Two-Period Supply Chain Coordination Strategies with Ambidextrous Sustainable Innovations

Abstract: This study considers a manufacturer with ambidextrous sustainable innovation capability selling products in environmentally conscious market through an independent retailer in a two-period game setting. We design a two-period game theoretic and dyadic supply chain (SC) model considering exploitative and exploratory nature of environmental innovations. We study five different contract types, viz. wholesale price contract, vertical Nash game structure, cost sharing contract, revenue sharing contract and two-part tariff contract. We demonstrate the impact of market sensitivity towards sustainable innovation and cost parameters on optimal level of decision parameters. The equilibrium results reveal that a suitably designed two-part tariff contract can be used to achieve coordination in a fragmented SC. The equilibrium results assist managers to optimise the SC based on the two-period contract model. The results obtained in this study can help the decision-makers to take decisions on investment in the ambidextrous sustainable innovation under different types of contract structures.

Keywords: Sustainable innovation; Exploratory innovation; Exploitative innovation; Supply chain coordination; Game theory; Optimal decision.

1. Introduction

Investment in sustainability leads to innovations which yield both net earnings and growth in sales revenue (Nidumolu et al., 2009; Hartmann and Vachon, 2018; Hizarci-Payne et al., 2021). The sustainability is being viewed as a source of innovation and new growth among business managers (KPMG, 2017; Wicki and Hansen, 2019; Wang, 2020). The extant literature discusses two basic forms of innovation that enhances the environmental performance, viz., exploratory and exploitative (Gibson and Birkinshaw, 2004; Awan et al., 2021). A business organisation that pursues exploitative (continuous) innovation builds on existing knowledge, whereas an organisation that pursues exploratory (disruptive) innovation relies on radical change built on new knowledge (Kim and Huh, 2015). The new knowledge thorough exploratory innovation could be regarding the development of more sustainable new product and services for existing customers, or developing product for new segments. For example, Abbott Laboratories is a medical devices and healthcare company that has achieved a high growth through disruptive innovations in medical devices and diagnostics and opened up several new markets in developing countries (Ahlstrom, 2010).

Through exploitative innovations, business organisations continuously strive to improve their existing products, processes and technologies. Proponent of this strategy for sustainability argues that it is based on addressing environmental and social issues thereby contributing to profit maximisation (Hosseini-Motlagh et al., 2019; Phan et al., 2019; Raza, 2018). For instance, GM's Flint plant in Michigan is saving approximately 174,299 kWh energy per year by shutting down plant during holidays (El Bizat, 2006). Instead of venting to the atmosphere, Statoil injects more than 1 million tonnes of CO_2 per year underneath the North Sea bed to save paying carbon tax to Norway (Stefan and Paul, 2008).

The gains from the exploratory innovations are not immediate. The exploratory innovations require concentrated efforts for a longer time periods and may not result in direct visible savings in the same time period when we invest into it. A lot of disruptive sustainable innovations have brought additional purchasers into the markets earlier who could not consume or meet the expense of the conventional product (Christensen and Raynor, 2003; Jakhar et al., 2020).

A firm engaging in both innovation strategies as discussed above is termed as ambidextrous (Lin et al., 2017). The recent development of ambidexterity stems from the recognition that exploration engenders prospects that an organisation can later exploit (Kim and Atuahene-Gima, 2010; Lavie et al., 2010; Mueller et al., 2013). Gupta et al. (2006) discussed ambidextrous innovative behaviour of Cisco and other firms in the semiconductor industry. Knott (2002) observed that exploration and exploitation coexisted in Toyota's product development system. The Toyota Fuel Cell System is an excellent example that includes both fuel cell technology and hybrid technology based ambidextrous sustainability innovation practices.

There are three ways to measure ambidextrous innovations as subtracting (He and Wong, 2004), multiplying (Gibson and Birkinshaw, 2004), and adding (Jansen et al., 2006, 2009; Kortmann et al., 2014) of exploratory and exploitative innovations. However, it has been proved that the additive model possesses greater explanatory power as compared to the other two approaches (see Jansen et al., 2009, p. 803 for a detailed analysis).

1.1. Research questions and goals

Motivated by the above background where the firms invest in the exploratory and exploitative innovation, we propose that environmental innovation has a two-pronged impact: (i) reduction in cost due to eco-efficiency and (ii) the expansion of emerging markets (e.g., the bottom of the pyramid). Moreover, investment in sustainability will cause an increase in demand due to environmentally conscious buyers in the existing markets (Figure 1).

The extant literature considers environmental innovation in various models (Hong and Guo, 2019; Shen et al., 2019; Xie et al., 2019; Nguyen et al., 2020). In sustainability literature, these two strategies are known as eco-efficiency and eco-branding, respectively (Orsato, 2006). Whereas the competitive focus of eco-efficiency strategy is on a manufacturing/service process, the competitive focus of eco-branding strategy is on the output of a manufacturing/service process. It is fundamental to recognize that focusing on eco-efficiency is not equivalent to focusing on eco-branding (or vice versa). One strategy is about reducing the environmental impact of a product during its manufacturing stage (e.g., using renewable energy sources to power the manufacturing plant, reducing water usage during the production process), whereas the other is about reducing the environmental impact of a product during its use stage (e.g., increasing the energy efficiency of a washer unit). Raz et al. (2013) examine a firm's design for the environment efforts that change the product's environmental impacts in each life-cycle stage and therefore its overall environmental impact. In their model, the cost to produce the product is decreasing in the innovation effort for the manufacturing stage (i.e. exploitative innovation), whereas end-customer demand is stochastic and depends on the use stage innovation effort (i.e., exploratory innovation). However, the most of literature overlooks the exploratory and exploitative nature of environmental innovation. This study takes breakthrough step and considers ambidextrous nature of sustainable innovation, and demonstrates the effectiveness of the two-period contract structure. Although some two-period contract models are available in literature (Chakraborty et al., 2019; Hartwig et al., 2015; Merckx and Chaturvedi, 2020; Pan et al., 2009), they do not consider exploratory and exploitative nature of environmental innovation. Driven by the above discussion the following research questions are posed:

- How an analytical model can be formed by simultaneously considering exploratory and exploitative nature of environmental innovation?

- In a dyadic supply chain, how does the decision maker's investment in environmental innovation influence the measures of supply chain performance? And, in which contract structure, the supply chain performance is better?

- What are the changes in optimal level of decision parameters of a two-period contract model considering ambidextrous nature of sustainable innovation?

- What is the impact of market sensitivity towards environmental innovation and its cost parameters on the measures of supply chain performance in a two-period contract setting?

- What is the impact of exploratory and exploitative nature of environmental innovation on the measures of supply chain performance in a two-period contract setting?

To address these questions, we design a two-period game theoretic and dyadic supply chain model considering simultaneously exploitative and exploratory nature of environmental innovations. The manufacturer, assumed to be a Stackelberg leader, invests in ambidextrous sustainable innovations. We discuss five different contract types, viz. wholesale price contract (WSP), vertical Nash game structure(VN), cost sharing contract (CSC), revenue sharing contract (RSC), and two-part tariff contract (2PT). First, we study wholesale price contract. As this contract structure leads to sub-optimal solution failing to coordinate the supply chain, we discuss vertical Nash game structure relaxing the assumption of Stackelberg structure. Subsequently, we consider other three different contracts, viz. CSC, RSC and 2PT.

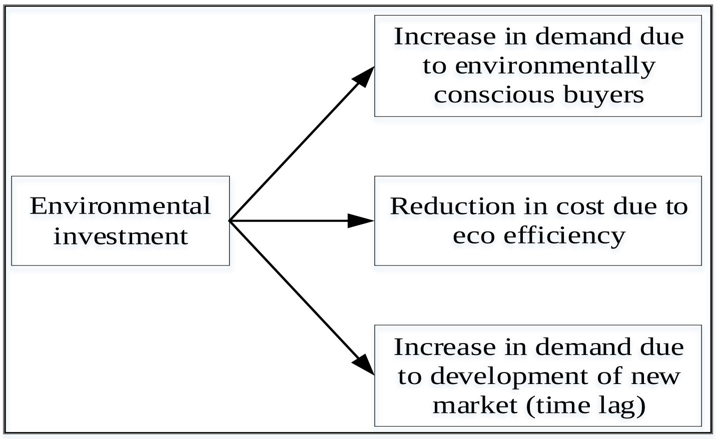

Figure 1: Impact of environmental investment

1.2. Research contribution

This study contributes to the literature in multiple ways. Firstly, we develop a two-period contract setting with ambidextrous sustainable innovations. Second, we study a two-period game using five different contract types and delineate its effectiveness using numerical examples. Third, we discuss the nature of changes in the level of optimal value of decision parameters in ambidextrous sustainable innovation based on the two-period contract setting. Fourth, we analyse the impact of consumer sensitivity of sustainable innovation and sustainable cost parameter on the decision parameters of the two-period contract models.

Fifth, we analyse the impact of exploratory and exploitative nature of environmental innovation in the two-period contract setting.

1.3. Knowledge gaps

The literature limits their analysis to supply chain coordination while considering the trade-off between "cost of sustainability" and increase in demand due to "environmental conscious buying". Analytical research on different types of sustainable innovations in product, process and value chain in supply chain coordination is scant. In particular, investigation of supply contracts with the integration of the exploratory and exploitative sustainable innovations is a knowledge gap in the extant literature. Designing contracts while considering both type of sustainable innovation may eliminate both environmental concerns and discoordination among supply chain partners. This article considers both the dimensions of innovation (i.e. exploratory and exploitative) with various contracts to attain sustainable supply chain coordination.

