Effects of price cap regulation on the pharmaceutical supply chain

Xu Chen[a,*], Huan Yang[a], Xiaojun Wang[b]

[a] School of Management and Economics, University of Electronic Science and Technology of China, Chengdu 611731, China
[b] School of Economics, Finance and Management, University of Bristol, Bristol BS8 1TZ, UK

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ABSTRACT

This paper considers a pharmaceutical supply chain composed of one pharmaceutical manufacturer and one pharmacy. We investigate how price cap regulation affects pharmaceutical firms' pricing decisions. We also evaluate the economic and social performance of the pharmaceutical supply chain and assess the risks associated with price cap regulation. The derived equilibriums under different price cap regulations, including retailer price cap regulation, manufacturer price cap regulation and linkage price cap regulation, are compared to that without regulation. Our results show that one-sided price cap regulation will damage the economic performance of the regulated firm, whereas the unregulated firm may gain a financial advantage. The regulation may increase the risk of a supply shortage if pharmaceutical firms cannot cope with the financial loss. In contrast, linkage price cap regulation can be an effective policy for improving both the economic and social performance of the pharmaceutical supply chain.

1. Introduction

The pharmaceutical industry plays an important role in the economy, society, and public health in almost every country in the world. The pricing of pharmaceutical products is a vital and contentious issue for both developed and developing countries (Danzon, Mulcahy, & Towse, 2015; Danzon, Towse, & Mestre-Ferrandiz, 2015). For middle- and low-income countries, effective pricing of pharmaceuticals is critical to the accessibility and affordability of medicines and the population's social welfare. For example, despite the rapid economic development in China, the high price of drugs has continuously been blamed for unaffordable healthcare service for less-advantaged people, which has triggered increasing complaints from the public (Yu, Li, Shi, & Yu, 2010). For developed countries, although the affordability of drugs may not be a challenge to their citizens due to extensive medical insurance, high drug prices have certainly increased the burden of government public expenditures.

In the context of a significant increase in pharmaceutical expenditures during the two last decades, there has been growing interest from governments in controlling the price of pharmaceutical products (Bardey, Bommier, & Jullien, 2010; Troyer & Krasnikov, 2011). Many governments frequently consider regulatory mechanisms, e.g., price cap regulation and reference pricing, to prevent pharmaceutical firms from charging high drug prices and protect their citizens from paying too much. Whereas price caps are often used to limit pharmaceutical firms' ability to exploit their market power by charging high prices, reference pricing aims at stimulating market competition by introducing more price elastic demand (Brekke, Königbauer, & Straume, 2007; Brekke, Grasdal, & Holmås, 2009). For instance, most Europe Union nations set caps on the consumer price of generic drugs and/or regulate the maximum reimbursement rate, whereas an intervention through price regulation seems to be less necessary in the drug market according to economic theory (Puig-Junoy, 2010). In China, pricing and reimbursement are important aspects of pharmaceutical policy that have been included in the central government's large-scale healthcare reform launched in April 2009 (Chen, 2009; Hu & Mossialos, 2016).

The Chinese government has set price caps on different pharmaceutical products in response to soaring drug prices (Hu & Mossialos, 2016). Unfortunately, evidence emerging from recent research (Han, Liang, Su, Xue, & Shi, 2013; Wu, Zhang, & Qiao, 2015; Yang et al., 2016) indicates that the price cap policies were ineffective and resulted in some unintended consequences. The media reported that there were shortages of thousands of drugs in pharmacies in Guangdong Province of China. This was echoed by Zhang et al. (2016), who claimed that the reduction of the price cap level is associated with a higher incidence of pharmaceutical firms' exit from markets. The introduction of new industry regulations could have a profound impact on firms' performance (Pugliese, Minichilli, & Zattoni, 2014) and contribute to business failure (Amankwah-Amoah, 2016). Regulators have to be conscious of the unintended consequence of a continuous reduction of the price cap level. A thoughtful design of drug pricing regulation and risk evaluation of price cap policies are essential to minimizing the risk of policy

failure.

The existing literature mainly examines pricing regulations from the perspective of macro health economics (Danzon, Mulcahy, et al., 2015; Danzon, Towse, et al., 2015; Håkonsen, Horn, & Toverud, 2009; Hu & Mossialos, 2016), whereas little attention has been paid to the evaluation of pharmaceutical pricing regulations considering how pharmaceutical firms and supply chains will behave under the regulations and how their behavior impacts the social and economic performance of the sector. By contrast, previous studies in the operation and supply chain literature on pharmaceutical products often focus on optimizing operations/supply chain decisions under different regulatory policies (Yu et al., 2010). Companies often respond to regulatory policies strategically and operationally to maximize their benefits. Therefore, when policy makers consider the development of new regulations, it is valuable for regulators to understand how firms will react to new regulations and the consequential economic and social performance. To address this gap in the literature, some key questions are discussed considering price cap regulation for the pharmaceutical supply chain.

(1) What are the optimal pricing decisions of the pharmaceutical manufacturer and pharmacy under price cap regulation?

(2) How can the government develop appropriate price cap regulation to improve social welfare and economic sustainability and mitigate the risk of policy failure?

(3) What are the key parameters of price cap regulation to achieve the coordination of the pharmaceutical supply chain?

To address the above questions, this research mainly focuses on price cap regulation and examines how the regulations affect the pharmaceutical firms' operational decisions and the consequential economic and social performance. This paper investigates a two-echelon pharmaceutical supply chain composed of one pharmaceutical manufacturer and one pharmacy. The pharmaceutical manufacturer is the Stackelberg leader, and the pharmacy is the follower. We not only consider retailer price cap regulation and manufacturer price cap regulation, which are often adopted by governments, but also propose a linkage price cap regulation where the whole pharmaceutical supply chain is regulated. Through a comparison of optimal prices, profits and social welfare between the scenarios with and without regulations, we analyze the effect of each regulatory policy. In this way, we aim to solve the problem of selecting an optimal regulation and examine the supply chain coordination.

The rest of the paper is organized as follows. Section 2 reviews relevant research streams. The models and equilibrium analysis are provided in Section 3. Based on the model formulation and assumptions, we use the model with no price cap regulation as a base model and then propose a retailer price cap regulation model, manufacturer price cap regulation model, and linkage price cap regulation model. In Section 4, the effects of alternative price cap regulations on the equilibriums and profits of the pharmacy and pharmaceutical manufacturer are discussed. In Section 5, we further discuss pharmaceutical supply chain coordination under the optimally designed price cap regulation. Finally, the main conclusions and future extensions are highlighted in Section 6.

2. Literature review

To provide the research background and highlight our contributions, we mainly review two relevant research streams: (i) the effect of price cap regulation on pharmaceutical pricing and (ii) the effect of regulation on the operational decisions of the pharmaceutical supply chain.

A substantial body of literature has examined price cap regulation in the pharmaceutical industry. Abbott (1995) is one of the early studies. The simulation study finds that launch prices are often optimally set 50% higher by pharmaceutical firms than that in an unregulated market. Ekelund and Persson (2003) compare how new pharmaceuticals are priced in the U.S. market with those in the price-regulated Swedish market, and their findings indicate that price competition between drugs with brand names is discouraged by price regulation. Brekke, Grasdal, and Holmås (2009) examine the relationship between pharmaceutical firms' pricing strategies and regulatory regimes using a reference price system called "index pricing" introduced in Norway in 2003. Their findings indicate that reference pricing is more effective than price cap regulation at lowering drug prices, while patient protection is a concern because of the cross-price effect. Through a comprehensive review of the impact of price cap regulation of generic medicines in Europe, Puig-Junoy (2010) indicates that although the application of price regulations leads to price reductions, they also create barriers to dynamic market competition in consumer prices. Consumers and insurers may not benefit from these regulations. In fact, there are also risks associated with price cap regulations. For instance, in an empirical study on the relationship between drug shortages and the retail price control policy introduced by the Chinese government, Liu (2007) finds that the policy widened the gap between the supply and market demand of those drugs over the 10-year period. Zhang et al. (2016) investigate the effect of price cap regulations on the exit of generic pharmaceutical firms, and their findings show that reducing the price cap level is associated with a higher incidence of pharmaceutical firms exiting from markets. Although most of the abovementioned studies focus on the effects of price cap regulation in the pharmaceutical industry, there have been very limited attempts to explain why the implementation of price cap regulations are not successful and how the policy results in unintended consequences, such as drug shortages (Liu, 2007) and subdued R&D investment (Troyer & Krasnikov, 2011). Our research aims to provide some insights into this research problem.

