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Can anticipatory supply chain decision making manage the pandemic's effect? A regime switching game

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Abstract: The COVID-19 pandemic has shown that stock outs of essential items like hand sanitizers, tissue papers and other items of hygiene and daily use have been characteristic of a supply chain, especially immediately following a pandemic wave. Consequently, retailers have to indulge in substantial supplier management efforts to ensure product availability during a pandemic wave. Using a piecewise deterministic differential game, we model a scenario where, while anticipating a pandemic wave, a supplier decides on product availability efforts to ensure product availability under the impending threat of stock outs. A market leader coordinating retailer, on the other hand, decides on the proportion of the costs of the efforts to be shared with the supplier.

Keywords: Pandemic; product availability; differential game; stochastic regime switching; cost-sharing

1. INTRODUCTION

The adverse socio-economic impacts of pandemics like Covid-19 are long-term in nature (Singh et al., 2021). The current COVID-19 pandemic caused millions of death, disrupted global economic systems, and reduced the gross domestic output and outlook across the globe (Guan et al., 2020; Worldometers, 2021). These adverse impacts have received significant scientific attention from the supply chain perspective (Choi, 2020; Guan et al., 2020; Nikolopoulos et al., 2021). These studies provide substantial evidence about the dynamic and varied impact on all industrial sectors. While demands for products and services like garments, tourism, and petroleum have declined, demands for essential items from the food, health, and hygiene sectors have seen exponential growth (Hobbs, 2020; Paul et al., 2021). The demand uncertainty resulted in a large unanticipated demand-supply gap at the retailer's end at the start of the pandemic, having a ripple effect on all other industries, thus prolonging the slow recovery. Multiple reasons like the universal adoption of just-in-time manufacturing strategy across all industries and panic buying for home-based consumption led to immediate stock out at the retail stores.

Although the impact of the COVID-19 pandemic has been severe, stock-outs of essential products at retail stores during such events are not uncommon (Queiroz et al., 2020). Retailers have adopted multiple supplier management strategies and efforts to manage the demand for high-demand items during a pandemic or shortage-inducing events. Existing studies indicate the much-needed integrated retailer supplier approach to managing such a sudden demand surge. Matopoulos et al. (2019) found that perceived organizational justice and fairness in the retailer-supplier relationship minimizes the negative impacts during a crisis. Improved partner commitment mainly achieves such supply chain cooperation Matopoulos et al. (2019). Further, Hobbs (2020) found that suppliers are more likely to go the extra mile when they perceive a collaborative relationship with retailers.

Therefore, appropriate strategies in the retailer-supplier relationship are critical for maintaining product availability and minimizing the negative impact of global crises. However, limited studies have focused on the equilibrium policies from the retailer-supplier relationship perspective from the pre-pandemic and pandemic scenarios. Further, the perceived likelihood and impacts of a pandemic upon retailer and supplier decisions regarding cost-sharing vis a vis effort required for maintaining product availability remains debatable. This study aims to develop a model that can answer the following two research questions: (1) What are the equilibrium policies of the retailer and the supplier in the pre-pandemic and pandemic regimes? (2) How do the pandemic's likelihood and impact influence the retailer's and the supplier's decisions?

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The remainder of the article is organized as follows. Key literature relevant to this study is discussed in Section 2. Section 3 provides the model, and Section 4 presents the results of the study. Section 5 provides the concluding remarks along with academic contributions, managerial implications, and limitations of the current study.