Moreover, the extant literature on coordination mechanisms and strategies with sustainability also assumes that the sustainable innovation does not change the marginal cost of manufacturers. We deviate from the extant literature by proposing that the supply chains invest in sustainable products and technology not only to satisfy environmentally conscious consumers but also to reduce material/production costs and to develop new markets. We consider two possible scenarios for investment in sustainable innovation, viz. (i) exploitative sustainable innovation and (ii) exploratory innovation. The exploitative sustainable innovation makes existing products more sustainable by reducing the consumption of material and energy. The resultant impact is cost saving (e.g. through low cost of production). The exploratory innovation develops new products and markets which will come with a time lag as exploration takes time. In this article we consider one period time lag.

This article attempts to address these knowledge gaps by considering two types of sustainable innovation in a two-period setting. We explain a game theoretic model for supply chain coordination (Cachon, 2003; Chen and Nie, 2020), and demonstrate the impact of sustainable innovation on demand and cost of a product. The game theoretic method is extensively used in literature to analyse the interaction between two or more players (Yazan et al., 2020). In this context, we analyse four contracts, viz. WSP, RSC, CSC and linear 2PT contract using non-cooperative game theory.

The remainder of the paper is organised as follows. The study model, its assumptions, and game constructs are presented in section 2. Section 3 details the results of the analysis.

Finally, section 4 elucidates conclusions and future research direction.

2. The Model

Consider a dyadic supply chain (SC) consisting of a manufacturer and retailer (Figure 2). The manufacturer supplies only one type of product while the retailer sells that product. Both the supply chain partners are considered to be individually rational (voluntary participation) and risk neutral (linear utility function) in nature. The manufacturer and retailer are assumed to be the Stackelberg leader and follower respectively. Consumers are sensitive towards environmental issues. The manufacturer performs incremental and radical in-nature sustainable innovations. For the radical innovation, the market potential of period (t+1) is linearly dependent on sustainable innovation level of period t (Christensen and Raynor, 2003), thus $a_{t+1} = a_t + \gamma\theta_t$. With incremental innovation, the manufacturer improves its processes and becomes more efficient which results in reduction of production cost in the second period (Sharma and Henriques, 2005) which is expressed as: $c_{t+1} = c_t - \beta\theta_t$. The linear, deterministic demand function with negative and positive correlation with price and sustainable innovation level is considered in our study as: $q_t = a_t - p_t + \alpha\theta_t$. Similar demand function is used in previous studies on single period contract models (Swami and Shah, 2013).

The selling price consists cost plus profit margin (Choi, 1991). Mathematically, $p_t = w_t + m_t$. The cost of sustainable innovation is supposed to be the quadratic function of level of sustainable innovation (Swami and Shah, 2013), which is $Cost\ of\ greening = I\theta_t^2$. Table 1 provides the notations used in this model.

2.1. Centralised supply chain

In the ‘coordination’ literature, the centralised case provides benchmark solution. In the centralised SC, the owner decides the level of sustainable innovation ($\theta_1\ and\ \theta_2$), retail prices ($p_1\ and\ p_2$), and order quantity ($q_1\ and\ q_2$). In the first period, the chain owner fixes the level of retail price (p_1) and sustainable innovation (θ_1). Similarly, in the second period, the chain owner fixes the level of retail price (p_2) and sustainable innovation (θ_2). The backward induction method is used to derive the optimal decision parameters of the two-period model. In this case, first of all, the equilibrium level of decision parameters ($\theta_2 and\ p_2$) of the second period are derived and then, based on results of second period, the equilibrium level of decision parameters ($\theta_1 and\ p_1$) of the first period are derived. In case of the centralised SC, the profit function π_{CENT} is jointly concave in (p, θ) when $(4I - \alpha^2) > 2(\beta + \gamma)\sqrt{I}$. The equilibrium results for the centralised SC are illustrated in Table 2. The steps of proof of equilibrium results are provided in Table A of Appendix and derivations are given in online supplementary material.

Table 1: The notations used in the model

Sl. No.	Parameters, decision variables and coordination strategies	Notations
1	Market potential in period *t*	a_t
2	Consumer sensitivity to price	b
3	Per unit variable cost of manufacturer in period *t*	c_t
4	Consumer sensitivity to sustainable innovation	α
5	Cost reduction coefficient due to sustainable innovation	β
6	Market development coefficient due to sustainable innovation	γ
7	Sustainable innovation level in period *t*	θ_t
8	Cost parameter of sustainable innovation	I
9	Margin of retailer in period *t*	m_t
10	Wholesale price of manufacturer in period *t*	w_t
11	Retail price in period *t*	p_t
12	Demand in period *t*	q_t
13	Aggregate profit of the manufacturer	π^M
14	Aggregate profit of the retailer	π^R
15	Aggregate profit of the supply chain	π^{SC}
16	Manufacturer's profit in period 1 and 2	π_{P1}^M *and* π_{P2}^M
17	Retailer's profit in period 1 and 2	π_{P1}^R *and* π_{P2}^R
18	Supply chain profit in period 1 and 2	π_{P1}^{SC} *and* π_{P2}^{SC}
19	Vertical Nash game	VN
20	Centralised decision making	CENT

Note: For the first period, a and c is used in the place of a_1 and c_1 respectively, i.e. Market potential of first period(a) and a_1 is used interchangeably.

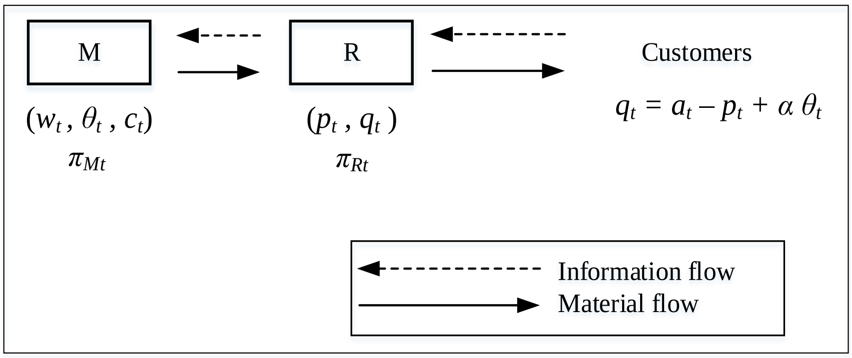

Figure 2: The model

2.2. Vertical Nash game

The vertical Nash game structure assumes that all the SC agents have similar market power. In the initial period, the retailer decides m_1 and the manufacturer decides w_1 and θ_1 simultaneously. Based on the response function of the initial period, in the second period, the retailer decides m_2 and the manufacturer decides w_2 and θ_2 simultaneously. The backward induction method is used to compute the optimal decision parameters of the vertical Nash game in the two-period model. In this scenario, first the equilibrium results for the second period are derived. Then based on the response functions of the second period, the equilibrium results of first period are derived. In other words, in the second period, the retailer decides m_2 and the manufacturer decides w_2 and θ_2 simultaneously. After getting the results of the second period, the retailer decides m_1 and the manufacturer decides w_1 and θ_1 simultaneously in the first period. The equilibrium results for the vertical Nash game are presented in Table 2. The steps of proof of equilibrium results are provided in Table A of Appendix and derivations are given in the online supplementary material.

2.3. Wholesale price contract

In the scenario, the manufacturer is considered as the market leader in the Stackelberg game while the retailer is considered as a follower. In the first period, based on the response function of the retailer, the manufacturer sets the wholesale price (w_1) and level of sustainable innovation (θ_1). Then the retailer decides their profit margin (m_1) using the values of w_1 and θ_1. Similarly, in the second period, based on the response function of the retailer, the manufacturer sets the wholesale price (w_2) and level of sustainable innovation (θ_2). The retailer decides their profit margin (m_2) using the level of w_2 and θ_2. The equilibrium results for the second period are derived using the backward induction method, and then, based on the response functions of the second period, the equilibrium results for first period are derived. Similarly, in the first period, based on the response function of second period, the retailer decides their profit margin (m_1). Finally, in the last stage of the game, the manufacturer decides their level of wholesale price (w_1) and sustainable innovation (θ_1) depending on the profit margin of the retailer (m_1). The equilibrium results for the two-period WSP contract are presented in Table 2. The steps of proof of equilibrium results are provided in Table A of Appendix. Derivations are given in the online supplementary material.

2.4. Cost sharing contract

In this contract, the retailer contributes a portion of the total cost of the sustainable innovation and if the manufacturer agrees to the offer, remaining fraction of sustainable innovation cost is borne by them. Due to sharing of cost by the retailer, the manufacturer can be motivated for sustainable performance. In the first period, first of all the retailer contributes $\psi_1$fraction of the total cost of sustainability, and given the level of cost sharing fraction by the retailer, the manufacturer decides w_1 and θ_1. The retailer decides their profit margin (m_1) considering $\psi_1, w_1,$ and θ_1. Similarly, in the second period, the retailer shares ψ_2 fraction of the total cost of sustainability. Then with the given level of cost sharing by the retailer, the manufacturer decides w_2 and θ_2. The retailer decides their profit margin (m_2) considering the level of $\psi_2, w_2,$ and θ_2. Similar to the vertical Nash game and WSP contract, the backward induction method is used to compute the equilibrium results for the CSC. The equilibrium results for the second period are derived followed by the solution of the equilibrium results for the first period. The equilibrium results of the two-period CSC are presented in Table 2. The steps of proof of equilibrium results are provided in Table A of Appendix and derivations are given in the online supplementary material.