The pharmaceutical supply chain has drawn substantial interest from business and management research, which is demonstrated by some recent published literature reviews (Dobrzykowski, Deilami, Hong, & Kim, 2014; Narayana, Pati, & Vrat, 2014; Settanni, Harrington, & Srai, 2017). The pharmaceutical industry is characterized by a high cost of R&D and innovation (DiMasi, Grabowski, & Hansen, 2016; Morgan, Grootendorst, Lexchin, Cunningham, & Greyson, 2011), complexity in the supply and distribution of pharmaceutical products in both developed (Rossetti, Handfield, & Dooley, 2011) and developing countries (Prado, Calderon, & Zúñiga, 2016), and supply-side market power (Brekke et al., 2007; Rossetti et al., 2011). For instance, Selva (2016) investigates a supply management system to choose suppliers, make purchasing policies and manage inventory in the healthcare industry of Latin America. There are also significant differences between the developed countries in Europe and America, with their well-developed healthcare systems and pharmaceutical markets, and the developing countries in Africa and Asia, with concerns on the demand side and inefficiencies downstream on the supply side (Narayana et al., 2014). Furthermore, the competitive and operational environment of the pharmaceutical supply chain is constantly sharpened by on-going macro-economic and regulatory events (Rossetti et al., 2011). Supply chain managers have to take these into consideration when making strategic and tactical decisions. In a recent study, Zhao, Xiong, Gavirneni, and Fein (2012) take fee-for-service (FFS) and investment buying (IB) contracts into account to solve the multi-period stochastic inventory problems for the pharmaceutical supply chain. To analyze the impact of the restriction policies, e.g., the Physician Payment Sunshine Act, Liu, Gupta, Venkataraman, and Liu (2015) create a structural model of how pharmaceutical firms compete dynamically to schedule detailing to physicians and discuss the policy implications. Raventós and Zolezzi (2015) conduct an empirical study and find that an electronic tendering policy could create a >8% price reduction for pharmaceuticals and medical devices in Chile. Although there are a growing number of studies focusing on various aspects of the pharmaceutical supply chain, including supply network design (Danese, Romano, & Vinelli, 2006; Mousazadeh, Torabi, & Zahiri, 2015; Nagurney, Li, & Nagurney, 2013), e-business implementation (Bhakoo & Chan, 2011; Cullen & Taylor, 2009), risk (Bhattacharya, Gaba, & Hasija, 2014;

Elleuch, Hachicha, & Chabchoub, 2014) and sustainability (Uthayakumar & Priyan, 2013; Xie & Breen, 2012), to the best of our knowledge, little attention has been paid to how pharmaceutical firms behave under price cap regulation and how their operational decisions are made in responding to the policy impact the economic and social performance of the pharmaceutical supply chain. Our research aims to address this research gap and examine the alternative options of price cap regulation through modeling the pharmaceutical supply chain's decision behavior and evaluating the consequential economic and social performance.

3. The models and equilibrium analysis

3.1. Module formulation and assumption

We consider a two-echelon pharmaceutical supply chain composed of one pharmaceutical manufacturer and one pharmacy. The pharmacy purchases drugs from the pharmaceutical manufacturer and then sells them to patients. We assume that the pharmaceutical manufacturer is the Stackelberg leader and that the pharmacy is the Stackelberg follower. This is common in the supply chain literature and in practice (Chen, Wang, & Chan, 2017; Luo, Chen, Chen, & Wang, 2017). For instance, Johnson & Johnson, one of the largest pharmaceutical manufacturing companies, usually takes a leadership position in its interaction with upstream suppliers or downstream pharmacies (Johnson & Johnson, 2017; Kathryn, 2016). In addition, we define some parameters and variables as summarized in Table 1.

In alignment with prior studies in operations management (Chen, Wang, & Jiang, 2016; Lee & Staelin, 1997; Yalabik & Fairchild, 2011), the demand curve is given as a function of price and denoted by $D = \alpha - \beta p$, where α is the primary market base and β is the self-price sensitivity, with $\beta > 0$. Based on the above demand function, the pharmaceutical manufacturer's profit $\pi_m(w)$ is:

$$\pi_m(w) = w(\alpha - \beta p) - c(\alpha - \beta p) \tag{1}$$

The first part of the formula represents the revenue from drug wholesaling, and the second part corresponds to the manufacturer's production cost.

The pharmacy's profit $\pi_r(p)$ is:

$$\pi_r(p) = p(\alpha - \beta p) - w(\alpha - \beta p) \tag{2}$$

The first part of the formula represents the revenue from drug retail sales, and the second part corresponds to the purchasing cost.

Social welfare consists of the patient surplus, the pharmaceutical manufacturer's profit and the pharmacy's profit (Baron & Myerson, 1982; Feng, Lan, & Zhao, 2017). Referring to the previous literature (Cowan, 1998; Jin, Wang, & Hu, 2015), the patient surplus is $C_s = \int_p^{\frac{\alpha}{\beta}} (\alpha - \beta x) \mathrm{d}x$. Then, social welfare is $W_s = C_s + \pi_m(w) + \pi_r(p)$.

3.2. The models

3.2.1. Base model

First, we propose a base model without price cap regulation (NPCR) and investigate the pricing decisions. The pharmacy's decision problem for the NPCR model is:

$$\max_p \pi_r(p)$$

The pharmaceutical manufacturer's decision problem for the NPCR model is:

$$\max_w \pi_m(w)$$

3.2.2. Retailer price cap regulation (RPCR) model

For the retailer price cap regulation (RPCR) model, the government regulates only the downstream pharmacy via limiting the maximum

Table 1
Notations.

Notation	Descriptions
c	Pharmaceutical manufacturer's unit production cost.
w	Pharmaceutical manufacturer's unit wholesale price.
p	Pharmacy's unit retail price, $p > w > c$.
D	Demand faced by the pharmacy.
$\overline{p}$	Retail price cap imposed by the government.
$\overline{w}$	Wholesale price cap imposed by the government.
θ	Linkage coefficient between the wholesale price cap and the retail price cap under the linkage price cap regulation, $0 < \theta < 1$.
$\pi_m(w)$	Pharmaceutical manufacturer's profit.
$\pi_r(p)$	Pharmacy's profit.
π_s	Total profit of the pharmaceutical supply chain, $\pi_s = \pi_m(w) + \pi_r(p)$.
C_s	Patient surplus.
W_s	Social welfare.

price (price cap $\overline{p}$) paid by the patient (Puig-Junoy, 2010). That means that the pharmacy must decide its retail price with the constraint $p \leq \overline{p}$. Then, the pharmacy's decision problem for the RPCR model is:

$$\max_p \pi_r(p)$$

$$s.\,t. \quad p \leq \overline{p}$$

The pharmaceutical manufacturer's decision problem for the RPCR model is:

$$\max_w \pi_m(w)$$

3.2.3. Manufacturer price cap regulation (MPCR) model

For the manufacturer price cap regulation (MPCR) model, we consider that the government regulates only the upstream pharmaceutical manufacturer by setting a wholesale price cap. That means that the manufacturer must decide his wholesale price with the constraint $w \leq \overline{w}$.

The pharmacy's decision problem for the MPCR model is:

$$\max_p \pi_r(p)$$

The pharmaceutical manufacturer's decision problem for the MPCR model is:

$$\max_w \pi_m(w)$$

$$s.\,t. \quad w \leq \overline{w}$$

3.2.4. Linkage price cap regulation model

First, we propose a *linkage price cap regulation* (LPCR) by assuming that $\overline{w}$ is the θ proportion of the retail price cap $\overline{p}$ and $\overline{w} = \theta\overline{p}$, where $\overline{p}$ represents the retail price cap that regulates the downstream pharmacy's pricing decision, that is, $p \leq \overline{p}$; $\overline{w}$ represents the wholesale price cap that regulates the upstream pharmaceutical manufacturer's pricing decision, namely $w \leq \overline{w}$; and θ is the linkage coefficient to keep a connection between the two price caps. Hence, instead of regulating part of the pharmaceutical supply chain, the linkage price cap regulation aims to regulate the whole pharmaceutical supply chain. Next, we investigate each pharmaceutical firm's pricing decisions for the LPCR model.

