A Game Theory Analytics for Intelligent Technology Developments for Robust Supply Chain Management

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Abstract

This paper develops an innovative game theory analytics that academics and practitioners can adopt to develop intelligent technologies for the efficient and robust supply chain management. Long-period disruptions were new to the global supply chains, and the disruptions associated with COVID-19 were an actual check on the robustness claim of supply chains. Unavailability of raw materials and workers, poor logistic facilities, etc., created unparalleled disruptions for production units during the lock-down period of COVID-19. Many studies analyze and model Dual-Channel Supply Chain (DCSC) and the associated disruptions. However, there is no existing literature in the field of COVID -19 related disruptions in the DCSC consisting of retailers and e-tailers. Moreover, there is no literature in this area where a game theory framework, the most suitable framework for modelling the DCSC, has been used for analyzing disruptions in DCSC consisting of retailers and e-tailers as downstream partners. In this study, we check the impact of lock-down induced production disruptions on DCSC comprising of a manufacturer, retailer, and e-tailer. The researchers employed the game theory framework to model the interaction for developing supply chain analytics for robust supply chains. We have obtained the channel partner's optimal pricing decisions, order quantity, and profitability during the pre-lock-down and lock-down periods. After that, we compare the models to quantify the increase or decrease in optimal decisions. We observed that the optimal price increased, and optimal order quantity and profit decreased for all the channel partners. Academics and practitioners can adopt the proposed game theory analytics to develop intelligent technologies for the efficient and robust supply chain management. The proposed Stackelberg and Nash algorithm can be implanted by Python game theory software to develop an intelligent system.

Keywords
Dual-channel supply chain, COVID-19, Stackelberg game, Production disruption, Horizontal Nash Game

1. Introductions

COVID-19 pandemic and the associated disruptions had unprecedented effects on the supply chains (Craighead et al. 2020; Gupta et al. 2021). The supply chains that claimed to be resilient failed miserably during the global pandemic as they were unprepared for long-term disruptions. Of all the disruptions, production side disruptions were the most acute, as they were long-lasting and affected almost all the chain partners (Mao et al. 2021). For instance, global manufacturers are struggling with the shortage of electronic chips, which have significantly affected the production of cars and mobile phones.

As the COVID situation is new, there is no existing literature yet in the field of COVID -19 related disruptions in the Dual Channel Supply Chain (DCSC) consisting of retailers and e-tailers. And indeed, no game theory framework, which can be considered the most suitable framework for modelling the DCSC, has been used for studying disruption in DCSC with retailer and e-tailer as downstream partners. Hence the researchers use the game theory framework (Pun et al. 2020) to study and model the COVID-19 induced production disruptions on the DCSC.

In most of the DCSC, the manufacturer will have superior channel power over the downstream partners. As a result, there is a leader-follower scenario between the upstream manufacturer and downstream partners. To model this channel power difference (leader-follower interaction), we use the Stackelberg game with the manufacturer as the Stackelberg leader (Wu et al. 2019). We assume comparable channel power between the downstream channel partners. So, to model their interaction, a horizontal Nash game is employed between them (Rofin & Mahanty 2018). Based on the associated business market and supply chain arrangement, we try to address the following objectives:
1. To answer: What are the optimal pricing decisions during the pre-lock-down and lock-down periods?
2. To answer: How does the lock-down act as a deterministic factor in changing the key decision factors?
3. To employ game theory to model the interactions among supply chain agents for developing supply chain analytics for intelligent technology development for the robust and efficient supply chain management.
In the succeeding section, we analyze the prevailing studies in the field of disruptions in DCSC

2. Literature Review

The presence of online channels along with the traditional brick-and-mortar retailer gives rise to the concept of a DCSC (Chiang 2003). But the presence of an online channel triggers the seamless flow of information, and as a result, disruptions were often. The first study in the field of disruptions in DCSC was made by Huang et al. (2012), and they studied demand disruptions. The disruption from the production side was modelled by Huang et al. (2013) in the same DCSC using linear demand function and game theory. They found that the original production plan needs to be revised during disruptions.