2.5. Revenue sharing contract

In this contract type, the retailer contributes a fraction of their revenue with the manufacturer to motivate the manufacturer to decrease the wholesale price, or increase the level of sustainability, or both. In the beginning of the first period, the retailer offers to share $(1 - \phi_1)$ fraction of revenue with the manufacturer. The retailer decides the level of the wholesale price (w_1) and sustainable innovation (θ_1) if the manufacturer decides to accept the offer. Finally, the retailer decides their profit margin (m_1) considering the level of ϕ_1, w_1 and θ_1. Similarly, in the second period, considering the response function of the first period, the retailer offers to share $(1 - \phi_2)$ fraction of revenue with the manufacturer. If the manufacturer accepts the offer, the retailer decides the level of w_2 and θ_2. Finally, the retailer decides their profit margin (m_2) considering the levels of ϕ_2, w_2 and θ_2. Similar to vertical Nash game, WSP and CSC, the backward induction method is applied to compute the equilibrium results of the two-period RSC. The equilibrium results of two-period RSC are presented in Table 2. The steps of proof of equilibrium results are provided in Table A of Appendix and derivations are given in the online supplementary material.

2.6. Two-part tariff contract

A linear two-part tariff (2PT) contract is considered where the manufacturer sets a lump-sum payment, level of sustainable innovation and wholesale price. From the level of lump-sum payment, sustainable innovation and wholesale price, the retailer decides the retail price. In the first period the manufacturer decides the lump-sum fee (l_1), level of sustainable innovation (θ_1), and wholesale price (w_1), and then the retailer fixes their profit margin (m_1) considering the levels of l_1, θ_1, and w_1. Similarly, in the second period, the manufacturer decides l_2, θ_2 and w_2, and the retailer decides their profit margin (m_2) considering the levels of l_2, θ_2 and w_2. The backward induction method is applied to compute the equilibrium results of the two-period linear 2PT contract. In the first period, the retailer arrives at m_1 considering the response functions of the first period and the response function of the manufacturer. At the end of the event, after considering the decision of the retailer on their profit margin (m_1), the manufacturer decides l_1, θ_1 and w_1. The equilibrium results of the two-period 2PT contract are presented in Table 2. The steps of proof of equilibrium results are provided in Table A of Appendix, and derivations are given in the online supplementary material.

3. Results and Discussion

This section presents the propositions derived through algebraic comparisons. The proofs of all the propositions are given in the online supplementary material. A numerical analysis is performed to compare the optimal results obtained for different contract types. Finally, the sensitivity analysis of the results is presented.

Proposition 1: In case of the two-period contract, the optimal level of the retail price follows the following order:

(a) $p_{WSP-P2} > p_{WSP-P1}$ if $2\sqrt{2I}(\beta+\gamma) < (8I-\alpha^2) < \frac{2I(\beta+\gamma)(3\gamma-\beta)}{\alpha\beta}$,

(b) $p_{CENT-P2} = p_{2PT-P2} > p_{CENT-P1} = p_{2PT-P1}$ if $2\sqrt{I}(\beta+\gamma) < (4I-\alpha^2) < \frac{2I(\beta+\gamma)(\gamma-\beta)}{\alpha\beta}$.

Proposition 1 demonstrates that for the WSP contract, the optimal level of retail price is higher in the second period than that of the first period. The same is the case for the 2PT contract and centralised SC. This proposition further demonstrates that in case of the 2PT contract, the optimal level of the retail price can be equated with the centralised SC. The reason for the same is that the one-time payment becomes sunk cost and the 2PT contract SC behaves like a centralised SC.

Proposition 2: In case of the two-period contract, the optimal levels of sustainable innovation are in order of:

(a) $\theta_{WSP-P1} > \theta_{WSP-P2}$,

(b) $\theta_{2PT-P1} = \theta_{CENT-P1} > \theta_{2PT-P2} = \theta_{CENT-P2}$.

Proposition 2 demonstrates that for the WSP, 2PT, CSC and vertical Nash game, the optimal level of sustainable innovation is less in the second period than the period one. The reason is the time lag for the benefit due to exploratory innovation. No future period is attached to the second period. Moreover, the other explanation could be diminishing marginal return as the low hanging fruits are plucked in the first period. This proposition further demonstrates that in the 2PT contract, the optimal level of the sustainable innovation can be equated to the optimal level of the sustainable innovation in the centralised SC for both the periods.

Proposition 3: For the two-period contract, the equilibrium level of the order quantity follows the following order:

(a) $q_{WSP-P2} > q_{WSP-P1}$ if $(8I\text{-}\alpha^2) > 2\sqrt{2I}(\beta+\gamma)$,

(b) $q_{2PT-P2} = q_{CENT-P2} > q_{2PT-P1} = q_{CENT-P1}$.

Proposition 3 demonstrates that in the case of the WSP, 2PT contract, and vertical Nash game, the optimal level of the order quantity is higher in the second period than the optimal level of the order quantity in the first period. The increase in the order size is due to an increase in market size because of the radical innovations. This proposition further illustrates that for the 2PT contract, the optimal level of order quantity can be equated to the optimal level of order quantity in the centralised SC in both the periods.

Proposition 4: In case of the two-period contract, the profit of the retailer follows the following order $\pi^R_{WSP-P2} > \pi^R_{WSP-P1}$, $\pi^R_{2PT-P2} = \pi^R_{2PT-P1}$.

Proposition 4 demonstrates that in case of the WSP contract, the optimal level of the profit of the retailer is higher in the second period than the optimal level of the profit of the retailer in the first period. The retailer is benefited by an increase in the market size which reflects an increase in the profit of the second period. However, the benefit of the cost reduction may not be transferred to the retailer by the manufacturer as we can see in Proposition 1 that retail price is higher in the second period. This proposition further exhibits that the optimal level of the profit for the retailer is same in both the periods in 2PT contract. This is due to the fact that the manufacturer may be barging for higher upfront payment in the second period as they are investing for the sustainable innovation. Moreover, the manufacturer only invests in the sustainable innovations. The following section presents numerical simulation results and graphical analysis to study the impacts of model parameters on the equilibrium results in different channel structures. The following parameter values are considered in our study: $a_1 = 500$, $c_1 = 20$, $I = 8.5\ to\ 10.5$, $\alpha = 2.5\ to\ 4$, $\gamma = 1\ to\ 2.4$, $\beta = 0\ to\ 0.7$, and $\bar{\pi}^R = 100000$.

Table 2: Equilibrium results

Supply chain coordination	**Equilibrium level of price, quantity, wholesale price, sustainable innovation level, profit of manufacturer, and profit of retailer**
Centralised supply chain	$p_{CENT-P1} = \left[c + \frac{2I(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(4I-\alpha^2)\}}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}}\right]$,$q_{CENT-P1} = \left[\frac{2I(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(4I-\alpha^2)\}}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}}\right]$, $\theta_{CENT-P1} = \left[\frac{(a-c)\{\alpha^3-4I(\alpha+\beta+\gamma)\}}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}}\right]$, $\pi_{CENT} = \left[\frac{I(a-c)^2[\{\alpha-(\beta+\gamma)\}^2-(8I-\alpha^2)]}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}}\right]$
Vertical Nash game structure	$p_{VN-P1} = \left[c + \frac{4I(a-c)}{G_2}H_1\right]$, $q_{VN-P1} = \left[\frac{(a-c)}{3}H_2\right]$, $w_{VN-P1} = \left[c + \frac{2I(a-c)}{G_2}H_3\right]$, $\theta_{VN-P1} = \left[\frac{(a-c)}{G_2}H_4\right]$, $\pi_{VN}^M = \left[\frac{(a-c)^2}{9}\left\{1 + \frac{G_4}{2G_2} + \frac{\alpha^2(6I-\alpha^2)^2 G_3}{2G_2^2}\right\}\right]$, $\pi_{VN}^R = \frac{(a-c)^2}{9}[1 + H_5]$
Wholesale price contract	$p_{WSP-P1} = \left[c + \frac{6I(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(8I-\alpha^2)\}}{\{8I(\beta+\gamma)^2-(8I-\alpha^2)^2\}}\right]$, $q_{WSP-P1} = \left[\frac{2I(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(8I-\alpha^2)\}}{\{8I(\beta+\gamma)^2-(8I-\alpha^2)^2\}}\right]$, $w_{WSP-P1} = \left[c + \frac{4I(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(8I-\alpha^2)\}}{\{8I(\beta+\gamma)^2-(8I-\alpha^2)^2\}}\right]$, $\theta_{WSP-P1} = \left[\frac{(a-c)\{\alpha^3-8I(\alpha+\beta+\gamma)\}}{\{8I(\beta+\gamma)^2-(8I-\alpha^2)^2\}}\right]$, $\pi_{WSP}^M = \left[\frac{I(a-c)^2\{(\beta+\gamma-\alpha)^2-(16I-\alpha^2)\}}{\{8I(\beta+\gamma)^2-(8I-\alpha^2)^2\}}\right]$, $\pi_{WSP}^R = \left[\frac{4I^2(a-c)^2(\beta+\gamma)}{\{8I(\beta+\gamma)^2-(8I-\alpha^2)^2\}}J\right]$
Cost sharing contract	$p_{CSC-P1} = \left[\frac{(a+3c)}{4} + K_1\right]$, $q_{CSC-P1} = \frac{(a-c)}{2}\left[\frac{1}{2} + K_2\right]$, $w_{CSC-P1} = \left[\frac{(a+5c)}{6} + K_3\right]$, $\theta_{CSC-P1} = \frac{2(a-c)[16I(\alpha+\beta+\gamma)-3\alpha^2]}{[(16I-3\alpha^2)^2-(\beta+\gamma)^2(48I-\alpha^2)]}$, $\pi_{CSC}^M = \frac{(a-c)^2}{4}\left[1 + \frac{\alpha^2}{4(16I-3\alpha^2)} - K_4\right]$, $\pi_{csc}^R = \frac{(a-c)^2}{8}\left[1 + \frac{\alpha^2}{4(16I-3\alpha^2)} + K_5\right]$
Revenue sharing contract	$p_{RSC-P1} = \left[\frac{(3a+c)}{4} + \frac{\alpha(a-c)}{4G_5}T_1\right]$,$q_{RSC-P1} = \frac{I(a-c)}{G_5}T_2$, $\theta_{RSC-P1} = \left[\frac{(a-c)}{G_5}T_3\right]$, $\pi_{RSC}^M = \frac{I(a-c)^2}{2G_5}T_4$, $\pi_{RSC}^R = \frac{I(a-c)^2}{4G_5}T_5$
Two-part tariff contract	$p_{2PT-P1} = \left[c + \frac{2I(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(4I-\alpha^2)\}}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}}\right]$, $q_{2PT-P1} = \left[\frac{2I(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(4I-\alpha^2)\}}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}}\right]$, $\theta_{2PT-P1} = \left[\frac{(a-c)\{\alpha^3-4I(\alpha+\beta+\gamma)\}}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}}\right]$, $l_{2PT-P1} = \left[\frac{4I^2(a-c)\{(\beta+\gamma)(\beta+\gamma-\alpha)-(4I-\alpha^2)\}^2}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}^2} - \bar{\pi}^R\right]$, $\pi_{2PT}^M = \left[\frac{I(a-c)^2[\{\alpha-(\beta+\gamma)\}^2-(8I-\alpha^2)]}{\{4I(\beta+\gamma)^2-(4I-\alpha^2)^2\}} - 2\bar{\pi}^R\right]$, $\pi_{2PT}^R=2\bar{\pi}^R$, $w_{2PT-P1} = c$