The pharmacy's decision problem for the LPCR model is:

$$\max_p \pi_r(p)$$

$$s.\,t. \quad p \leq \overline{p}$$

The pharmaceutical manufacturer's decision problem for the LPCR model is:

Table 2
Optimal solutions for the four models.

Models			p^i	w^i
NPCR model ($i = n$)			$\frac{3\alpha + c\beta}{4\beta}$	$\frac{\alpha + c\beta}{2\beta}$
RPCR model ($i = r$)	$\overline{p} \geq p^n$		$\frac{3\alpha + c\beta}{4\beta}$	$\frac{\alpha + c\beta}{2\beta}$
	$\overline{p} < p^n$		$\overline{p}$	$\overline{p}$
MPCR model ($i = m$)	$\overline{w} \geq w^n$		$\frac{3\alpha + c\beta}{4\beta}$	$\frac{\alpha + c\beta}{2\beta}$
	$\overline{w} < w^n$		$\frac{\alpha + \beta\overline{w}}{2\beta}$	$\overline{w}$
LPCR model ($i = s$)	$\overline{p} \geq p^n$ and $\overline{w} \geq w^n$		$\frac{3\alpha + c\beta}{4\beta}$	$\frac{\alpha + c\beta}{2\beta}$
	$\overline{p} \geq p^n$ and $\overline{w} < w^n$		$\frac{\alpha + \beta\theta\overline{p}}{2\beta}$	$\theta\overline{p}$
	$\overline{p} < p^n$ and $\overline{w} \geq w^n$		$\overline{p}$	$\overline{p}$
	$\overline{p} < p^n$ and $\overline{w} < w^n$		$\overline{p}$	$\theta\overline{p}$

$$\max_{w} \pi_m(w)$$

$$s.\ t.\quad w \leq \theta\overline{p}$$

Furthermore, we can derive the optimal retail price (p^i) of the pharmacy and the optimal wholesale price (w^i) of the pharmaceutical manufacturer for the NPCR, RPCR, MPCR and LPCR models ($i = n, r, m, s$), which is shown in Table 2.

4. Evaluation of price cap regulations

In this section, we study the effect of price cap regulation on the prices and profits of the pharmacy and pharmaceutical manufacturer via comparing the optimal pricing decisions and profits for the different price cap regulation models developed in Section 3. In this way, we aim to explore how each price cap regulation affects the firms' pricing decisions, the patient surplus and social welfare, and whether and how each price cap regulation can benefit pharmaceutical firms. The results may shed light on how to develop an effective price cap regulation for policy makers.

4.1. Effect of RPCR on decisions and performance

First, by examining relevant equilibriums in Table 2, we obtain the effect of the retail price cap, $\overline{p}$, on the optimal retail and wholesale prices, the patient surplus and social welfare. Therefore, we propose the following:

Lemma 1. *For the RPCR model, (1) i) if $\overline{p} \geq p^n$, then $\boldsymbol{p^r} = \boldsymbol{p^n}$ and $\boldsymbol{w^r} = \boldsymbol{w^n}$. ii) If $\overline{p} < p^n$, then $\boldsymbol{p^r} < \boldsymbol{p^n}$. If $w^n < \overline{p} < p^n$, then $\boldsymbol{w^r} > \boldsymbol{w^n}$; if $\overline{p} < w^n$, then $\boldsymbol{w^r} < \boldsymbol{w^n}$.*
(2) If $\overline{p} \geq p^n$, then $\boldsymbol{W_s^r}$ and $\boldsymbol{C_s^r}$ are independent on $\overline{p}$; if $\overline{p} < p^n$, then $\boldsymbol{W_s^r}$ and $\boldsymbol{C_s^r}$ decrease in $\overline{p}$.

Part (1) of this lemma means that if the retail price cap is higher than the optimal unregulated retail price ($\overline{p} \geq p^n$), the optimal retail and wholesale prices will equal those for the NPCR model. That is, the price cap regulation has no effect on the prices in this case. If the price cap is lower than the optimal unregulated retail price ($\overline{p} < p^n$), the optimal retail price will equal the price cap, which is lower than that for the NPCR model. Meanwhile, if the retail price cap is also higher than the optimal unregulated wholesale price ($\overline{p} > w^n$), the optimal wholesale price will increase under the regulation. This can be explained by the fact that a cap on the retail price results in a stationary customer demand. Any decrease in the wholesale price from the manufacturer will not influence the demand of end consumers. Therefore, the manufacturer will charge a higher wholesale price to maximize its own profits. In contrast, if the retail price cap is lower than the value of the optimal unregulated wholesale price, the wholesale price under the regulation will be lower accordingly.

From part (2) of this lemma, if the retail price cap $\overline{p}$ exceeds the optimal retail price for the NPCR model ($\overline{p} \geq p^n$), price cap regulation has no effect on the patient surplus and social welfare. If the price cap is lower ($\overline{p} < p^n$), the regulation can always increase the patient surplus and social welfare. Such an impact will be magnified with a lower price cap.

Second, we investigate the regulation effect on the profits of the pharmacy and pharmaceutical manufacturer for the RPCR model. Since the price cap has no impact when the price cap is high ($\overline{p} \geq p^n$), as illustrated in Lemma 1, here we mainly focus on the situation where there is a low retail price cap, $\overline{p} < p^n$. We obtain the following:

Proposition 1. *For the RPCR model, $\pi_r(\boldsymbol{p^r}) < \pi_r(\boldsymbol{p^n})$. If $\overline{p} < \frac{\alpha + c\beta}{2\beta} - \frac{\sqrt{2}(\alpha - c\beta)}{4\beta}$, then $\pi_m(\boldsymbol{w^r}) < \pi_m(\boldsymbol{w^n})$; if $\overline{p} > \frac{\alpha + c\beta}{2\beta} - \frac{\sqrt{2}(\alpha - c\beta)}{4\beta}$, then $\pi_m(\boldsymbol{w^r}) > \pi_m(\boldsymbol{w^n})$.*

This proposition shows that under the retailer price cap regulation, the pharmacy's profit is always lower than that without regulation. For the pharmaceutical manufacturer, when the price cap is lower than one threshold ($\overline{p} < \frac{\alpha + c\beta}{2\beta} - \frac{\sqrt{2}(\alpha - c\beta)}{4\beta}$), its profit under the regulation will decrease. In contrast, when the price cap is higher than this threshold, the manufacturer will be better off. The reason is that a lower price cap induces not only a lower wholesale price but also higher demands. When the loss from a decreased marginal profit exceeds the benefit of the increased demands, the profit will be lower under the retail price cap regulation. Conversely, when the benefit of increased demands can compensate for the losses from a decreased profit margin, the retail price cap regulation can lead to an increase in profit for the manufacturer. Based on the findings of Lemma 1 and Proposition 1, it is clear that a high cap on the retail price will have no impact on pharmaceutical firms' pricing decisions and the economic and social performance of the pharmaceutical supply chain. In contrast, a low cap, on the one hand, will improve the social welfare of patients. In this case, the price cap policy can protect the patient from a high price of pharmaceutical products. In addition, this policy can also be conducive to increasing the total social welfare. However, on the other hand, a low cap will certainly have a negative impact on the pharmacy's economic performance. Depending on the value of the cap, it may benefit or harm the pharmaceutical manufacturer's economic performance. Since the pharmaceutical manufacturer can benefit from a relatively high cap, he can offer a profit sharing contract to the pharmacy to persuade him to sell the regulated drugs and achieve a win-win outcome. However, if the retail price cap is very low, the negative economic impact on the pharmacy and pharmaceutical manufacturer will be severe. It will increase the risk of drug shortage because there is less incentive for the pharmacy and the manufacturer to sell and supply those price-regulated drugs. Therefore, policy makers should be careful in setting the cap when implementing retail price cap regulation. Other supporting policies, such as giving the pharmacy and manufacturer subsidies, may be considered if the drug prices are reduced significantly because of retail price cap regulation.