2. LITERATURE REVIEW

2.1 Supply Chain and COVID-19

The ongoing pandemic of COVID-19 have significantly disrupted business operations and its supply chains. COVID-19 has significantly altered the performance of organizations' supply chains, especially its resiliency and sustainability (Ivanov, 2020a,b, 2021; Sodhi, 2016). Furthermore, the severe disruption caused by nationwide lockdowns, restricted capacities, labor shortage, and COVID norms has negatively impacted all nodes and points of supply chain (Paul and Chowdhury, 2020). Therefore, this has forced organizations to design strategies to improve their business operations and resiliency of their supply chain to combat the threats posed by 'low frequency high impact' events like COVID-19. According to Ivanov and Das (2020), the global pandemic has impacted a plethora of components of supply chain, which in turn has affected its downstream flow. COVID-19 has also managed to expose not only the shortcoming of global supply chains, but also the lack of proper resiliency strategies to combat a devastating event like the global pandemic. The pandemic has also managed to pose significant challenges in regards to uncertainties in demand and supply, shortages of labor, channel instability, and visibility of the supply chain (Sodhi and Tang, 2021). As a result, these have highlighted the need for revisiting and if necessary, reconfiguring, supply chain management strategies of business organizations (Farooq et al., 2021).

2.2 Product Availability during Pandemic

The consumption behavior during the Covid-19 has changed significantly due to panic purchase, leading to unanticipated demand supply gaps questioning resiliency and robustness of supply chains from the product availability perspective (Addo et al., 2020; Nicole et al., 2020). Chowdhury et al. (2021) found that demand spike and shortage of essential products (including food supply), supply-side shock management, and production disruption and backlog were the most researched supply chain aspects related to pandemic. Li et al. (2021) emphasize upon a cross-section and regional level coordinated decisions for supply chain echelons, with time-sensitive containment strategies to manage pandemic control and economic losses. Their mathematical model based decision-making using lean resource allocation strategy found a reduction of supply chain shortage from 11.91 to 1.11% in North America. Rahman et al. (2021), using an agent based model, studied face masks demand-supply in Australia. Their model proposes an emergency supply strategy that focuses upon relocating supplies, maximizing emergency stock piles, redeployment of inventory from other industries and then to increase production capacity for recovery. Paul and Chowdhury (2020) model for high demand products found that the right approach of using increased production as well as emergency sourcing and allocation can be the ideal management system and can also mitigate the lost profit by meeting the demand. However, Scala and Lindsay (2021) found that for healthcare sector in the UK and Ireland pre-pandemic collaborative relationships with the supplier did not led to increased tier visibility. These mixed findings across geographies and across products therefore require a more apt model to look into the phenomenon of product availability during pandemic.

2.3 Decision Making during Pandemic

The high-impact low-probability nature of the pandemic forces such strategies to remain generic in nature (Koonin, 2020). Researchers have looked into the various events requiring decision-making or anticipation based on the Covid-19 situation (Chowdhury et al., 2021). Ivanov (2020a) showed using the early Covid-19 data that closing and opening timings of facilities across the supply chain echelons play an important role in managing demand. Further, he also found that lead-time, epidemic propagation speed and location (upstream or downstream) of the disruption play an important part in the overall simulation and prediction. Decision-making for supply chain viability during and post pandemic needs to emphasize upon resiliency, stability and robustness (Sharma et al., 2020). Study of ready-made garment manufacturing sector of Bangladesh during pandemic revealed that decision-making regarding competitive resources and dynamic capabilities related to global and local resources needs to be explored for resiliency and recovery for the buyer-supplier perspective (Paul et al., 2021). Study of a B2B oil and gas firm in India found that decision-making during pandemic should have two dimensions – tactical decisions including information and relationship and operational decision-making for continuity, network, customers, and intelligence. Both these should be short to medium term in nature, feeding into the long-term strategic decisions (Kumar and Sharma, 2021). From these multiple dimensions across the echelons of supply chain, and the implications of disruption Cavinato (2004) had argued about governance style decision-making across the whole supply chain.

2.4 Problem description

From the above literature, we notice that most of the studies have focused on supply chain decision making during the pandemic. However, there is a paucity of research in investigating the important question of how firms should take decision while anticipating the pandemic and how should they change such decisions after the pandemic. We address this gap in our study by consider a dyadic supply chain with a supplier and a retailer. Under the framework of differential game which captures the dynamic aspect of decision making, we build a model where the demand depends on the the availability of a product. A supplier puts substantial efforts to ensure this availability. To facilitate a win win situation for the retailer shares the cost of the supplier availability management efforts.