Note: The details of **alias** used in Table 2 are given in Appendix A.1.

3.1. Effect of consumer sensitivity to sustainable innovation

The numerical parameter values for the analysis in this section are chosen in a way to satisfy the conditions of profit function concavity, along with demand functions positivity (conditions are provided in the online supplementary material) and satisfy the assumptions of model. It is observed from Figures 3 and 4 that consumer sensitivity to the sustainable innovation (α) has increasing impact on sustainable innovation level (θ) (Figure 3a), retail price (p) (Figure 3b), order quantity (q) (Figure 4(a)), and profit of retailer (π^R) (Figure 4(b)). However, the rate of increase is different for different contract types. Further, the consumer sensitivity to the sustainable innovation has mixed impact on the profit of the manufacturer (Figures 5(a) and 5(b)). In the first period, the profit of the manufacturer (π^M)

decreases with the increase in consumer sensitivity to the sustainable innovation for the cases of vertical Nash game and CSC. However, for the WSP and RSC, first it increases then decreases with the increase in consumer sensitivity to the sustainable innovation (Figure 5(a)). In the second period, π^M increases with the increase in α. For a 2PT contract, the π^M decreases in the first period whereas it increases in the second period (Figure 5(a)). The aggregate profit of the manufacturer, retailer and total supply increases with an increase in consumer sensitivity to the sustainable innovation. These interesting results provide a justification regarding why there is a need to analyse contracts for sustainability for multiple time periods. Furthermore, it also provides a key guidance to the SC managers regarding how the manufacturer is going to behave with respect to deciding investment level for the sustainable innovations. For example, for the WSP and RSC, there is an optimal investment level for a given customer sensitivity level of sustainable. Moreover, for the vertical Nash, CSC and 2PT contract, the manufacture should consider both the periods together for deciding the optimal investment level. If the manufacturer considers only a single period, then the investment is going to be lowered as compared with both the periods. These results justify the needs to consider multi-period setting while analysing the level of sustainability by the manufacture in different contract types.

Figure 3(a) shows that the level of sustainable innovation in the second period (θ_{P2}) is lower than the level of sustainable innovation in the first period (θ_{P1}) for all the contract types. One of the reasons behind this is a time lag for benefit accrual in terms of reduction in cost and increase in market size. Further, there is no future associated with the second (and last) period, therefore, the manufacturer invests less. The other reason could be diminishing marginal return in cost saving or increase in the market size. However, this also depends on contract types.

The optimal level of sustainable innovation (θ) is the highest in the 2PT contract and centralised supply chain (CENT) and it is the lowest in the WSP (Figure 3(a)). The lower level of sustainable innovation for some contracts (e.g. WSP) is due to the problem of double marginalisation and externality. The cost for sustainability is absorbed by the manufacture but benefits are shared with the retailer specifically for increase in the market size. However, in case of the 2PT contract the manufacture may barging for higher upfront fee for the second period that repay cost incurred and the resultant benefit of the sustainable innovation. As shown in Figure 3(b), the retail price is higher in the second period as compared with the first period for all cases, viz. CENT, 2PT, RSC, CSC, vertical Nash game, and WSP contract. The lower level of price in the first period can help to attract the customer in the first period, however the increased market size due to radical sustainable innovation can help the retailer to charge more in the second period. The analysis also suggests that as the level of sustainability increases, product becomes more costlier (Paparoidamis et al., 2019).

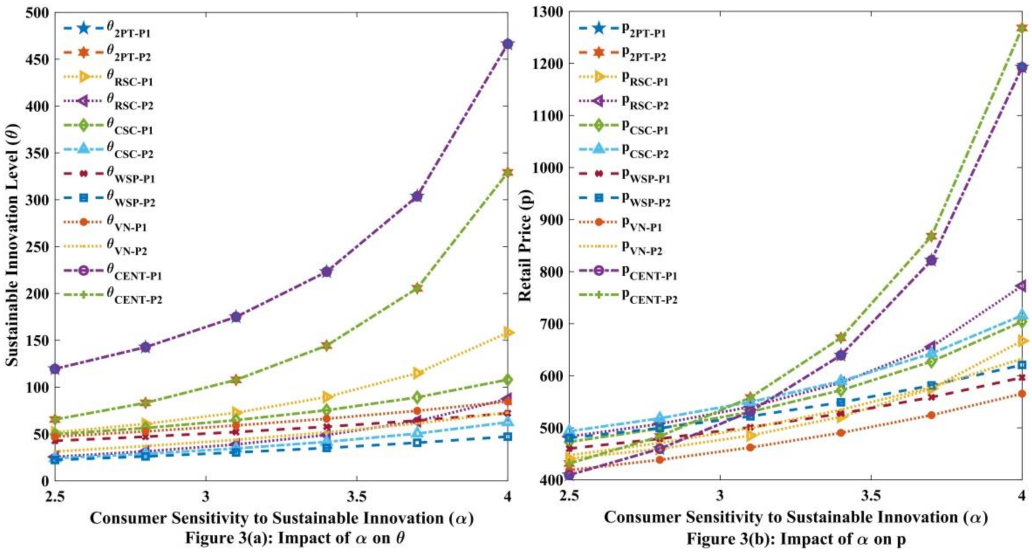

Figure 3: Impact of α on θ and p

From Figure 4(a), it is observed that the order quantity (equivalent to the demand) of the product is higher in the second period as compared with the demand in the first period. Figure 4(a) also illustrates that the order quantity is highest in the CENT and 2PT contract, and it is the lowest in the WSP contract. In the WSP contract the retailer pays same amount for every unit purchased from the manufacturer where the expected profit (i.e. price × probability to able to sell) goes down and the retailer ends up ordering less units.

It is apparent from Figure 4(b) that in case of the 2PT contract, the profit of the retailer is independent of the change in consumer sensitivity of the sustainable innovation (α), while it shows an increasing trend in case of the RSC, CSC, WSP contract, and vertical Nash game structure. The profit of the retailer is higher in the second period as compared with the profit in the first period (Figure 5(b)) in case of the RSC, CSC, WSP contract, and vertical Nash game structure. In case of the 2PT contract, the profit of the retailer is same in both the periods.