4.2. Effect of MPCR on decisions and performance

Now, we examine the effect of the wholesale price cap on the pricing decisions and profits of the pharmacy and pharmaceutical manufacturer for the MPCR model. Similar to the RPCR model, we first propose Lemma 2 regarding the effect of the wholesale price cap, $\overline{w}$, on the optimal retail and wholesale prices, the patient surplus and social welfare.

Lemma 2. *For the MPCR model, (1) if $\overline{w} \geq w^n$, then $\boldsymbol{p^m} = \boldsymbol{p^n}$ and $\boldsymbol{w^m} = \boldsymbol{w^n}$. If $\overline{w} < w^n$, then $\boldsymbol{p^m} < \boldsymbol{p^n}$ and $\boldsymbol{w^m} < \boldsymbol{w^n}$. (2) If $\overline{w} \geq w^n$, then $\boldsymbol{W_s^m}$ and $\boldsymbol{C_s^m}$ are independent on $\overline{w}$; if $\overline{w} < w^n$, then $\boldsymbol{W_s^m}$ and $\boldsymbol{C_s^m}$ decrease in $\overline{w}$.*

This lemma generates similar results compared to Lemma 1. From

part (1) of Lemma 2, if the wholesale price cap $\overline{w}$ is higher than the optimal wholesale price for the NPCR model ($\overline{w} \geq w^n$), the optimal retail price and wholesale price will be equal to those for the NPCR model, respectively. If the wholesale price cap $\overline{w}$ is lower than the unregulated wholesale price ($\overline{w} < w^n$), both the retail and wholesale prices will be lower than those without price cap regulation.

Part (2) of Lemma 2 implies that if the wholesale price cap $\overline{w}$ is higher ($\overline{w} \geq w^n$) than the optimal wholesale price for the NPCR model, the price cap regulation will have no effect on the patient surplus and social welfare. If the wholesale price cap $\overline{w}$ is lower than the unregulated wholesale price ($\overline{w} < w^n$), then a low cap on wholesale price will increase both the patient surplus and social welfare.

Second, we discuss the regulation effect on the profits. Similar to the RPCR model, we primarily focus on the condition $\overline{w} < w^n$ where the regulation has effects on pricing decisions. The results are shown in the following proposition.

Proposition 2. For the MPCR model, $\pi_r(p^m) > \pi_r(p^n)$, $\pi_m(w^m) < \pi_m(w^n)$.

This proposition indicates that under the manufacturer price cap regulation, the pharmacy's profit will increase; however, the regulated pharmaceutical manufacturer's profit will always decrease. Therefore, the manufacturer is worse off under the wholesale price cap regulation. Based on the findings of Lemma 2 and Proposition 2, it is clear that a cap on the wholesale price can have a positive impact on the pharmacy's economic benefit and the social performance of the pharmaceutical supply chain but harm the profit margin of the pharmaceutical manufacturer. Therefore, the manufacturer price cap regulation will be welcomed by the patient due to lower drug prices. However, it will reduce the incentives for the manufacturer to supply these regulated drugs. More seriously, if the manufacturer cannot bear the loss imposed by the price cap regulation, there is a risk of supply shortage for the regulated drugs. Thus, to avoid the shortage, the pharmacy may compensate the manufacturer by distributing part of his increased profit to the manufacturer to ensure the supply of drugs. From the policy makers' perspective, they must take the drug shortage risk into consideration and come up with additional policies to mitigate the risk before implementing the manufacturer price cap regulation.

4.3. Effect of LPCR on decisions and performance

In this subsection, we discuss the regulatory effect on the pharmacy's and the pharmaceutical manufacturer's prices and profits for the LPCR model. First, we explore the effects of the retail price cap, $\overline{p}$, and the wholesale price cap, $\overline{w}$, on the optimal pricing decisions, the patient surplus and social welfare, which is shown in Lemma 3.

Lemma 3. For the LPCR model, (1) i) if $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then $p^s = p^n$ and $w^s = w^n$. ii) If $\overline{p} < p^n$ and $\overline{w} \geq w^n$, then $p^s < p^n$ and $w^s > w^n$. iii) If $\overline{w} < w^n$, then $p^s < p^n$ and $w^s < w^n$.

(2) If $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then W_s^s and C_s^s are independent on $\overline{p}$; otherwise, W_s^s and C_s^s decrease in $\overline{p}$.

Similar to the results for the RPCR and MPCR models, part (1) depicts that when both the retail price cap and wholesale price cap are respectively higher than those for the NPCR model, the optimal pricing decisions will be the same as those for the NPCR model. Therefore, the regulation does not make any impact. Otherwise, the linkage price cap regulation with lower caps can have a knock-on effect on the pricing decisions. At this time, the optimal retail price will always be lower than that without regulation. However, for the manufacturer, its optimal wholesale price may be higher or lower than that without regulation, which depends on whether the wholesale price cap is higher or lower than that for the NPCR model.

Part (2) of Lemma 3 indicates that if the retail and wholesale price
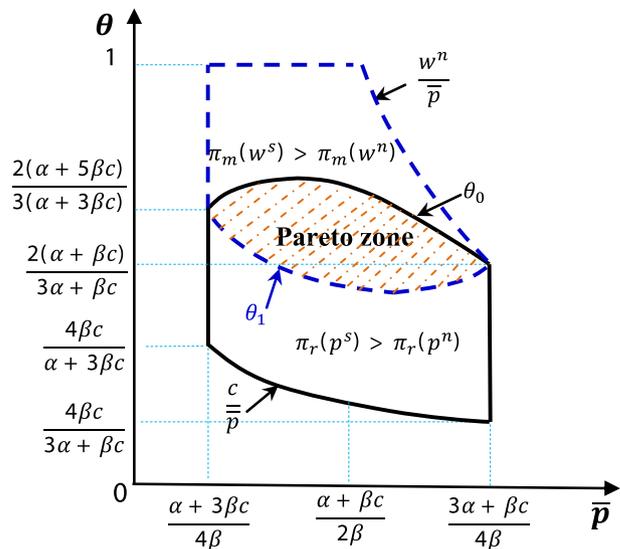
Fig. 1. Pareto zone for the LPCR model.

caps are higher than the optimal unregulated retail price and wholesale price, respectively, the regulation will not have any impact on the patient surplus and social welfare. Otherwise, the lower the retail price cap is, the better the patient surplus and social welfare.

Second, as to the effects on the firms' profits, our analysis mainly focuses on the condition where the regulation has impacts on the retail and wholesale prices. That is, 1) $\overline{p} \geq p^n$ and $\overline{w} < w^n$; 2) $\overline{p} < p^n$ and $\overline{w} \geq w^n$; and 3) $\overline{p} < p^n$ and $\overline{w} < w^n$ in Table 2. We can obtain some interesting results as shown in the following proposition.

Proposition 3. If $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} \leq \frac{3\alpha + c\beta}{4\beta}$ and $\theta_1 < \theta < \theta_o$, then $\pi_r(p^s) > \pi_r(p^n)$ and $\pi_m(w^s) > \pi_m(w^n)$, where $\theta_0 = \frac{16\beta\overline{p}(\alpha - \beta\overline{p}) - (\alpha - c\beta)^2}{16\beta\overline{p}(\alpha - \beta\overline{p})}$ and $\theta_1 = \frac{\alpha^2 + 6c\alpha\beta + c^2\beta^2 - 8c\beta^2\overline{p}}{8\beta\overline{p}(\alpha - \beta\overline{p})}$.

This proposition means that under the linkage price cap regulation, the profits of the pharmacy and pharmaceutical manufacturer can increase. As illustrated in the following Fig. 1, a Pareto zone exists that is defined by the values of the retail price cap ($\overline{p}$) and the linkage coefficient (θ) and is marked with the shaded area. The curve below the Pareto zone (θ_1) depicts that the manufacturer can be better off than that for the NPCR model and achieve Pareto improvement. The curve above the Pareto zone (θ_0) means that the pharmacy can earn more profits and achieve Pareto improvement. In the Pareto zone, both the pharmacy and manufacturer can gain increased profit and achieve Pareto improvement. Thus, an appropriate designed linkage price cap regulation will balance the retail and wholesale prices of regulated drugs via adjusting the retail price cap and linkage coefficient. Compared to one-sided price cap regulation, it not only protects the pharmacy's economic performance from the retail price cap but also avoids the manufacturer being hurt from the wholesale price cap. As a result, the risk of drug shortage and market exit for either the pharmacy or the pharmaceutical manufacturer can be mitigated. Recalling Lemma 3, the linkage price cap can also increase the patient surplus and social welfare. Thus, for policy makers, linkage price cap regulation can be easily implemented without adverse effect. Pharmaceutical firms can make pricing decisions to maximize their own profit and do not need to negotiate to distribute the increased profit, like retailer price cap regulation or manufacturer price cap regulation. It is also beneficial to the patient since the drug prices also decrease. In a word, an optimally design linkage price cap regulation can be an effective regulation for improving the economic and social performance of the pharmaceutical supply chain simultaneously.