A coordination mechanism against demand disruption using a revenue-sharing contract was suggested by Cao (2014). Soleimani et al. (2016) analyzed simultaneous demand and production disruptions and derived optimal decisions in a DCSC. A high correlation between the demand disruption and production cost disruption was observed, and they concluded that these disruptions significantly affected the pricing and production decisions. Later, Tang et al. (2018) analyzed channel competition and coordination of a DCSC during the simultaneous disruption of demand and cost disruption. The unprecedented COVID -19 situation motivated us to consider the disruptions in the DCSC consisting of retailers and e-tailers using a game theory framework. The following section presents a new game theory model in the DCSC consisting of retailers and e-tailers and its assumptions.

3. Assumptions and the game theory analytics

We assume a monopolist manufacturer selling the products to the end customer using a duopoly channel consisting of a retailer and e-tailers, as shown in Figure 1. The manufacturer is expecting a profit of π_m will be selling the goods to the retailer and e-tailer charging a wholesale price, w. The retailer and e-tailer who are expecting a profit of π_r and π_e respectively will be selling the product to the end customer at a respective price P_r and P_e.

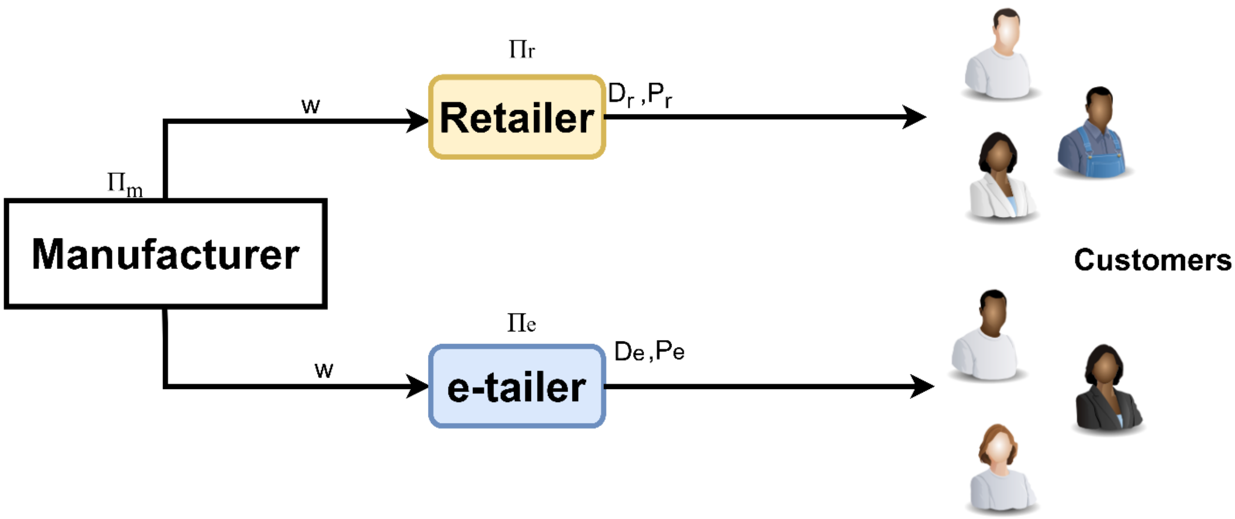

Figure 1. Dual Channel Supply Chain under consideration

Since manufacturer holds superior power over downstream partners, we model their interaction using the Stackelberg game (Yan et al. 2018). To delineate the channel power in the game, we assume the manufacturer as the game leader and downstream members as game followers. To analyze the interaction amid the downstream channel partners, we took the aid of the horizontal Nash game (Rofin & Mahanty 2018). The entire decision-making process is shown in Figure 2

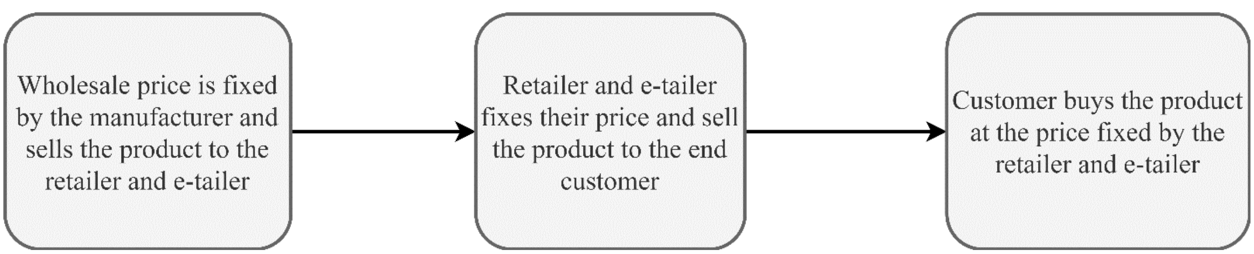

Figure 2. Decision making process

Similar to previous research (Li et al. 2019; Pi et al. 2019; Rofin & Mahanty 2019), we employ a basic linear demand function, $D = b - \alpha p$ to study the relation between demand and price . Here b denotes base market potential. We assume that the demand of the product is price sensitive (Li et al. 2019) and is represented by α. With these assumptions, the following equations were derived.