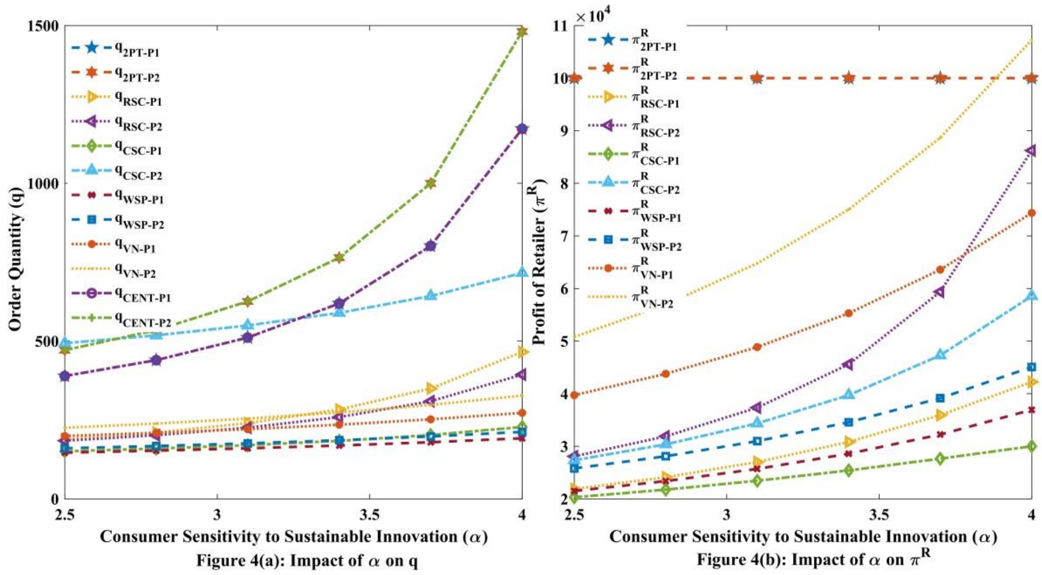

Figure 4(a): Impact of α on q
Figure 4(b): Impact of α on π^R

Figure 4: Impact of α on q and π^R

Figures 5(a) and 5(b) compare the π^M in different game structures with respect to a change in consumer sensitivity to the sustainable innovation (α). As shown in Figures 5(a) and 5(b), the π^M is higher in the second period as compared with the first period. The reason behind this is the reduction of the cost due to exploratory innovations and increase in market size due to exploitative innovations. We also observe that the π^M is the highest in the 2PT and RSC contracts and the lowest in the vertical Nash game structure. Moreover, the π^M behaves differently in both the periods. The profit decreases in the first period and increases in the second period. The reason behind this is that as the consumer sensitivity towards sustainable products increases, the manufacturer invests more in sustainable innovations. This results in more upfront investment in period 1 which decreases it profitability in the same period. However, it results in more profitability in longer run as reflected in profit in second periods. These results indicate that the manufacture needs to account long term profitability while investing in the sustainable innovations. The short-term profitability orientation may not provide true potential of the sustainable investment.

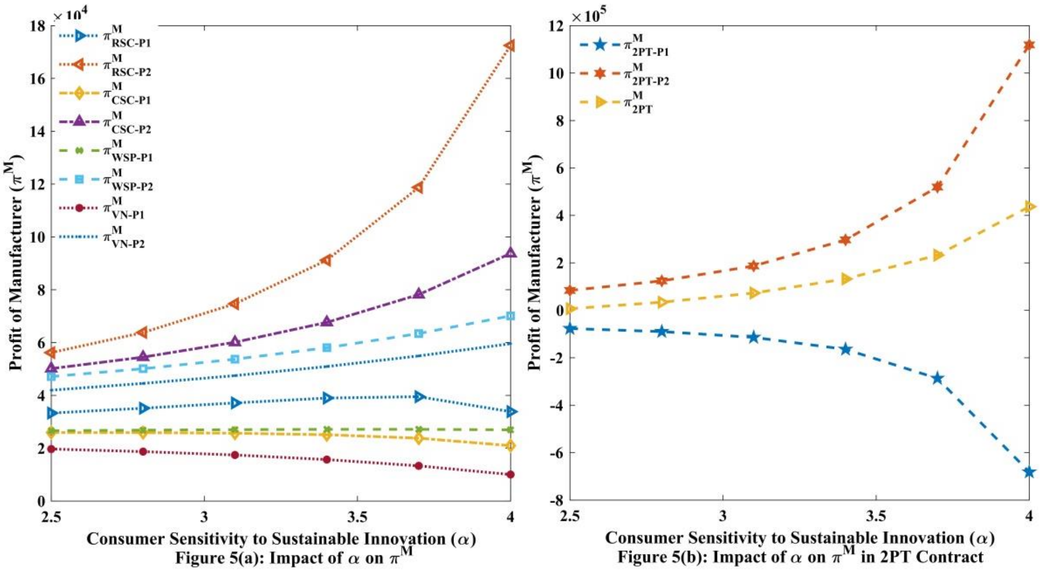

Figure 5: Impact of α on π^M

3.2. Effect of cost reduction coefficient

Figure 6(a) demonstrates the impact of cost reduction coefficient (β) on the optimal level of sustainable innovation (θ) across the various contracts and game structures in a multi-period setting. The value of β has an increasing impact on the level of sustainable innovation in all settings. Similar to the previous case (Figure 3(a)), the optimal level of sustainable innovation is lower in the second period as compared with the optimal level of sustainable innovation in the first period. Furthermore, the increasing impact of β on the optimal level of sustainable innovation (θ) is higher in the CENT and 2PT contract as compared to RSC, CSC, WSP contract and vertical Nash game. We also find that difference between the sustainable innovation level of the first and second period is lower at a lower level of cost reduction coefficient as compared with the higher values of the cost reduction coefficient.

Figure 6(b) highlights an interesting relationship between the cost reduction coefficient (β) and retail price (p). The β has increasing impact on the retail price. Figure 6(b) also elucidates that in case of CENT, 2PT contract, CSC, WSP contract, and vertical Nash game, the difference between the retail price of the first and second periods is higher at the lower level cost reduction coefficient as compared with the higher level of the cost reduction coefficient. We get opposite result in case of the RSC. In case of the RSC, the difference between the retail price of the second and first periods is lower at the lower level of β as compared with the higher level of β.

As shown in Figure 7(a), the cost reduction coefficient (β) has an increasing impact on the demand or order quantity of the product in both periods of the contracts. In case of the CENT, 2PT contract, CSC, WSP contract and vertical Nash game, the order quantity of the second period is higher than the order quantity of the first period. We get the opposite result in case of the RSC, in which the order quantity of the first period is higher than the order quantity of the second period. In case of the CENT and 2PT contract, CSC, WSP contract and vertical Nash game, the difference between the order quantity of the second and first periods is lower at the lower level of the cost reduction coefficient as compared with the higher level of the coefficient. For the RSC the difference between order quantity of the first and second periods is lower at the lower level of the cost reduction coefficient.

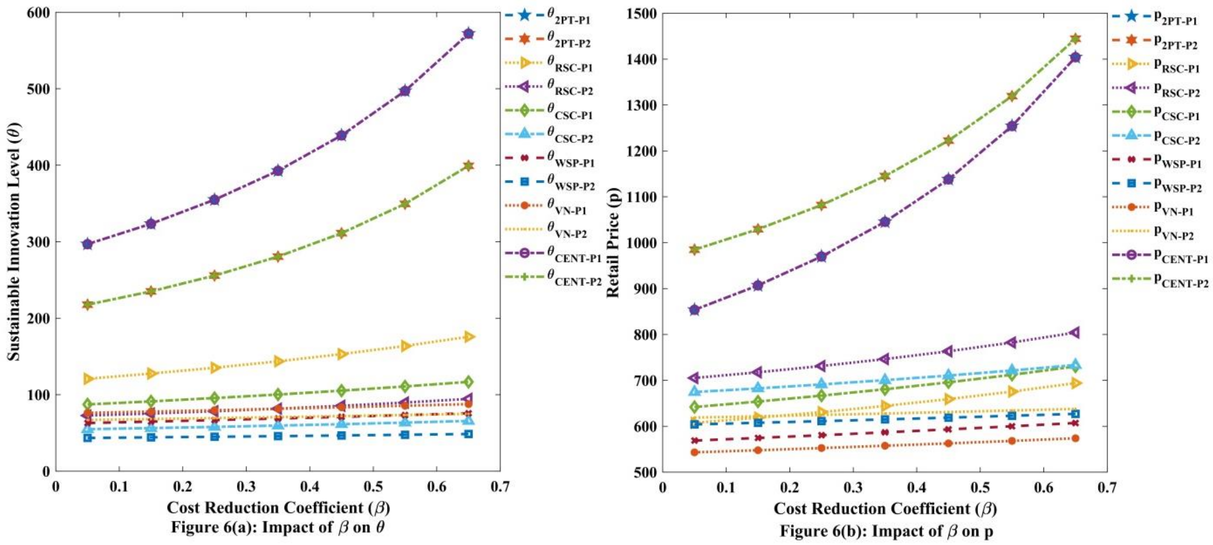

Figure 6: Impact of β on θ and p

Figure 7(b) presents the impact of the cost reduction on the profit of the manufacturer (π^M). The value of β has a mixed impact on π^M. In the first period of the contract, the profit decreases with an increase in the cost reduction coefficient, while in the second period, the profit increases with an increase in the cost reduction coefficient. Figure 7(b) also illustrates that the difference between the value of π^M in the second and first periods increases with respect to an increase in the cost reduction coefficient.

As shown in Figure 7(c), the cost reduction coefficient (β) has a mixed impact on the optimal profit level of the retailer. The β has a non-decreasing impact on the difference between the second and first periods profit level of the retailer. In case of the 2PT contract, the retailer’s profit is same in both the contract periods.

In case of the RSC, CSC, WSP contract and vertical Nash game, the optimal profit level of the second period is higher than that of the first period. In case of the first period of the RSC and CSC, the optimal level of the retailer’s profit increases and then it decreases after a certain level of the coefficient.