5. Coordination of the pharmaceutical supply chain

In this section, we discuss whether the pharmaceutical supply chain can achieve coordination under price cap regulation through an optimal design of the price cap. According to the analysis in Section 4, neither retailer price cap regulation nor manufacturer price cap regulation can improve the economic performance of the pharmacy and manufacturer. In contrast, under linkage price cap regulation, the retail price cap and linkage coefficient can be optimally designed to make both the pharmacy and manufacturer achieve Pareto improvement. Therefore, we focus on analyzing whether the pharmaceutical supply chain can achieve coordination under the Pareto improvement conditions.

First, we investigate the optimal retail price of the integrated pharmaceutical supply chain under no price cap regulation. The following lemma can be obtained.

Lemma 4. *For the integrated supply chain model, $p^I = \frac{\alpha + c\beta}{2\beta}$.*

Compared to the decentralized pharmaceutical supply chain without regulation, the integrated supply chain charges a lower retail price yet gains more profit. This is because the manufacturer and pharmacy make their decisions separately to maximize their own profit in the decentralized supply chain, which causes double marginalization.

To alleviate double marginalization and achieve supply chain coordination under the Pareto improvement conditions proposed in the linkage price cap regulation model, we obtain the following proposition.

Proposition 4. The pharmaceutical supply chain can be coordinated by linkage price cap regulation when $\overline{p} = \frac{\alpha + \beta c}{2\beta}$ and $\frac{\alpha + 3c\beta}{2(\alpha + c\beta)} < \theta < \frac{3\alpha + 5c\beta}{4(\alpha + c\beta)}$.

This proposition indicates that the government can design an optimal retail price cap and linkage coefficient to coordinate the pharmaceutical supply chain. An optimally designed linkage price cap regulation is an effective regulation strategy for increasing social welfare, improving the economic performance of the pharmacy and pharmaceutical manufacturer, and coordinating the pharmaceutical supply chain.

6. Conclusions and suggestions for future research

In this paper, we investigate a two-echelon pharmaceutical supply chain composed of one pharmaceutical manufacturer and one pharmacy. Using the Stackelberg game, we derive the optimal pricing decisions under no price cap regulation, retailer price cap regulation, manufacturer price cap regulation and linkage price cap regulation. Then, we analyze the effect of each price cap regulation on the optimal prices and profits, the patient surplus and social welfare. The main results are as follows.

- Under each price cap regulation, the situation always exists where the price cap regulation has no effect on the pricing decisions and social welfare, that is, if the price caps are high ($\overline{p} \geq p^n$ or $\overline{w} \geq w^n$). Conversely, setting a lower price cap will always reduce the retail prices of drugs and improve the patient surplus and social welfare. Therefore, an effective price cap regulation that prevents pharmaceutical firms from making excessive profits and ensures social welfare requires policy makers to set more restricted price caps.
- However, restricted price caps also have an adverse effect. For instance, our analysis of pharmaceutical firms' financial performance proves that one-sided price cap regulations, e.g., retailer price cap regulation and manufacturer price cap regulation, will certainly economically harm the regulated firm, whereas the unregulated firm may gain a financial advantage. There is the risk of a policy failure that results in a drug supply shortage if pharmaceutical firms cannot cope with the financial loss brought by the price cap regulation. To mitigate the risk of policy failure, policy makers may consider providing subsidies to the regulated firm to compensate for the loss

caused by price cap regulations. For the pharmaceutical firms that benefit from regulations (the unregulated firms), one should consider supply chain coordination mechanisms, e.g., a revenue-sharing contract or a quantity discount contract to redistribute the increased profits with their supply chain partners, since the supply stoppage of associated pharmaceutical goods will have a knock-on effect on their performance.

- Our analysis also demonstrates that linkage price cap regulation can be an effective regulatory policy that improves both the economic and social performance of the pharmaceutical supply chain. We also design an optimal region of the retail price cap $\overline{p}$ and the linkage coefficient θ to enable both the pharmacy and pharmaceutical manufacturer to achieve Pareto improvement. Policy makers can set the retail price cap and wholesale price cap simultaneously according to the linkage regulation mechanism designed in this paper. In this case, the pharmaceutical firms and patients can achieve a win-win outcome. Moreover, we also provide the optimal retail price cap and linkage coefficient to coordinate the pharmaceutical supply chain. In this way, an optimally designed linkage price cap regulation can succeed in mitigating the risk of policy failure and achieving social and economic objectives simultaneously.

Since the pharmaceutical industry plays an important role in the healthcare system, many countries in the world, e.g., Germany, Norway, Austria, and China, have imposed policies to regulate this particular industry. Price cap regulation is one of the commonly used regulation policies to reduce drug prices and protect patients (Pavenik, 2002; Godman et al., 2008; Puig-Junoy, 2010). However, price cap regulations may also cause risks to the pharmaceutical supply chain because of the negative economic impact on the regulated pharmaceutical firms. Hence, how to design the price cap regulation and how to manage the risk associated with the policy implementation are crucial and emergent problems for governments and the pharmaceutical sector. Our research proposes a novel approach of evaluating alternative price cap regulations by modeling pharmaceutical firms' decision behavior as well as the consequential economic and social performance. This approach enables policy makers to effectively examine the effect of price cap regulations and assess the risks associated with different regulatory settings. The results shed some light for policy makers on developing an optimal regulatory policy that not only improves the social welfare of the general public but also protects the essential economic benefits of pharmaceutical firms and therefore improves the sustainability of the pharmaceutical sector.

Similar to the existing studies in the literature, our work has some limitations that can lead to several extensions in the future. First, our model discusses the supply chain setting of only one pharmaceutical manufacturer and one pharmacy using linear deterministic demand. One important extension is to consider stochastic demand (Chen & Wang, 2016; Shi, Zhang, & Ru, 2013) and conduct an investigation with multiple manufacturers and multiple pharmacies (Sana, Chedid, & Navarro, 2014; Wang & Chen, 2017). Second, we consider the pharmaceutical manufacturer as the Stackelberg leader. A future investigation can consider the pharmacy Stackelberg structure and the Nash structure (Chen & Wang, 2015; Shi et al., 2013). Different power structures may generate some interesting insights about the effect of price cap regulations. Third, our research considers only price cap regulations. Since other regulatory policies (e.g., quality regulation) have also been widely adopted, one future extension is to consider other regulations and examine their impacts on the economic and social performances of the pharmaceutical supply chain.

Appendix A

Proof of Table 2

NPCR model

From formula (2), we obtain $\frac{d\pi_r(p)}{dp} = \alpha - \beta p - \beta(p - w)$ and $\frac{d^2\pi_r(p)}{dp^2} = -2\beta < 0$, so $\pi_r(p)$ is concave in p. From $\frac{d\pi_r(p)}{dp} = 0$, we get $p^n = \frac{\alpha + \beta w}{2\beta}$. Replace p^n in formula (1), and obtain $\frac{d\pi_m(w)}{dw} = \frac{\alpha + \beta c - 2\beta w}{2}$ and $\frac{d^2\pi_m(w)}{dw^2} = -\beta < 0$, so $\pi_m(w)$ is concave in w. Let $\frac{d\pi_m(w)}{dw} = 0$, we obtain $w^n = \frac{\alpha + \beta c}{2\beta}$, then $p^n = \frac{3\alpha + \beta c}{4\beta}$.