3. MODEL

We consider a dyadic supply chain with one retailer and one supplier in a dynamic setting. Both the firms anticipate the occurrence of a pandemic wave. Since there are many waves of a long term pandemic, it is expected that the firms learn from the first wave and would anticipate subsequent waves. We assume that the demand function, realized at the retailer's end increases with the availability of product, $A(t)$. The availability can be measured by the amount of inventory on the shelf or immediately available on demand. Therefore, the demand at time t is given by,

$$D(t) = \alpha + \gamma A(t) \tag{1}$$

where the availability of the product is a state variable. The evolution of this state variable is captured by the following equation:

$$\dot{A}(t) = kg_i(t) - \delta A(t), \text{ and } A(0) = A_0. \tag{2}$$

In the above equations, $\alpha > 0$ is the marketing potential, $\gamma > 0$ is the consumer sensitivity towards product availability. The state equation is similar to Nerlove and Arrow (1962). $0 \leq \delta \leq 1$ is a decay factor and can be interpreted as the loss of availability due to various supply chain issues which can be observed but not controlled during the pandemic. The index i refers to the period. $i = 1$ implies a pre-pandemic period and $i = 2$ refers to the pandemic period. $g_i(t)$ is the instantaneous effort of the supplier to ensure that the product is supplied to the retailer during the pandemic. Thus $g_i(t)$ is the decision variable of the supplier. However, efforts do not guarantee that the product will always be available. The cost of such efforts by the supplier is given by a quadratic function $\frac{\mu}{2}g^2(t)$. Such cost functions are widely used in the literature Mukherjee and Chauhan (2021).

The retailer is the market leader and shares costs of ensuring product availability with the supplier. The retailer announces the proportion $0 \leq \phi_i(t) \leq 1$ of costs that she would share with the supplier. The supplier takes her decision on effort after the retailer's decision is made. Thus the cost $\frac{\mu}{2}g^2(t)$ can be broken down in the following manner:

$$\frac{\mu}{2}g^2(t) = \phi_i(t)\frac{\mu}{2}g^2(t) + (1 - \phi_i(t))\frac{\mu}{2}g^2(t). \tag{3}$$

Such retailer-supplier cost sharing has been discussed in the literature(Wang et al., 2020; Mukherjee and Carvalho, 2021).

Occurrence and impact of the pandemic wave: We assume that a pandemic wave occurs at a random time *tau* in the infinite planning horizon $[0, \infty)$. Let λ be the likelihood of a pandemic wave. We define the regime switching of the pre-pandemic period to the pandemic period using the stochastic process $[S(t) : t \geq 0]$. Therefore, the realization of the pandemic period splits the horizon into two periods - $[0, \tau) \cup [\tau, \infty)$. We denote the pre pandemic period by $[S(t) = 1]$ and the pandemic period by $[S(t) = 2]$. Such regime switching games have been discussed in Dockner et al. (2000). We assume that the random time τ follows a negative exponential distribution.

$$\lim_{dt\to 0} \frac{P[S(t+dt) = 2|S(t) = 1]}{dt} = \lambda,$$
$$\lim_{dt\to 0} \frac{P[S(t+dt) = 1|S(t) = 2]}{dt} = 0 \tag{4}$$

The impact of the pandemic is captured by a sudden jump in availability $A(t)$ of products. We assume that during the pandemic due to unforeseen reasons or unavoidable circumstances like lock downs, lack of resources or global transportation issues there may be a sudden decrease in the availability. If τ^+ is the time just after the pandemic begins and τ^- is the time just after the pandemic, then $A(\tau^+) = (1 - \omega)A(\tau^-)$ where $\omega \in [0, 1]$ signifies the loss in inventory due to the pandemic. This can happen due to transportation delays, lock downs etc.