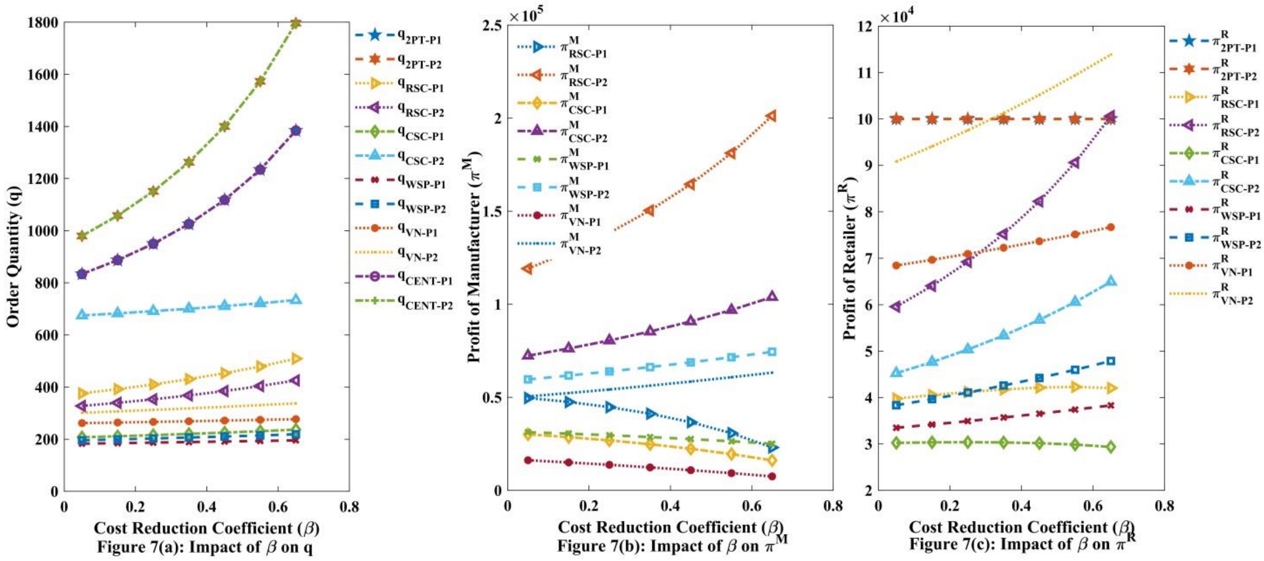

Figure 7: Impact of β on q, π^M and π^R

3.3. Effect of sustainability cost parameter

Figures 8(a), 8(b), 9(a) and 9(b) highlight the impact of the cost parameter of the sustainable innovation (I) on the retail price, order quantity, profit of the manufacturer, and profit of the retailer respectively. Interestingly the retail price decreases as the sustainable innovations become costlier (Figure 8). The reason behind this is that the costlier sustainable innovation becomes less attractive for the manufacturer to invest, which results in less demand from the sustainable sensitive customers. So, the retailer reduces the price to attract more customers. The rate of decrease is the highest for 2PT contract as the retailer paid upfront initial cost and needs more customer to recover the initial investment.

The order quantity (Figure 8(b)) also decreases with an increase in the cost parameter of the sustainable innovation. The reason is the decrease in demand due to less investment in the sustainable innovations from the manufacturer. The profit of the manufacturer (Figure 9(a)) decreases in the second period with an increase in the cost parameter of the sustainable innovation. The rate of decrease is the highest for the RSC. On the contrary there is a slight increase in the manufacturer's profit for the first period. Due to the high cost for the sustainable innovation, the manufacturer tends to invest less and save some initial investment cost in the first period. However, this leads to significant reduction in the manufacturer's profit in the second period. The profit of the retailer (Figure 9(b)) also shows the same pattern as that of the manufacturer.

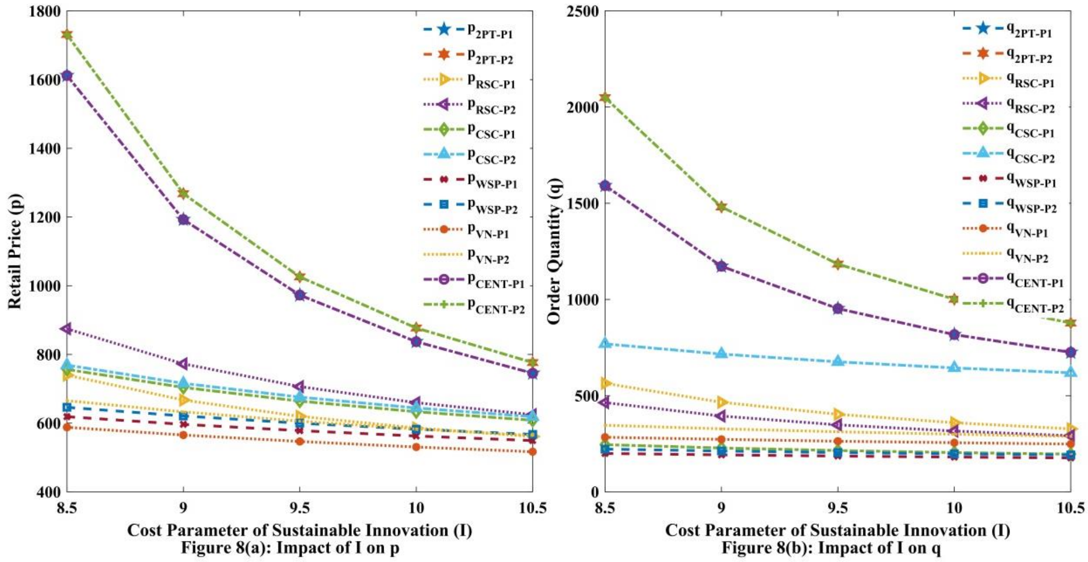

Figure 8: Impact of I on p and q

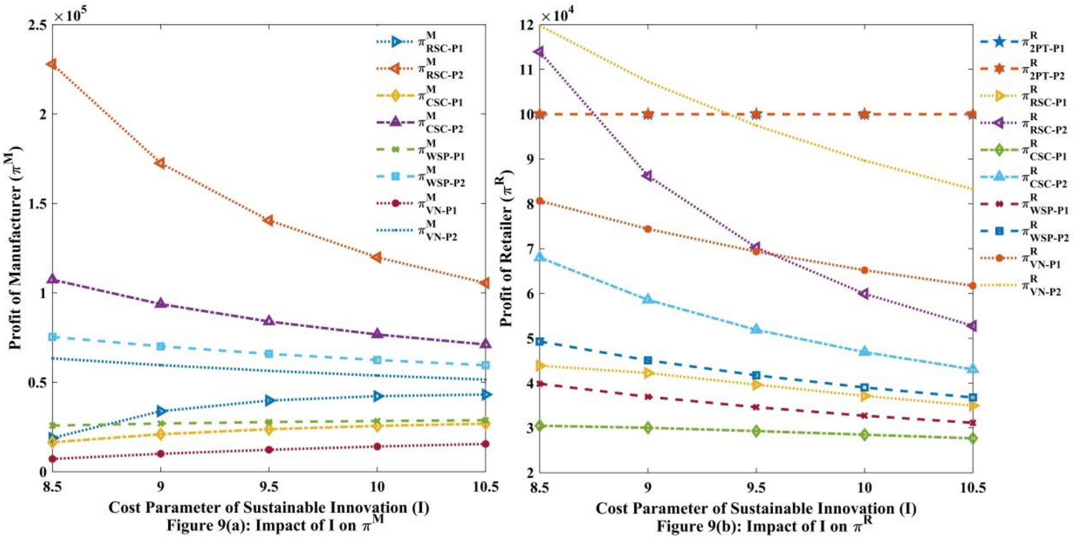

Figure 9: Impact of I on π^M and π^R

3.4. Effect of market development coefficient

Figures 10(a) and 10(b) demonstrate the impact of market development coefficient (γ) on profit of the manufacturer and retailer respectively. Market development coefficient has overall increasing impact on the aggregate profit of the manufacturer, retailer and SC. However, it shows contrasting trend in both the periods. The profit of the manufacturer increases in the second period whereas it decreases in the first period with an increase in the value of the market development coefficient. For the retailer, it depends on contract type. In case of RSC and CSC it first increases and then decreases for the first period. For all other contract types, it increases in both the periods. It is profitable for the retailer to have vertical Nash as compared with the RSC when the market with development coefficient value is less than 1.8. However, the retailer earns more profit in the RSC when the market development coefficient value is greater than 1.8. These results provide valuable guidance to the retailer on the type of contract that maximises its profit for a given value of γ.