RPCR model

First, for the pharmacy, we solve $\max_p \pi_r(p) = \max_p (p - w)(\alpha - \beta p)$ subject to $p \leq \overline{p}$.

i) If $\overline{p} \geq p^n$, then the regulation does not work, so the optimal prices are $p^r = p^n$ and $w^r = w^n$.

ii) If $\overline{p} < p^n$, then the regulation works, so the pharmacy's optimal retail price is $p^r = \overline{p}$. Second, for the manufacturer, replace $p^r = \overline{p}$ in formula (1). Then, we should solve $\max_w \pi_m(w) = \max_w (w - c)(\alpha - \beta\overline{p})$. Since $\pi_m(w)$ increases in w and $c < w < p^r = \overline{p}$, the optimal wholesale price is $w^r = \overline{p}$.

In summary, (1) if $\overline{p} \geq p^n$, then $p^r = p^n$ and $w^r = w^n$; (2) if $\overline{p} < p^n$, then $p^r = \overline{p}$ and $w^r = \overline{p}$.

MPCR model

First for the pharmacy, from the proof of the NPCR model, the response function is $p^m = \frac{\alpha + \beta w}{2\beta}$. Then, replace p^m in formula (1); we should solve $\max_w \pi_m(w) = \max_w (w - c)\left(\alpha - \beta\frac{\alpha + w\beta}{2\beta}\right)$ subject to $w \leq \overline{w}$.

i) If $\overline{w} \geq w^n$, then the regulation does not work, so the optimal prices are $p^m = p^n$ and $w^m = w^n$.

ii) If $\overline{w} < w^n$, then the regulation works, so the manufacturer's optimal wholesale price is $w^m = \overline{w}$. Then, the pharmacy's optimal retail price is $p^m = \frac{\alpha + \beta w^m}{2\beta} = \frac{\alpha + \beta\overline{w}}{2\beta}$.

LPCR model

(1) If $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then the linkage regulation has no effect on either the pharmacy or the manufacturer, so the optimal prices are $p^s = p^n$ and $w^s = w^n$.

(2) If $\overline{p} \geq p^n$ and $\overline{w} < w^n$, then the linkage regulation has an effect only on the manufacturer. Then, from ii) of the proof of the MPCR model, we obtain $p^s = \frac{\alpha + \beta\theta\overline{p}}{2\beta}$ and $w^s = \theta\overline{p}$.

(3) If $\overline{p} < p^n$ and $\overline{w} \geq w^n$, then the linkage regulation has an effect only on the pharmacy. Then, from ii) of the proof of the RPCR model, we obtain $p^s = \overline{p}$ and $w^s = \overline{p}$.

(4) If $\overline{p} < p^n$ and $\overline{w} < w^n$, then the linkage regulation has an effect on both the pharmacy and the manufacturer. First, for the pharmacy, the optimal retail price is $p^s = \overline{p}$. Replace it in formula (1), and we should solve $\max_w \pi_m(w) = \max_w (w - c)(\alpha - \beta\overline{p})$ subject to $w \leq \theta\overline{p}$. Since $\pi_m(w)$ increases in w and $c < w \leq \theta\overline{p}$, the optimal wholesale price is $w^s = \theta\overline{p}$.

Proof of Lemma 1

(1) From Table 2, if $\overline{p} \geq p^n$, then $p^r = p^n$ and $w^r = w^n$. If $\overline{p} < p^n$, then $p^r - p^n = \overline{p} - p^n < 0$, so $p^r < p^n$. In addition, $w^r - w^n = \overline{p} - w^n$. If $\overline{p} < w^n$, then $w^r < w^n$; if $w^n < \overline{p} < p^n$, then $w^r > w^n$.

(2) If $\overline{p} \geq p^n$, then $W_s^r = \frac{7(\alpha - c\beta)^2}{32\beta}$ and $C_s^r = \frac{(\alpha - c\beta)^2}{32\beta}$; both are independent on $\overline{p}$. If $\overline{p} < p^n$, then $W_s^r = \frac{(\alpha - \beta\overline{p})(\alpha - 2c\beta + \beta\overline{p})}{2\beta}$ and $\frac{dW_s^r}{d\overline{p}} = \beta(c - \overline{p}) < 0$; $C_s^r = \frac{(\alpha - \overline{p}\beta)^2}{2\beta}$ and $\frac{dC_s^r}{d\overline{p}} = -\alpha + \overline{p}\beta < 0$. Therefore, W_s^r and C_s^r decrease in $\overline{p}$.

Proof of Proposition 1

From Table 2 and formula (2), we obtain $\pi_r(p^r) - \pi_r(p^n) = 0 - \frac{(\alpha - c\beta)^2}{16\beta} < 0$, and $\pi_r(p^r) < \pi_r(p^n)$. From Table 2 and formula (1), we obtain $\pi_m(w^r) - \pi_m(w^n) = (\overline{p} - c)(\alpha - \beta\overline{p}) - \frac{(\alpha - c\beta)^2}{8\beta}$. Then, $\frac{d[\pi_m(w^r) - \pi_m(w^n)]}{d\overline{p}} = \alpha + c\beta - 2\beta\overline{p}$ and $\frac{d^2[\pi_m(w^r) - \pi_m(w^n)]}{d\overline{p}^2} = -2\beta < 0$; hence, $\pi_m(w^r) - \pi_m(w^n)$ is concave in $\overline{p}$. The roots of $\pi_m(w^r) - \pi_m(w^n)$ are $\overline{p}^0 = \frac{\alpha + c\beta}{2\beta} - \frac{\sqrt{2}(\alpha - c\beta)}{4\beta}$ and $\overline{p}^1 = \frac{\alpha + c\beta}{2\beta} + \frac{\sqrt{2}(\alpha - c\beta)}{4\beta}$. Since $c < \overline{p} < \frac{3\alpha + c\beta}{4\beta}$, $\overline{p}^1$ should be rejected. Further, if $\overline{p} < \frac{\alpha + c\beta}{2\beta} - \frac{\sqrt{2}(\alpha - c\beta)}{4\beta}$, we obtain $\pi_m(w^r) - \pi_m(w^n) < 0$, so $\pi_m(w^r) < \pi_m(w^n)$; if $\overline{p} > \frac{\alpha + c\beta}{2\beta} - \frac{\sqrt{2}(\alpha - c\beta)}{4\beta}$, we obtain $\pi_m(w^r) - \pi_m(w^n) > 0$, so $\pi_m(w^r) > \pi_m(w^n)$.

Proof of Lemma 2

(1) From Table 2, if $\overline{w} \geq w^n$, then $p^m = p^n$ and $w^m = w^n$. If $\overline{w} < w^n$, then $p^m - p^n = -\frac{\alpha + c\beta - 2\beta\overline{w}}{4\beta} < -\frac{\alpha + c\beta - 2\beta w^n}{4\beta} = 0$, so $p^m < p^n$. In addition, $w^m - w^n = \overline{w} - \frac{\alpha + c\beta}{2\beta} < 0$, and $w^m < w^n$.

(2) If $\overline{w} \geq w^n$, we obtain $W_s^m = \frac{7(\alpha - c\beta)^2}{32\beta}$ and $C_s^m = \frac{(\alpha - c\beta)^2}{32\beta}$; both are independent on $\overline{w}$. If $\overline{w} < w^n$, we obtain $W_s^m = \frac{(\alpha - \beta\overline{w})(3\alpha - 4c\beta + \beta\overline{w})}{8\beta}$ and $\frac{dW_s^m}{d\overline{p}} = \frac{1}{4}(-\alpha + 2c\beta - \beta\overline{w}) < \frac{1}{4}(-\alpha + 2c\beta - \beta c) = \frac{1}{4}(-\alpha + c\beta) < 0$. $C_s^m = \frac{(\alpha - \beta\overline{w})^2}{8\beta}$ and $\frac{dC_s^m}{d\overline{p}} = -\alpha + \beta\overline{w} < 0$. So W_s^m and C_s^m decrease in $\overline{w}$.

Proof of Proposition 2

From Table 2 and Formula (2), we obtain $\pi_r(p^m) - \pi_r(p^n) = \frac{(3\alpha - c\beta - 2\beta\overline{w})(\alpha + c\beta - 2\beta\overline{w})}{16\beta}$. Since $\overline{w} < w^n$, $3\alpha - c\beta - 2\beta\overline{w} > 3\alpha - c\beta - 2\beta\frac{\alpha + c\beta}{2\beta} = 2(\alpha - c\beta) > 0$. Therefore, $\pi_r(p^m) - \pi_r(p^n) > 0$ and $\pi_r(p^m) > \pi_r(p^n)$. From Table 2 and formula (1), we obtain $\pi_m(w^m) - \pi_m(w^n) = -\frac{(\alpha + c\beta - 2\beta\overline{w})^2}{8\beta} < 0$, so $\pi_m(w^m) < \pi_m(w^n)$.