Demand for the retailer, $D_r = b_r - \alpha P_r + \beta P_e$ (1)

Demand for the e-tailer, $D_e = b_e - \alpha P_e + \beta P_r$ (2)
Here β represents cross-price elasticity. We also assume that $\alpha, \beta > 0 \; and \; \alpha > \beta$.

The profit can be derived using the following formulae:

Profit of the retailer, $\pi_r = (P_r - w)D_r$

$$= (P_r - \mathrm{w})(b_r - \alpha P_r + \beta P_e) \quad (3)$$

Profit of the e-tailer, $\pi_e = (P_e - \mathrm{w})D_e$

$$= (P_e - \mathrm{w})(b_e - \alpha P_e + \beta P_r) \quad (4)$$

Profit of the manufacturer, $\pi_m = (\mathrm{w} - s)(Q_r + Q_e)$ (5)

Here s denotes the unit production cost and Q_r, Q_e are respectively the optimal order quantities (OOQ) of retailer and e-tailer. Wholesale price, w can be derived using backward induction, as shown in Figure 3. To study the production disruptions, we assume disruptions in production cost (Huang et al. 2014; Soleimani et al. 2016) and is denoted by Δs. Suffix 1 denotes pre-lock-down period and 2 denotes lock-down period.

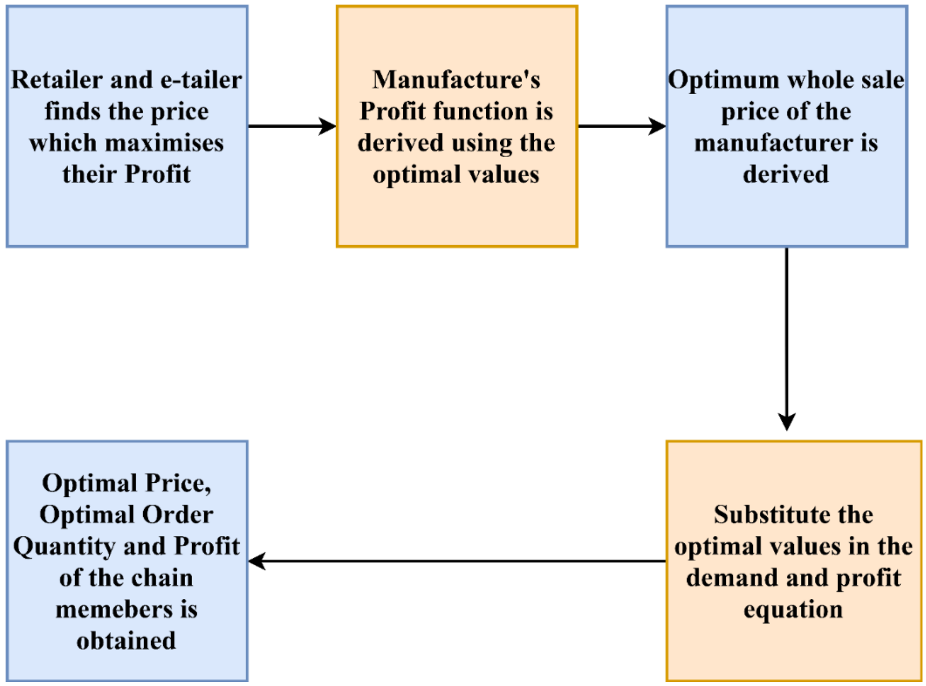

Figure 3. Principle of backward induction

4. Optimal decisions during the pre-lock-down period

Based on the assumptions, we have derived the optimal decisions for the pre-lock-down period

PROPOSITION

Optimal pricing decisions during pre-lock-down period is given by:

$$P_{r1} = \frac{2w_1\alpha^2 + w_1\alpha\beta + \beta b_e + 2\alpha b_r}{4\alpha^2 - \beta^2} \quad (5)$$

$$P_{e1} = \frac{2w_1\alpha^2 + w_1\alpha\beta + 2\alpha b_e + \beta b_r}{4\alpha^2 - \beta^2} \quad (6)$$

Substituting P_{r1} and P_{e2} in (1) *and* (2), respectively, OOQ of downstream partners can be derived.