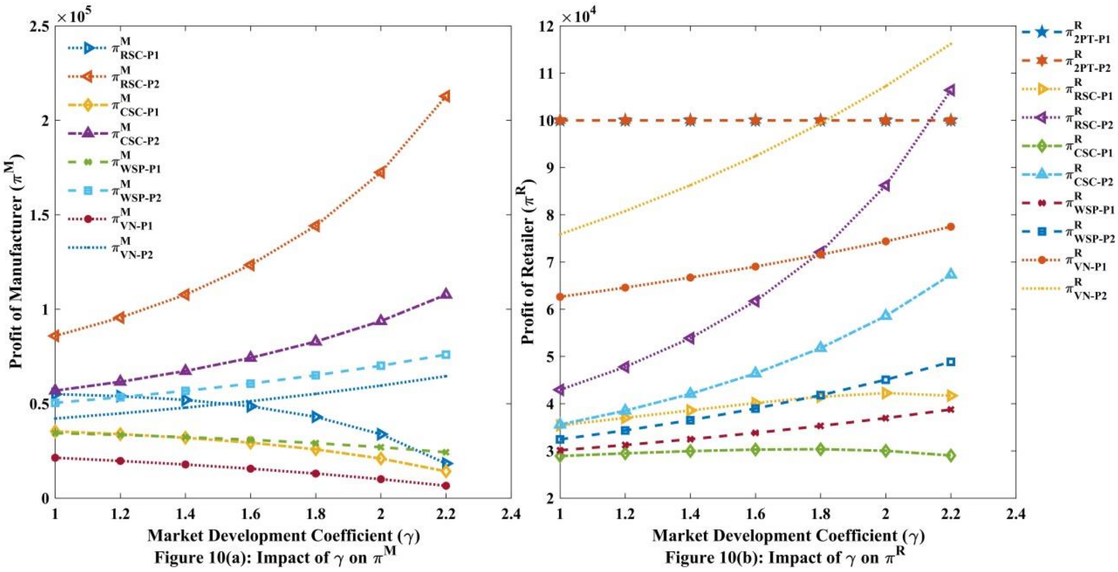

Figure 10: Impact of γ on π^M and π^R

4. Conclusions and Future Research Directions

This study analyses the two-period supply chain coordination strategies with ambidextrous sustainable innovations. The manufacturer is responsible for investing in sustainable innovations and selling the product through an independent retailer. The study assumes that market is sensitive towards environmental performance. The model considers a linear, deterministic, price and ambidextrous sustainable innovation dependent demand function, i.e. $q_t = a_t - p_t + \alpha\theta_t$. Due to the exploitative nature of the ambidextrous sustainable innovation, the marginal cost of the manufacturer in the period t+1 is considered to be dependent on the level of innovation in time period t, i.e. $c_{t+1} = c_t - \beta\theta_t$. For the exploratory nature of innovation, the market potential for the period t+1 is assumed to be dependent on the level of innovation for the period t, i.e. $a_{t+1} = a_t + \gamma\theta_t$. This study investigates the impact of decision maker's investment in the ambidextrous sustainable innovations on the measures of supply chain performance using five different two-period game structures, viz. wholesale price contract, vertical Nash game, cost sharing contract, revenue sharing contract, and two-part tariff contract. The study compares the results of period one and period two, and discusses the nature of changes in the optimal level of decision parameters. Further, the study demonstrates the impact of market sensitivity towards sustainable innovation and its cost parameter on optimal level of decision parameters of the two-period models. Finally, this study investigates the impacts of exploratory and exploitative nature of innovation on the decision parameters of the two-period contract models. The results demonstrate that a suitably designed 2PT contract can be used for coordination of a decentralised supply chain. A sensitivity analysis is performed for sustainability cost parameter, consumer sensitivity to sustainable innovation and cost reduction coefficient.

Based on the analysis of the results, we submit that in ongoing business relationships, the promise of future rewards, may provide incentives for good behaviour today. Here we refer the ‘good behaviour’ as ‘environmentally responsible manufacturing’. Some gains from the investment in sustainable innovations are noticed after a time lag, particularly for the case of exploratory innovations. This provides justification for considering multi-period setting for the supply chain coordination using the sustainable investment. Furthermore, the study reveals that the investment in sustainable innovation is significantly lower in the second period. There is no future period available to receive benefits of the investment in this period and the manufacture invests less in this period. Therefore, we propose that consideration of long-term gain perspective can incentivize the manufacturer to put their investment more in the sustainable innovations. Moreover, as the innovation literature agrees that for the exploratory innovations, the fruits can only be reaped after a time lag. By considering only a single period setting, the manufacture may not be willing to invest in the exploratory sustainable innovations. By considering a two period setting, the long term perspective for sustainability is incorporated in our model. The manufacturer may be willing to invest in exploratory sustainable innovations to reap long term benefits. We believe that this is the first study to incorporate the two period setting for ambidextrous sustainable innovation. Table 3 summarises the key research findings and their managerial implications.

In this study, we considered linear deterministic demand curve for our analysis. Various other types of demand functions such as nonlinear, stochastic etc. can be used in future studies. Further, this study assumes deterministic impact of the exploratory and exploitative innovation on the market potential and the marginal cost of manufacturer. The model can be extended under stochastic impact of ambidextrous sustainable innovation, i.e. exploratory and exploitative innovation both. Although the study considers the full information scenario, one can extend the study considering information asymmetry cases of demand information and cost information or the both. Additionally, this model can be extended for closed loop supply chain. This study excludes the discounting factor, uncertainty and moral hazard. The discounting factor, uncertainty and moral hazard can be further explored using multi-periodic coordination model.

Table 3: Findings and implications

Research question	Findings	Managerial / Policy implications
How an analytical model can be formed by simultaneously considering exploratory and exploitative nature of environmental innovation?	We have designed and demonstrated the effectiveness to two-period contract models with simultaneous consideration of exploratory and exploitative nature of environmental innovations. For modelling two-period contract, five different contract types have been used.	The equilibrium results presented in Table 2 can help managers to optimise the supply chain based on the two-period contract model.
In a dyadic supply chain, how does the decision maker's investment in environmental innovation influence the measures of supply chain performance? And, in which contract structure, the supply chain performance is better?	The manufacture's investment in ambidextrous sustainable (environmental) innovation increases the demand, level of sustainability in the product, profit of supply chain agent and total supply chain profit, that improves the supply chain efficiency. Two-part tariff contract coordinates the supply chain with channel efficiency equivalent to centralised decision making. revenue sharing contract partially coordinates the supply chain and performs better than the cost sharing contract. The channel efficiency is the lowest in the wholesale price contract.	Firms should invest in the environmental innovation to improve the level of sustainability. For perfect channel coordination, the firms should consider a two-part tariff contract.
What will be changes in optimal level of decision parameters of a two-period contract	The optimal level of investment in the sustainable innovation is higher in the first period as compared to the second period in the two-period setting. The retail price and demand of product is	The reason for the same is the time lag for the benefit due to the exploratory and exploitative innovation. The exploratory innovation leads to cost reduction

model considering ambidextrous nature of sustainable innovation?	higher in the second period than the first period. The profit of the manufacturer, retailer, and supply chain is higher in the second period than the first period.	whereas the exploratory innovation leads to new product development and generation of new markets (e.g., the base of the pyramid). Since no future period is attached to the second period, managers tend to invest less in the second period. This result provides insights regarding consideration of a long-term perspective for the sustainable investment. A short term perspective inhibits the investment in the sustainable innovation.
What is the impact of market sensitivity towards environmental innovation and its cost parameters on the measures of supply chain performance in a two-period contract model?	The consumer sensitivity to sustainable innovation (α) varies with the manufacturer's profit for different contract types and time periods. The consumer sensitivity to the sustainable innovation has increasing impact on the retail price, order quantity, and profit of the retailer. The retail price, order quantity, level of sustainability decreases with an increase in the sustainable cost parameter.	Firms should invest to increase the consumers' awareness about the sustainable products and sustainability performance of the firms. These can be accomplished through advertisements and promotional activities. Government can provide subsidies to the firms to lower the level of the cost parameter of sustainable innovation.
What is the impact of exploratory and exploitative nature of environmental innovation on the measures of supply chain performance in a two-period contract model?	Due to exploratory nature of innovation, the profit of the manufacturer slightly increases and decreases in the first period. However, it increases in the second period with an increase in the market development coefficient. In case of the retailer, the impact of the market development coefficient depends on the type of the contract. Due to the exploitative nature of the sustainable innovation, the retail	The results obtained in this study can help the decision makers to take decision on investment in the ambidextrous sustainable innovation under different types of contract structures.

	price, order quantity, and level of sustainability increases with an increase in the level of cost reduction coefficient (β). In the first period, the profit of the manufacturer decreases with an increases in the cost reduction coefficient, while in the second period, it is found to increase with an increase in β. β has non-decreasing impact on difference between the second period and first period profit of the retailer.	

Appendix A: Appendix

Appendix A.1: Alias

$G_1 = \{\alpha^5(\alpha^2 - 10I) - 6\gamma I(\alpha^2 - 4I)^2 + 12\alpha I^2(I + 2\alpha^2)\}$,

$G_2 = [6I(\alpha^2 - 4I)(\beta + \gamma)^2 - (\alpha^2 - 6I)^3]$, $G_3 = (6I-\alpha^2)(\alpha^4 - 24I^2)-12\alpha I(\beta+\gamma)(4I-\alpha^2)$

$G_4=(4I-\alpha^2)[24\alpha I(\beta+\gamma)+108\alpha^2-(2I+\alpha^2)^2]+16I^3$

$G_5=4[(\beta+\gamma)^2\{4I\alpha^2+4I(\beta+\gamma)^2-(8I-\alpha^2)^2\}-48I\alpha^2(4I-\alpha^2)]$

$H_1 = [\alpha^2\{\alpha^2 + (\beta + \gamma)^2\} + (\beta + \gamma)\{\alpha(4I - \alpha^2) - 4I(\beta + \gamma)\} + 12I(3I - \alpha^2)]$

$$H_2 = \left[1 + \frac{\alpha}{G_2}\{\alpha^5 + 6I\{2I(3\alpha + 2\beta + 2\gamma) - \alpha^2(2\alpha + \beta + \gamma)\}\}\right]$$

$H_3 = [\alpha^2\{\alpha^2 + (\beta + \gamma)^2\} + (\beta + \gamma)\{\alpha(4I - \alpha^2) - 4I(\beta + \gamma)\} + 12I(3I - \alpha^2)]$