The problems of the retailer and supplier: For the solution of this problem we have to use a "backward induction" approach. Similar treatments can be found in problems dealt in Haurie and Moresino (2006). We first state the profit maximization problems of the retailer and the supplier in the second regime and then show how to derive the problem of the first regime while anticipating the pandemic. Assuming m_{s2} and m_{r2} to be the unit profit margins of the supplier and the retailer in the pandemic regime, the second period's problems are:

$$V_{r2} = \max_{\phi_2} \int_{\tau}^{\infty} e^{-rt}\left(D(t)m_{r2}(t) - \frac{\phi_2(t)\mu}{2}{g_2}^2(t)\right)dt$$
$$V_{s2} = \max_{g_2} \int_{\tau}^{\infty} e^{-rt}\left(D(t)m_{s2}(t) - \frac{(1-\phi_2(t))\mu}{2}{g_2}^2(t)\right)dt$$
$$\text{Subject to}$$
$$\dot{A}(t) = kg_2(t) - \delta A(t), \text{ and } A(\tau^+) = (1 - \omega)A(\tau^-). \tag{5}$$

In the pre-pandemic regime, the long term expected profit at the beginning of the planning horizon is (J_i is the overall profit in the regime i and π_i is the instantaneous profit in regime i):

$$J_1 = \mathbb{E}_\tau \left[\int_0^\tau e^{-rs}\pi_1(s)ds + e^{-r\tau}J_2\right]$$
$$= \int_0^\infty e^{-(r+\lambda)t}\left(\pi_2(t)dt + \lambda J_2\right)dt. \tag{6}$$

The above derivation can be found in Rubel et al. (2011). Using equations (5) and (6), the first period's problems of the players are:

$$V_{r1}(A) = \max_{\phi_1} \int_0^\infty e^{-(r+\lambda)t}\Big(D(t)m_{r1}(t) - \frac{\phi_1(t)\mu}{2}{g_1}^2(t)$$
$$+ \lambda(V_{r2}(1-\omega)A)\Big)dt$$
$$V_{s1}(A) = \max_{g_1} \int_0^\infty e^{-(r+\lambda)t}\Big(D(t)m_{s1}(t)$$
$$- \frac{(1-\phi_1(t))\mu}{2}{g_1}^2(t) + \lambda(V_{s2}(1-\omega)A)\Big)dt$$
$$\text{Subject to}$$
$$\dot{A}(t) = kg_1(t) - \delta A(t), \text{ and } A(0) = A_0. \tag{7}$$

In the following section we highlight the solution approach and some Propositions and lemmas.

4. RESULTS

In this section, we present the equilibrium policies of the retailer and the supplier and investigate the effect of the pandemic on the policies. As a standard solution method we use the Hamilton-Jacobi-Bellman (HJB) equations to solve the maximizing problems of the players. From equations (7) and (5), the pre-pandemic and the pandemic regime's HJB equations are:

$$\begin{aligned}(r+\lambda)V_{r1}(A) &= D(t)m_{r1}(t) - \frac{\phi_1(t)\mu}{2}{g_1}^2(t)\\ &\quad + \frac{\partial V_{r1}}{\partial A}\dot{A}(t) + \lambda(V_{r2}(1-\omega)A)\\ (r+\lambda)V_{s1}(A) &= D(t)m_{s1}(t) - \frac{(1-\phi_1(t))\mu}{2}{g_1}^2(t)\\ &\quad + \frac{\partial V_{s1}}{\partial A}\dot{A}(t) + \lambda(V_{s2}(1-\omega)A)\\ rV_{r2} &= D(t)m_{r2}(t) - \frac{\phi_2(t)\mu}{2}{g_2}^2(t)\\ &\quad + \frac{\partial V_{r2}}{\partial A}\dot{A}(t)\\ rV_{s2} &= D(t)m_{s2}(t) - \frac{(1-\phi_2(t))\mu}{2}{g_2}^2(t)\\ &\quad + \frac{\partial V_{s2}}{\partial A}\dot{A}(t) \end{aligned} \tag{8}$$

The solution to the problems of the retailer and the supplier are obtained by taking the first order conditions of the equations (8) with respect to the decision variables. However,since the retailer is the Stackelberg leader, we start by finding the reaction function of the second mover, supplier and substituting the same in the retailer's problem. Consequently, we have the following proposition.