COROLLARY

Under pre-lock-down period, OOQ is given by

$$Q_{r1} = \frac{\alpha(w_1(\beta^2 - 2\alpha^2 + \alpha\beta) + \beta b_e + 2\alpha b_r)}{4\alpha^2 - \beta^2} \quad (7)$$

$$Q_{e1} = \frac{\alpha(w_1(\beta^2 - 2\alpha^2 + \alpha\beta) + 2\alpha b_e + \beta b_r)}{4\alpha^2 - \beta^2} \quad (8)$$

Profit of manufacturer under pre-lock-down period is given by

$$\pi_{m1} = (w_1 - s)(Q_{r1} + Q_{e1}) \quad (9)$$

By obtaining first-order conditions (FOC) of π_{m1} w.r.t w_1, optimal w_1 for the manufacturer can be derived.

PROPOSITION

Under pre-lock-down period, when the downstream channel partners are interacting using horizontal Nash game, the following wholesale price can be charged by the manufacturer to maximize the benefits of channel partners

$$w_1 = \frac{2s\alpha - 2s\beta + b_e + b_r}{4\alpha - 4\beta} \tag{10}$$

COROLLARY

Using the optimal pricing and OOQ, the chain partners can maximize their profit and accordingly, we have the following optimal profit functions,

$$\pi_{r1} = \frac{\alpha(w_1(\beta^2 - 2\alpha^2 + \alpha\beta) + \beta b_e + 2\alpha b_r)^2}{(\beta^2 - 4\alpha^2)^2} \tag{11}$$

$$\pi_{e1} = \frac{\alpha(w_1(\beta^2 - 2\alpha^2 + \alpha\beta) + 2\alpha b_e + \beta b_r)^2}{(\beta^2 - 4\alpha^2)^2} \tag{12}$$

$$\pi_{m1} = \frac{(s - w_1)\alpha(2w_1(\alpha - \beta) - b_e - b_r)}{2\alpha - \beta} \tag{13}$$

Further, we can use the concept of backward induction by substituting w_1 in $eqns$ 5,6,7,8,11,12,13 to obtain optimum outcomes.

5. Optimal decisions during the lock-down period

PROPOSITION

Optimal pricing decisions during lock-down period is given by:

$$P_{r2} = \frac{2w_2\alpha^2 + \alpha\beta + \beta b_e + 2\alpha b_r}{4\alpha^2 - \beta^2} \tag{14}$$

$$P_{e2} = \frac{2w_2\alpha^2 + w_2\alpha\beta + 2\alpha b_e + \beta b_r}{4\alpha^2 - \beta^2} \tag{15}$$

Substituting P_{r2} and P_{e2} in (1) and (2), respectively, OOQ of downstream partners can be derived.

COROLLARY

During lock-down period, OOQ is given by

$$Q_{r2} = \frac{\alpha(w_2(\alpha\beta + \beta^2 - 2\alpha^2) + \beta b_e + 2\alpha b_r)}{4\alpha^2 - \beta^2} \tag{16}$$

$$Q_{e2} = \frac{\alpha(w_2(\alpha\beta + \beta^2 - 2\alpha^2) + 2\alpha b_e + \beta b_r)}{4\alpha^2 - \beta^2} \tag{17}$$

Profit of manufacturer under lock-down period is given by

$$\pi_{m2} = [w_2 - (s + \Delta s)](Q_{r2} + Q_{e2}) \tag{18}$$

By obtaining FOC of π_m with respect to w_2, optimal w_2 of the manufacturer can be derived.