Proof of Lemma 3

(1) From Tables 2, 1) if $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then $p^s = p^n$ and $w^s = w^n$.

2) If $\overline{p} \geq p^n$ and $\overline{w} < w^n$, then $p^s = \frac{\alpha + \beta\theta\overline{p}}{2\beta}$ and $w^s = \theta\overline{p}$. Therefore, $p^s - p^n = -\frac{\alpha + c\beta - 2\beta\theta\overline{p}}{4\beta} < -\frac{\alpha + c\beta - 2\beta w^n}{4\beta} = 0$, and $p^s < p^n$; $w^s - w^n = \theta\overline{p} - \frac{\alpha + \beta c}{2\beta} = \overline{w} - \frac{\alpha + \beta c}{2\beta} < 0$, and $w^s < w^n$.

3) If $\overline{p} < p^n$ and $\overline{w} \geq w^n$, then $p^s = \overline{p}$ and $w^s = \overline{p}$. Therefore, $p^s < p^n$; $w^s - w^n = \overline{p} - w^n = \frac{\overline{w}}{\theta} - w^n > 0$, and $w^s > w^n$.

4) If $\overline{p} < p^n$ and $\overline{w} < w^n$, then $p^s = \overline{p}$ and $w^s = \theta\overline{p}$. Therefore, $p^s < p^n$; $w^s - w^n = \theta\overline{p} - \frac{\alpha + \beta c}{2\beta} < 0$, and $w^s < w^n$.

In summary, we obtain that if $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then $p^s = p^n$ and $w^s = w^n$. If $\overline{p} < p^n$ and $\overline{w} \geq w^n$, then $p^s < p^n$ and $w^s > w^n$. If $\overline{w} < w^n$, then $p^s < p^n$ and $w^s < w^n$.

(2) If $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then $W_s^s = \frac{7(\alpha - c\beta)^2}{32\beta}$ and $C_s^s = \frac{(\alpha - c\beta)^2}{32\beta}$. Therefore, W_s^s and C_s^s are independent on $\overline{p}$.

If $\overline{p} \geq p^n$ and $\overline{w} < w^n$, then $W_s^s = \frac{(\alpha - \beta\theta\overline{p})(3\alpha - 4c\beta + \beta\theta\overline{p})}{8\beta}$ and $\frac{dW_s^s}{d\overline{p}} = -\frac{1}{4}\theta(\alpha - 2c\beta + \beta\theta\overline{p}) < -\frac{1}{4}\theta(\alpha - 2c\beta + \beta c) = -\frac{1}{4}\theta(\alpha - c\beta) < 0$; $C_s^s = \frac{(\alpha - \beta\theta\overline{p})^2}{8\beta}$ and $\frac{dC_s^s}{d\overline{p}} = \frac{1}{4}\theta(-\alpha + \beta\theta\overline{p}) < 0$. Therefore, W_s^s and C_s^s decrease in $\overline{p}$.

If $\overline{p} < p^n$ and $\overline{w} \geq w^n$, or if $\overline{p} < p^n$ and $\overline{w} < w^n$, then $W_s^s = \frac{(\alpha - \beta\overline{p})(\alpha - 2c\beta + \beta\overline{p})}{2\beta}$ and $\frac{dW_s^s}{d\overline{p}} = \beta(c - \overline{p}) < 0$; $C_s^s = \frac{(\alpha - \overline{p}\beta)^2}{2\beta}$ and $\frac{dC_s^s}{d\overline{p}} = -\alpha + \overline{p}\beta < 0$. Therefore, W_s^s and C_s^s decrease in $\overline{p}$.

Hence, if $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then W_s^s and C_s^s are independent on $\overline{p}$. Otherwise, W_s^s and C_s^s decrease in $\overline{p}$.

Proof of Proposition 3

(1) From Table 2, if $\overline{p} \geq p^n$ and $\overline{w} \geq w^n$, then $p^s = p^n$ and $w^s = w^n$. Therefore, $\pi_r(p^s) = \pi_r(p^n)$ and $\pi_m(w^s) = \pi_m(w^n)$. In this case, Pareto improvement cannot be achieved.

(2) If $\overline{p} \geq p^n$ and $\overline{w} < w^n$, then $p^s = \frac{\alpha + \beta\theta\overline{p}}{2\beta}$ and $w^s = \theta\overline{p}$. So $\pi_m(w^s) - \pi_m(w^n) = \frac{1}{2}(\theta\overline{p} - c)(\alpha - \theta\beta\overline{p}) - \frac{(\alpha - c\beta)^2}{8\beta} = -\frac{(\alpha + c\beta - 2\theta\beta\overline{p})^2}{8\beta} < 0$. In this case, Pareto improvement cannot be achieved.

(3) If $\overline{p} < p^n$ and $\overline{w} \geq w^n$, then $p^s = \overline{p}$ and $w^s = \overline{p}$. Therefore, $\pi_r(p^s) = 0$ and $\pi_r(p^s) < \pi_r(p^n)$. In this case, Pareto improvement cannot be achieved.

(4) If $\overline{p} < p^n$ and $\overline{w} < w^n$, then $p^s = \overline{p}$ and $w^s = \theta\overline{p}$. To ensure that the marginal profits and demand are positive, we obtain $\theta > \frac{c}{\overline{p}}$.

From Tables 1 and 2, we obtain $\pi_s^s - \pi_s^n = -\frac{(3\alpha + c\beta - 4\beta\overline{p})(\alpha + 3c\beta - 4\beta\overline{p})}{16\beta}$. Since $\overline{p} < p^n = \frac{3\alpha + c\beta}{4\beta}$, $3\alpha + c\beta - 4\beta\overline{p} > 3\alpha + c\beta - 4\beta\frac{3\alpha + c\beta}{4\beta} = 0$. To discuss the Pareto zone, $\pi_s^s > \pi_s^n$ must be satisfied. So $\alpha + 3c\beta - 4\beta\overline{p} < 0$ must be satisfied, and $\overline{p} > \frac{\alpha + 3c\beta}{4\beta}$. Next, we will discuss the pharmacy's and the manufacturer's profits under the conditions $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < p^n = \frac{3\alpha + c\beta}{4\beta}$ and $\theta\overline{p} < w^n$.

1) For the pharmacy, $\pi_r(p^s) - \pi_r(p^n) = (1 - \theta)\overline{p}(\alpha - \beta\overline{p}) - \frac{(\alpha - c\beta)^2}{16\beta}$ and it decreases in θ. We can get one root $\theta_0 = \frac{16\beta\overline{p}(\alpha - \beta\overline{p}) - (\alpha - c\beta)^2}{16\beta\overline{p}(\alpha - \beta\overline{p})}$. Since $\theta\overline{p} < w^n$ and $\frac{c}{\overline{p}} < \theta < 1$, $\frac{c}{\overline{p}} < \theta < min\left\{\frac{w^n}{\overline{p}}, 1\right\}$. Therefore, we should compare θ_0 with these thresholds. First, it is easy to obtain $\theta_0 < 1$. Then, compare θ_0 with $\frac{w^n}{\overline{p}}$; we get $\theta_0 - \frac{w^n}{\overline{p}} = -\frac{(3\alpha + c\beta - 4\beta\overline{p})^2}{16\beta\overline{p}(\alpha - \beta\overline{p})} < 0$, so $\theta_0 < \frac{w^n}{\overline{p}}$. Finally, compare θ_0 with $\frac{c}{\overline{p}}$, we get $\theta_0 - \frac{c}{\overline{p}} = \frac{-16\beta^2\overline{p}^2 + 16\beta(\alpha + c\beta)\overline{p} - (\alpha - c\beta)^2 - 16\alpha\beta c}{16\beta\overline{p}(\alpha - \beta\overline{p})}$. Let $F(\overline{p}) = -16\beta^2\overline{p}^2 + 16\beta(\alpha + c\beta)\overline{p} - (\alpha - c\beta)^2 - 16\alpha\beta c$. Then, $F(\overline{p})$ is concave in $\overline{p}$. Since $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < \frac{3\alpha + c\beta}{4\beta}$, $F(\overline{p})|_{\overline{p} = \frac{\alpha + 3c\beta}{4\beta}} = 2(\alpha - c\beta)^2 > 0$ and $F(\overline{p})|_{\overline{p} = \frac{3\alpha + c\beta}{4\beta}} = 2(\alpha - c\beta)^2 > 0$. Then, we can conclude $F(\overline{p}) > 0$, so $\theta_0 > \frac{c}{\overline{p}}$.