4.1 Analytical results and discussion

Proposition 1. The equilibrium decisions of the retailer and the supplier in the pre-pandemic (index $i = 1$) and pandemic regime (index $i = 2$) are:

$$\begin{aligned} g_1(t) &= \frac{km_{s1}\gamma}{\mu(1-\phi_1(t))(r+\delta+\lambda)},\\ g_2(t) &= \frac{km_{s2}\gamma}{\mu(1-\phi_2(t))(r+\delta)},\\ \phi_1(t) &= \frac{(2m_{r1}-m_{s1})(r+\delta)-(mr2-2ms2)\lambda(1-\omega)}{(2m_{r1}+m_{s1})(r+\delta)+(mr2+2ms2)\lambda(1-\omega)},\\ \phi_2(t) &= \frac{2m_{r2}-m_{s2}}{2m_{r2}+m_{s2}} \end{aligned} \tag{9}$$

and the value functions of the retailer and the supplier are given by:

$$\begin{aligned} V_{r1}(A) &= \frac{\gamma(m_{r1}(\delta+r)-\lambda m_{s2}(\omega-1))}{(\delta+r)(\delta+\lambda+r)}A(t)+\Theta_r,\\ V_{s1}(A) &= \frac{\gamma(m_{s1}(\delta+r)-\lambda m_{r2}(\omega-1))}{(\delta+r)(\delta+\lambda+r)}A(t)+\Theta_s\\ V_{r2}(A) &= \frac{\gamma m_{r2}}{\delta+r}A(t)+\left(\frac{\gamma^2k^2(2m_{r2}+m_{s2})^2}{8r\mu(\delta+r)^2}+\frac{\alpha m_{r2}}{r}\right)\\ V_{s2}(A) &= \frac{\gamma m_{s2}}{\delta+r}A(t)+m_{s2}\left(\frac{\alpha}{r}+\frac{k^2\gamma^2(2m_{r2}+m_{s2})}{4r\mu(\delta+r)^2}\right) \end{aligned} \tag{10}$$

where Θ_r and Θ_s are constants.

Proof: The proof of the proposition follows from the HJB equations and the relevant first order conditions. We omit the proof due to limited space available. If need be we can furnish the proof readily.

The above proposition shows that the solution of the problem and the value function is unique for a given set of parameter values. The pre-pandemic regimes decisions incorporate the stochastic parameters ω and λ. This emphasizes the farsighted nature of the players.

Lemma 1. The pre-pandemic cost-sharing proportion $\phi_1(t)$ of the retailer increases with the impact ω(or likelihood λ) if and only if $m_{r1}m_{r2} > m_{s1}m_{s2}$ (or $m_{r1}m_{r2} < m_{s1}m_{s2}$).

Proof: The first order condition of ϕ_1 with respect to ω and λ are:

$$\frac{d\phi_1}{d\omega} = \frac{4\lambda(\delta+r)\left(m_{\mathrm{r}1}m_{\mathrm{r}2}-m_{\mathrm{s}1}m_{\mathrm{s}2}\right)}{\left((\delta+r)\left(2m_{\mathrm{r}1}+m_{\mathrm{s}1}\right)-\lambda(\omega-1)\left(m_{\mathrm{r}2}+2m_{\mathrm{s}2}\right)\right)^2} \tag{11}$$

$$\frac{d\phi_1}{d\lambda} = \frac{4(\omega-1)(\delta+r)\left(m_{\mathrm{r}1}m_{\mathrm{r}2}-m_{\mathrm{s}1}m_{\mathrm{s}2}\right)}{\left((\delta+r)\left(2m_{\mathrm{r}1}+m_{\mathrm{s}1}\right)-\lambda(\omega-1)\left(m_{\mathrm{r}2}+2m_{\mathrm{s}2}\right)\right)^2} \tag{12}$$