$H_4 = [\alpha^5 + 6I\{2I(3\alpha + 2\beta + 2\gamma) - \alpha^2(2\alpha + \beta + \gamma)\}]$

$$H_5 = \left[\frac{2\alpha\{6I\beta(4I - \alpha^2)^2 - G_1\}}{(4I - \alpha^2)G_2} + \frac{(6I - \alpha^2)^2(\alpha^4 + 2\alpha^2 I - 36I^2)G_3}{(4I - \alpha^2)G_2^2}\right]$$

$$J = \left[\frac{(\beta + \gamma - 2\alpha)\{(\beta + \gamma)^2 + 4\alpha^2\} + 4\alpha(8I + \alpha^2)}{\{8I(\beta + \gamma)^2 - (8I - \alpha^2)^2\}} - \frac{2}{(\beta + \gamma)}\right]$$

$$K_1 = \frac{(a - c)[\{\alpha(\beta + \gamma) + 16I\}^2 + 16I\{\alpha(\beta + \gamma) - 3\alpha^2 - 3(\beta + \gamma)^2\}]}{2[(16I - 3\alpha^2)^2 - (\beta + \gamma)^2(48I - \alpha^2)]}$$

$$K_2 = \left[\frac{\alpha\{16I(\alpha + \beta + \gamma) - 3\alpha^2\}}{\{(16I - 3\alpha^2)^2 - (\beta + \gamma)^2(48I - \alpha^2)\}}\right]$$

$$K_3 = \frac{(a - c)[\{\alpha(\beta + \gamma) + 16I\}^2 + 16I\{\alpha(\beta + \gamma) - 3\alpha^2 - 3(\beta + \gamma)^2\}]}{3[(16I - 3\alpha^2)^2 - (\beta + \gamma)^2(48I - \alpha^2)]}$$

$$K_4 = \frac{\alpha^2\{21\alpha^2 + (\beta + \gamma)(4\alpha + \beta + \gamma)\} - 16I\{3\alpha^2 + 4(\alpha + \beta + \gamma)^2\}}{4[(16I - 3\alpha^2)^2 - (\beta + \gamma)^2(48I - \alpha^2)]}$$

$$K_5 = \frac{128I(\alpha + \beta + \gamma)^2 + \alpha^2\{144I - 51\alpha^2 - 3(\beta + \gamma)^2\}}{4[(16I - 3\alpha^2)^2 - (\beta + \gamma)^2(48I - \alpha^2)]}$$

$T_1 = [\{4(\alpha + \beta + \gamma)I - \alpha^3\}\{4(4I - \alpha^2) - 3(\beta + \gamma)^2\}]$

$T_2 = [(\beta + \gamma)^2\{(\beta + \gamma)(\beta + \gamma - \alpha) - 4(4I - \alpha^2)\} + 4(4I - \alpha^2)\{\alpha(\beta + \gamma) + (4I - \alpha^2)\}]$

$T_3 = [\{4(\alpha + \beta + \gamma)I - \alpha^3\}\{2(4I - \alpha^2) - (\beta + \gamma)^2\}]$

$T_4 = [(\beta + \gamma)^2\{(\beta + \gamma - \alpha)^2 - 4(6I - \alpha^2)\} + 2(4I - \alpha^2)\{3\alpha(\beta + \gamma) + 4(4I - \alpha^2)\}]$

$T_5 = [(\beta + \gamma)^2\{(\beta + \gamma - \alpha)^2 - 4(6I - \alpha^2)\} + 8(4I - \alpha^2)\{\alpha(\beta + \gamma) + (4I - \alpha^2)\}]$

Appendix A.2: Game constructs and solution approach of mathematical models

Table A: Game constructs and solution approach of mathematical models

Sl. No.	Decision making and contract	Game construct		Solution method: Backward induction method	
		Period 1	Period 2	Period 2	Period 1
1	Centralised	Centralised supply chain decide p_1, θ_1	Centralised supply chain decide p_2, θ_2	$\max_{p_2,\theta_2} \pi_2^{CENT} = \max_{p_2,\theta_2}\{(p_2 - c_2)q_2 - \alpha\theta_2^2\}$	$\max_{p_1,\theta_1} \pi_1^{CENT} = \max_{p_1,\theta_1}\{(p_1 - c_1)q_1 - \alpha\theta_1^2 + \pi_2^{CENT}\}$
2	WSP	M decides w_1, θ_1 and R decides p_1 simultaneously	M decides w_2, θ_2 and R decides p_2 simultaniously	$\max_{w_2,\theta_2} \pi_2^M = \max_{w_2,\theta_2} \{(w_2 - c_2)q_2 - \alpha\theta_2^2\}$ $\max_{m_2} \pi_2^R = \max_{m_2}\{m_2 q_2\}$	$\max_{w_1,\theta_1} \pi_1^M = \max_{w_1,\theta_1}\{(w_1 - c_1)q_1 - \alpha\theta_1^2 + \pi_2^M\}$ $\max_{m_1} \pi_1^R = \max_{m_1}\{m_1 q_1 + \pi_2^R\}$
3	WSP	M decides $w_1, \theta_1 \rightarrow$ R decides p_1	M decides $w_2, \theta_2 \rightarrow$ R decides p_2	$\max_{w_2,\theta_2} \pi_2^M = \max_{w_2,\theta_2}\{(w_2 - c_2)q_2 - \alpha\theta_2^2\}$ Subject to, $m_2 = \operatorname{argmax}_{m_2} \pi_2^R = \operatorname{argmax}_{m_2} m_2 q_2$	$\max_{w_1,\theta_1} \pi_1^M = \max_{w_1,\theta_1}\{(w_1 - c_1)q_1 - \alpha\theta_1^2 + \pi_2^M\}$ Subject to, $m_1 = \operatorname{argmax}_{m_1} \pi_1^R = \operatorname{argmax}_{m_1}\{m_1 q_1 + \pi_2^R\}$
4	CSC	R decides $\psi_1 \rightarrow$ M decides $w_1, \theta_1 \rightarrow$ R decides p_1	R decides $\psi_2 \rightarrow$ M decides $w_2, \theta_2 \rightarrow$ R decides p_2	$\max_{\psi_2} \pi_2^R = \max_{\psi_2}\{m_2 q_2 - \psi_2 \alpha\theta_2^2\}$ Subject to, $(w_2, \theta_2) = \operatorname{argmax}_{w_2,\theta_2} \pi_2^M = \operatorname{argmax}_{w_2,\theta_2}\{(w_2 - c_2)q_2 - (1 - \psi_2)\alpha\theta_2^2\}$ Subject to , $m_2 = \operatorname{argmax}_{m_2} \pi_2^R = \operatorname{argmax}_{m_2}\{m_2 q_2 - \psi_2 \alpha\theta_2^2\}$	$\max_{\psi_1} \pi_1^R = \max_{\psi_1}\{m_1 q_1 - \psi_1 \alpha\theta_1^2 + \pi_2^R\}$ Subject to, $(w_1, \theta_1) = \operatorname{argmax}_{w_1,\theta_1} \pi_1^M = \operatorname{argmax}_{w_1,\theta_1}\{(w_1 - c_1)q_1 - (1 - \psi_1)\alpha\theta_1^2 + \pi_2^M\}$ Subject to, $m_1 = \operatorname{agrmax}_{m_1} \pi_1^R = \operatorname{agrmax}_{m_1}\{m_1 q_1 - \psi_1 \alpha\theta_1^2 + \pi_2^R\}$
5	RSC	R decides $\phi_1 \rightarrow$ M decides $w_1, \theta_1 \rightarrow$ R decides p_1	R decides $\phi_2 \rightarrow$ M decides $w_2, \theta_2 \rightarrow$ R decides p_2	$\max_{\phi_2} \pi_2^R = \max_{\phi_2}\{\phi_2 p_2 q_2 - w_2 q_2\}$ Subject to, $(w_2, \theta_2) = \operatorname{argmax}_{w_2,\theta_2} \pi_2^M = \operatorname{argmax}_{w_2,\theta_2}\{(1 - \phi_2)p_2 q_2 + (w_2 - c_2)q_2 - \alpha\theta_2^2\}$ Subject to, $m_2 =$	$\max_{\phi_1} \pi_1^R = \max_{\phi_1}\{\phi_1 p_1 q_1 - w_1 q_1 + \pi_2^R\}$ Subject to, $(w_1, \theta_1) = \operatorname{argmax}_{w_1,\theta_1} \pi_1^M = \operatorname{argmax}_{w_1,\theta_1}\{(1 - \phi_1)p_1 q_1 + (w_1 - c_1)q_1 - \alpha\theta_1^2 + \pi_2^M\}$

				$\underset{m_2}{\operatorname{argmax}}\, \pi_2^R = \underset{m_2}{\operatorname{argmax}}\{\phi_2 p_2 q_2 - w_2 q_2\}$	Subject to , $m_1 = \underset{m_1}{\operatorname{argmax}}\, \pi_1^R = \underset{m_1}{\operatorname{argmax}}\{\phi_1 p_1 q_1 - w_1 q_1 + \pi_2^R\}$
6	2PT	M decides $L_1, \theta_1 \rightarrow$ R decides p_1	M decides $L_2, \theta_2 \rightarrow$ R decides p_2	$\max_{w_2,\theta_2} \pi_2^M = \max_{w_2,\theta_2}\{(w_2 - c_2) q_2 - \alpha\theta_2^2 + l_2\}$ Subject to, $q_2 = \underset{q_2,l_2}{\operatorname{argmax}}\, \pi_2^R = \underset{q_2,l_2}{\operatorname{argmax}}\{(p_2 - w_2) q_2 - l_2\} \geq \bar{\pi}^R$	$\max_{w_1,\theta_1} \pi_1^M = \max_{w_1,\theta_1}\{(w_1 - c_1) q_1 - \alpha\theta_1^2 + l_1 + \pi_2^M\}$ Subject to, $q_1 = \underset{q_1,l_1}{\operatorname{argmax}}\, \pi_1^R = \underset{q_1,l_1}{\operatorname{argmax}}\{(p_1 - w_1) q_1 - l_1 + \pi_2^R\} \geq 2\bar{\pi}^R$

WSP: Wholesale price; CSC: Cost sharing contract; RSC: Revenue sharing contract; 2PT: Two-part tariff contract; VN: Vertical Nash game; M: Manufacturer; R: Retailer

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