PROPOSITION

Under lock-down period for a given production cost disruption, Δs; the following wholesale price can be charged by the manufacturer to maximize the benefits of channel partners

$$w_2 = \frac{2(s + \Delta s)(\alpha - \beta) + b_e + b_r}{4(\alpha - \beta)} \tag{19}$$

COROLLARY

Using the optimal pricing and OOQ, the chain partners can maximize their profit and accordingly, we have the following optimal profit functions for lock-down period,

$$\pi_{r1} = \frac{\alpha(w_2(\beta^2 - 2\alpha^2 + \alpha\beta) + \beta b_e + 2\alpha b_r)^2}{(\beta^2 - 4\alpha^2)^2} \tag{20}$$

$$\pi_{e2} = \frac{\alpha(w_2(\beta^2 - 2\alpha^2 + \alpha\beta) + 2\alpha b_e + \beta b_r)^2}{(\beta^2 - 4\alpha^2)^2} \tag{21}$$

$$\pi_{m2} = \frac{(s + \Delta s - w_2)\alpha(2w_2(\alpha - \beta) - b_e - b_r)}{\beta - 2\alpha} \tag{22}$$

Further, we can use the concept of backward induction by substituting w_2 in $eqns$ 14,15,16,17,20,21,22 to obtain optimum outcomes.

In the next session, we compare both periods to derive the impact.

6. Impact of lock-down on decision variables

COROLLARY

Optimal price of the downstream partners increased significantly by $\frac{\Delta s\alpha}{4\alpha - 2\beta}$ during lock-down period

Unavailability of raw materials and workers has affected the production process hence the supply of goods was severely affected. As a result, the law of supply came to play, and the product's price shot up irrespective of channel. The scarcity of the product in the market also aided the channel partners to take leverage and increase the price. We also find that the increase in the price was proportional to the rise in production cost.

COROLLARY

OOQ of the downstream partners decreased significantly by $\frac{\Delta s\alpha(\beta - \alpha)}{4\alpha - 2\beta}$ during lock-down period

The disruption in the production process has affected the availability of the product. As a result, the OOQ of the product decreased for both the downstream channel partners. Along with this, the research period also witnessed an increase in product price (as shown in corollary 6.1). This alienated the customers from the product. Mathematically we found that the decrease in optimal order quantity was proportional to the disruption in production cost.

COROLLARY

Profit of the downstream partners decreased significantly during the lock-down period by

$$\frac{\Delta s\alpha(\alpha - \beta)[(\Delta s + 2s)(2\alpha^2 - \alpha\beta - \beta^2) + (\beta - 6\alpha)b_e + (2\alpha - 3\beta)b_r]}{4(\beta - 2\alpha)^2(2\alpha + \beta)}$$

As shown in Corollary 6.1, the price of downstream channel partners increased significantly. But due to disruption in production process, the sales volume decreases. The high price charged by the partners during this period further catalysed the alienation of the customers from the product. As a culmination of all these effects, the profit of the downstream partners decreased considerably.

COROLLARY

The optimal profit of the manufacturer decreased significantly during lock-down period by $\frac{\Delta s\alpha[(\Delta s + 2s)(\alpha - \beta) - b_e - b_r]}{4\alpha - 2\beta}$

The manufacturer was the channel partner who faced the highest setback during the period. The unavailability of the raw materials, workers etc., have affected the production process. This reduced the sales volume. Leveraging the market condition of low supply of goods, the downstream channel partners increased the price of the product. This further alienated the buyers from the goods.

7. Results and Discussion

In this study, we model the production disruptions associated with COVID-19 lock-down. We separately modelled the optimal policies of Dual-Channel Supply Chain for pre-lock-down and lock-down periods and compared them to determine the impact of production disruption.

We found that the period was detrimental to all the chain partners. The optimal prices of both the downstream channel partners increased. The price increase was associated with a decrease in sales volume. As a result, the profit of all the chain partners, namely retailers, e-tailers and manufacturers, decreased.

The manufacturer needs to regulate the price of the product during such disruption scenarios. Due to the product's unavailability, there was a demand-supply mismatch, and consequently, the wholesale price and optimal price of the product witnessed an increase. Following the law of demand, this price increase further decreased the demand(sales volume).

Adding to this, the inability of the manufacturer to supply enough product worsen the situation. Manufacturers need to maintain enough backup for these unforeseen events. Along with this, he can surely overcome the hostile business environment with fewer effects by regulating the product's price in the market.

8. Conclusion

A new game theory model for the interactions among supply chain agents is used to develop supply chain analytics for robustly and efficiently managing supply chains during a prolonged lock-down situation caused by COVID. The channel partner's optimal pricing decisions, order quantity, and profitability during the pre-lock-down and lock-down periods are obtained. Academics and practitioners can adopt the developed new game theory analytics to develop intelligent and automated technologies for efficient and robust supply chain management during critical times like the COVID period. Further work can be done in the future to develop these intelligent technologies for online and web-based applications.

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