Clearly, for (11) the denominator is positive and the numerator is positive iff $m_{r1}m_{r2} - m_{s1}m_{s2} > 0$. It follows that, for $\frac{d\phi_1}{d\omega} > 0$, the necessary and sufficient condition is $m_{r1}m_{r2} - m_{s1}m_{s2} > 0$.
Similarly for (12), the denominator is positive and the numerator is positive iff $m_{s1}m_{s2} - m_{r1}m_{r2} > 0$ as $(\omega - 1) < 0$. □

The expressions $m_{r1}m_{r2}$ or $m_{s1}m_{s2}$ can be interpreted as the level of combined unit profit margin, assuming all margins are positive. The above lemma signifies that if the retailer has a higher combined profit margin in the two periods than the supplier, the pre-pandemic cost sharing proportion of the retailer will increase with the impact ω of the pandemic. The retailer, who makes high profit is thus willing to share a substantial cost in order to reduce the effect of the pandemic on the supply chain.

Lemma 2. The suppliers efforts to ensure availability of product decrease with the pandemic's impact ω.

Proof: The first order condition of g_1 with respect to ω yields:

$$\frac{dg_1}{d\omega} = -\frac{\gamma k\lambda(m_{r2}+2m_{s2})}{2\mu(\delta+r)(\delta+\lambda+r)} < 0. \tag{13}$$

Therefore, the effort of the supplier is decreasing with the impact of the pandemic. □

The suppliers begin farsighted realizes that in the pandemic regime substantial management efforts will be needed to ensure product availability. Therefore, the supplier reduces her efforts in the pre-pandemic regime as the impact is high. One way to interpret this is that the supplier is saving for the future to invest more in the pandemic regime.

Lemma 3. The suppliers efforts to ensure availability of product increase with the retailer's cost-sharing proportion ϕ_i in both the pre-pandemic and pandemic regimes.

Proof: The proof of the above lemma is as follows:

$$\frac{dg_1}{d\phi_1} = \frac{\gamma k\left(m_{\mathrm{s}1}(\delta+r)+\lambda(1-\omega)m_{\mathrm{r}2}\right)}{\mu(\phi_1-1)^2(\delta+r)(\delta+\lambda+r)} \tag{14}$$

$$\frac{dg_2}{d\phi_2} = \frac{\gamma k m_{\mathrm{s}2}}{\mu(\phi-1)^2(\delta+r)} \tag{15}$$

From the positivity of the model parameters in equation (13), the above derivative is positive. Therefore, the effort pre-pandemic availability effort $g_1(t)$ of the supplier is increasing with the retailer's cost-sharing proportion ϕ_1. The proof of equation (14)>0 is similar. Therefore, g_i

increases with ϕ_i for $i \in \{1,2\}$. □

The above lemma shows that if the retailer supports the supplier by sharing costs of the efforts, the supplier becomes more inclined to invest more in the product availability efforts.

4.2 How should the decisions of the players vary in the two regimes?

Due to the complexity of the expressions of the decisions $\phi_i(t)$ and $g_i(t)$, it is difficult to analytically determine how the pre-pandemic level of effort and cost-sharing proportion compare to the pandemic regime's effort and cost-sharing. We therefore numerically illustrate the equilibrium strategies of the players. We assume the following parameter values:

$k = 0.5; \alpha = 10; \gamma = 0.5; \delta = 0.05; \mu = 10; m_{s1} = m_{s2} = 0.6; m_{r1} = m_{r2} = 1; r = 0.06;$

From figures (1) and (2), it is clear that the pandemic regimes efforts of the supplier and cost-sharing proportion of the retailer are higher than the pre-pandemic regimes efforts and cot-sharing for all values of λ and ω.

