution which can be obtained from the first order necessary conditions $\frac{\partial \mathrm{PM}_l}{\partial w} = 0$, $\frac{\partial \mathrm{PM}_l}{\partial \theta} = 0$ as

$$w^* = \frac{3\beta^2(\delta-1)^2 - 2bs\beta(\delta-1)\phi_1 - b^2s^2\phi_1^2 + 4\phi_1\lambda\{A(1-\delta) + (c+as)\phi_1\}}{8\phi_1^2\lambda}$$

$$\theta^* = \frac{bs\phi_1 + \beta(1-\delta)}{2\phi_1\lambda}$$

$$m^* = \frac{2bs\beta(\delta-1)(2\delta+1)\phi_1 - \beta^2(\delta-1)^2(6\delta+1) + b^2s^2\phi_1^2(2\delta-1) - 4\phi_1\lambda\big\{(c+as)(2\delta-1)\phi_1 + A(\delta-1)^2\big\}}{16\lambda(\delta-1)\phi_1^2}$$

$$p^* = \frac{6bs\beta\phi_1(\delta-1) - 7\beta^2(\delta-1)^2 + b^2s^2\phi_{15}^2 - 4\phi_1\lambda\{(c+as)\phi_1 - 3A(\delta-1)\}}{16\lambda\phi_1^2(\delta-1)}$$

$$t^* = \delta\frac{6bs\beta\phi_1(\delta-1) - 7\beta^2(\delta-1)^2 + b^2s^2\phi_1^2 - 4\phi_1\lambda\{(c+as)\phi_1 - 3A(\delta-1)\}}{16\lambda\phi_1^2(\delta-1)}$$

□

Appendix F.

Proof of Proposition 4.6. In manufacturer led Stackelberg game the retailer chooses the values of his/her decision variables and provides the reaction to the manufacturer.

Retailer's reaction

The retailer's profit function is given in equation (4.24). As the profit function PR_i given in the equation (4.24) has one key decision variable m, so to find the reaction of the retailer, we first differentiate equation (4.24) with respect to m and determine the optimal value of m.

For concavity of the profit function given in equation (4.24), the second order partial derivative with respect to the decision variable must be negative. We have, $\frac{\partial^2 \mathrm{PR}_i}{\partial m^2} = \frac{-A\phi_2\theta^\beta}{(m+w)^{\phi_2+2}\delta^\gamma}[2w + (m+w)\delta(\phi_2-1) - m(\phi_2-1)]$.

Therefore the condition for concavity is $2w + (m+w)\delta(\phi_2-1) > m(\phi_2-1)$. This gives a unique optimal reaction as

$$m^* = \frac{w(\delta-1) - w\delta\phi_2}{(\phi_2-1)(\delta-1)}.$$

Manufacturer's reaction

The manufacturer's profit function given in equation (4.23) has two decision variables w and θ. The manufacturer then determines the optimal values of w^* and θ^* using the reaction of the retailer and the necessary conditions for optimality of PM_i. We need to differentiate equation (4.23) with respect to w and θ. For concavity of the profit function given in equation (4.23), all the second order partial derivatives with respect to the decision variables must be negative and the associated Hessian matrix must be negative definite. We have, $\frac{\partial^2\mathrm{PM}_i}{\partial w^2} = \frac{-A\phi_2\theta^\beta}{w^2\phi_9^{\phi_2}\delta^\gamma}[w+(c+as+\theta^2\lambda)(\phi_2+1)-bs\theta-\phi_2(w+bs\theta)]$, $\frac{\partial^2\mathrm{PM}_i}{\partial\theta^2} = \frac{-A\theta^{\beta-2}}{\phi_9^{\phi_2}\delta^\gamma}[\beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda-\beta(\beta+1)bs\theta]$, where $\phi_9 = \frac{w\phi_2}{(\phi_2-1)(\delta-1)}$.

Therefore for concavity $w+(c+as+\theta^2\lambda)(\phi_2+1) > bs\theta+\phi_2(w+bs\theta)$ and $\beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda > \beta(\beta+1)bs\theta$. The associated Hessian matrix is given by $H = \begin{bmatrix} \frac{\partial^2\mathrm{PM}_i}{\partial w^2} & \frac{\partial^2\mathrm{PM}_i}{\partial w\partial\theta} \\ \frac{\partial^2\mathrm{PM}_i}{\partial\theta\partial w} & \frac{\partial^2\mathrm{PM}_i}{\partial\theta^2} \end{bmatrix}$, where $\mid H \mid = \frac{A^2\theta^{2(\beta-1)}}{w^2\phi_9^{\phi_2}\delta^{2\gamma}}[\phi_2\{w+(c+as+\theta^2\lambda)(\phi_2+1)-bs\theta-\phi_2(w+bs\theta)\}\{\beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda-\beta(\beta+1)bs\theta\}-[w\beta(\phi_2-1)-\phi_2\{\beta(c+as)-(\beta+1)bs\theta+(\beta+2)\theta^2\lambda\}]^2]$. Now $\mid H \mid > 0$ if $\phi_2[w+(c+as+\theta^2\lambda)(\phi_2+1)-bs\theta-\phi_2(w+bs\theta)][\beta(\beta+1)bs\theta < \beta(\beta-1)(c+as-w)+(\beta+1)(\beta+2)\theta^2\lambda] > [w\beta(\phi_2-1)-\phi_2\{\beta(c+as)-(\beta+1)bs\theta+(\beta+2)\theta^2\lambda\}]^2$.

There exists a unique optimal solution which can be obtained from the first order necessary conditions $\frac{\partial\mathrm{PM}_i}{\partial w} = 0$, $\frac{\partial\mathrm{PM}_i}{\partial\theta} = 0$ as

$$
\begin{aligned}
w^* &= \frac{\phi_2(bs\phi_{11}-\phi_{10})}{2\lambda\phi_{12}^2} \\
\theta^* &= \frac{bs(\phi_2-\beta-1)-\phi_{11}}{2\lambda\phi_{12}} \\
m^* &= \frac{\phi_2\{(\phi_2-1)\delta+1\}(\phi_{10}-bs\phi_{11})}{2\lambda\phi_{12}^2(\phi_2-1)(\delta-1)} \\
p^* &= \frac{\phi_2^2(\phi_{10}-bs\phi_{11})}{2\lambda\phi_{12}^2(\phi_2-1)(\delta-1)} \\
t^* &= \delta\frac{\phi_2^2(\phi_{10}-bs\phi_{11})}{2\lambda\phi_{12}^2(\phi_2-1)(\delta-1)}
\end{aligned}
$$

where

$$
\begin{aligned}
&\phi_{10} = b^2s^2(\phi_2-\beta-1)+4\lambda(c+as)\phi_{12}, \\
&\phi_{11} = \sqrt{b^2s^2(\phi_2-\beta-1)^2-4\lambda\beta(c+as)\phi_{12}}, \\
&\phi_{12} = (2+\beta-2\phi_2).
\end{aligned}
$$

□

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