From above analysis, we obtain if $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < \frac{3\alpha + c\beta}{4\beta}$ and $\frac{c}{\overline{p}} < \theta < \theta_0$, then $\pi_r(p^s) > \pi_r(p^n)$.

2) For the manufacturer, $\pi_m(w^s) - \pi_m(w^n) = (\theta\overline{p} - c)(\alpha - \beta\overline{p}) - \frac{(\alpha - c\beta)^2}{8\beta}$ and it increases in θ. We can obtain the root $\theta_1 = \frac{\alpha^2 + 6c\alpha\beta + c^2\beta^2 - 8c\beta^2\overline{p}}{8\beta\overline{p}(\alpha - \beta\overline{p})}$. First, we compare θ_1 with $\frac{c}{\overline{p}}$, and $\theta_1 - \frac{c}{\overline{p}} = \frac{(\alpha - c\beta)^2}{8\beta\overline{p}(\alpha - \beta\overline{p})} > 0$. Second, from 1), when $\overline{p} > w^n = \frac{\alpha + \beta c}{2\beta}$, $\frac{w^n}{\overline{p}} < 1$, so $\theta < \frac{w^n}{\overline{p}}$ and $\theta_1 - \frac{w^n}{\overline{p}} = \frac{(\alpha - c\beta)(\overline{p} - p^n)}{2\overline{p}(\alpha - \beta\overline{p})} < 0$. That means that when $\frac{\alpha + \beta c}{2\beta} < \overline{p} < \frac{3\alpha + c\beta}{4\beta}$ and $\theta_1 < \theta < \frac{w^n}{\overline{p}}$, $\pi_m(w^s) > \pi_m(w^n)$. When $\overline{p} < w^n = \frac{\alpha + \beta c}{2\beta}$, $\frac{w^n}{\overline{p}} > 1$, so $\theta < 1$ and $\theta_1 - 1 = \frac{8\beta^2\overline{p}^2 - 8\beta(\alpha + c\beta)\overline{p} + \alpha^2 + 6c\alpha\beta + c^2\beta^2}{8\beta\overline{p}(\alpha - \beta\overline{p})}$. Let $G(\overline{p}) = 8\beta^2\overline{p}^2 - 8\beta(\alpha + c\beta)\overline{p} + \alpha^2 + 6c\alpha\beta + c^2\beta^2$. Then, $G(\overline{p})$ is convex in $\overline{p}$. Since $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < \frac{\alpha + c\beta}{2\beta}$, $G(\overline{p})|_{\overline{p} = \frac{\alpha + 3c\beta}{4\beta}} = -\frac{1}{2}(\alpha - c\beta)^2 < 0$ and $G(\overline{p})|_{\overline{p} = \frac{\alpha + \beta c}{2\beta}} = -(\alpha - c\beta)^2 < 0$. Hence, we can conclude that $G(\overline{p}) < 0$ and $\theta_1 < 1$. That means that when $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < \frac{\alpha + c\beta}{2\beta}$ and $\theta_1 < \theta < 1$, we obtain $\pi_m(w^s) > \pi_m(w^n)$.

From above analysis, we obtain that if $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < \frac{\alpha + \beta c}{2\beta}$ and $\theta_1 < \theta < 1$, or $\frac{\alpha + \beta c}{2\beta} < \overline{p} < \frac{3\alpha + c\beta}{4\beta}$ and $\theta_1 < \theta < \frac{w^n}{\overline{p}}$, then $\pi_m(w^s) > \pi_m(w^n)$.

From 1) and 2), we should take the intersections. Since $\theta_0 - \theta_1 = \frac{\beta\left(\frac{3\alpha + c\beta}{4\beta} - \overline{p}\right)\left(\overline{p} - \frac{\alpha + 3c\beta}{4\beta}\right)}{\overline{p}(\alpha - \beta\overline{p})} > 0$, if $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < \frac{3\alpha + c\beta}{4\beta}$ and $\theta_1 < \theta < \theta_0$, we obtain $\pi_r(p^s) > \pi_r(p^n)$ and $\pi_m(w^s) > \pi_m(w^n)$, where $\theta_0 = \frac{16\beta\overline{p}(\alpha - \beta\overline{p}) - (\alpha - c\beta)^2}{16\beta\overline{p}(\alpha - \beta\overline{p})}$ and $\theta_1 = \frac{\alpha^2 + 6c\alpha\beta + c^2\beta^2 - 8c\beta^2\overline{p}}{8\beta\overline{p}(\alpha - \beta\overline{p})}$.

Proof of Lemma 4

From Table 1, we obtain $\frac{\partial \pi_s}{\partial p} = \alpha - \beta p - \beta(p - c)$ and $\frac{\partial^2 \pi_s}{\partial p^2} = -2\beta < 0$. Therefore, π_s is concave in p. Let $\frac{\partial \pi_s}{\partial p} = 0$; we obtain $p^I = \frac{\alpha + \beta c}{2\beta}$.

Proof of Proposition 4

From Proposition 3, if $\frac{\alpha + 3c\beta}{4\beta} < \overline{p} < \frac{3\alpha + c\beta}{4\beta}$ and $\theta_1 < \theta < \theta_0$, both the pharmacy and the manufacturer can achieve Pareto improvement. Therefore, it is meaningful to discuss the supply chain coordination under this case.

First, for the pharmacy, we should solve $\max_p \pi_r(p) = \max_p (p - w)(\alpha - \beta p)$ subject to $p \leq \overline{p}$. Recall the proof for the LPCR model: when $\overline{p} < p^n = \frac{3\alpha + c\beta}{4\beta}$, then $p^s = \overline{p}$. To coordinate the supply chain, $p^s = p^I = \frac{\alpha + \beta c}{2\beta}$ must be satisfied, so $\overline{p} = \frac{\alpha + \beta c}{2\beta}$.

Second, for the manufacturer, we should solve $\max_w \pi_m(w) = \max_w (w - c)(\alpha - \beta \overline{p})$ subject to $w \leq \theta \overline{p}$. Recall the proof for the LPCR model,

i) If $\overline{w} \geq w^n = \frac{\alpha + \beta c}{2\beta}$, then the regulation has no effect on the manufacturer, and we get $w^s = \overline{p} = \frac{\alpha + \beta c}{2\beta}$. However, in this case, $\pi_r(p^s) < \pi_r(p^n)$, so the supply chain cannot be coordinated.

ii) If $\overline{w} < w^n = \frac{\alpha + \beta c}{2\beta}$, then $w^s = \theta \overline{p} = \frac{\theta(\alpha + \beta c)}{2\beta}$. Moreover, to coordinate the supply chain, $\pi_r(p^s) > \pi_r(p^n)$ and $\pi_m(w^s) > \pi_m(w^n)$ must be satisfied. $\pi_r(p^s) - \pi_r(p^n) = \frac{-(\alpha - \beta c)[4(\alpha + \beta c)\theta - (3\alpha + 5\beta c)]}{16\beta} > 0$, and $\theta < \frac{3\alpha + 5c\beta}{4(\alpha + c\beta)}$. In addition, $\pi_m(w^s) - \pi_m(w^n) = \frac{(\alpha - c\beta)[2(\alpha + \beta c)\theta - (\alpha + 3\beta c)]}{8\beta} > 0$, and $\theta > \frac{\alpha + 3c\beta}{2(\alpha + c\beta)}$. Hence, when $\overline{p} = \frac{\alpha + c\beta}{2\beta}$ and $\frac{\alpha + 3c\beta}{2(\alpha + c\beta)} < \theta < \frac{3\alpha + 5c\beta}{4(\alpha + c\beta)}$, the supply chain can be coordinated.

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