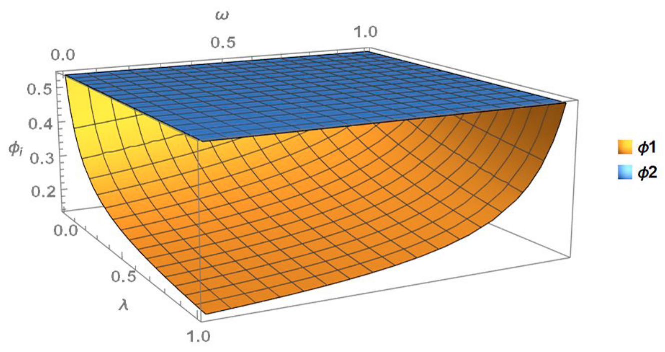

Fig. 1. Variation of ϕ_i with λ and ω

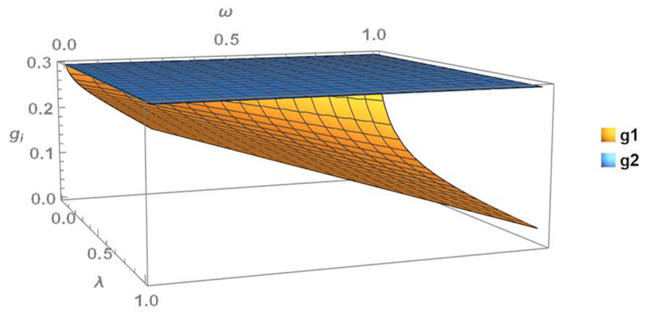

Fig. 2. Variation of g_i with λ and ω

5. CONCLUSION

In this article, we investigate how a retailer and a supplier make decisions on efforts to ensure product availability and cost-sharing decisions of such efforts while anticipating the advent of a pandemic wave. Our findings highlight the importance of the anticipation of the pandemic wave as the pre-pandemic regime's decisions will be based on the likelihood and impact of the pandemic.

Contribution: From a theoretical perspective, we develop a novel model in the context of the pandemic and supply chain. Specifically we captured the lesser studied yet important properties of decision making in a supply chain while considering the dynamic aspect. One may argue that time dependent cost-sharing might bear significantly operational overhead for a retailer. However, the simple linear structure of our game enables us to get piece-wise stationary strategies, implying over a regime the strategy remains fixed. Thus the retailer just reacts to the pandemic and in the entire horizon changes her strategy only once after the pandemic.

Our study also has significant managerial implications: First, management of a retail firm and that of its supplier should appropriately estimate the likelihood and impact of the pandemic. Second, the retailer should promote cost-sharing in order to incentivize the supplier to put more efforts in minimizing the inventory shortage. Third, the retailer and the supplier should monitor the possibilities of changing profit margins in the two regimes. This can impact their optimal decisions. Lastly, in the best of interest of the supply chain, the supplier should put more effort in the pandemic regime than in the pre-pandemic regime and the retailer should share a higher proportion of costs in the post-pandemic regime.

Drawbacks of our study: There are some drawbacks of our study. Our model is simple but still has several parameters. Therefore, it takes quite a bit of effort to understand which parameter values are suitable. While our model aptly investigates a product availability based demand function, making the model more parsimonious and introducing more decision variables can be challenging.

Future research: Our work can be extended in several directions. We assumed a negative exponential hazard function resulting in constant hazard rate. One can consider a time dependent hazard rate like a Weibull's distribution to capture that the effect of pandemic decreases with time. Other players like a manufacturer can be added to the model. It will be interesting to introduce competition as well in the context of the model.

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