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Evaluating the effects of quality regulations on the pharmaceutical supply chain

Xu Chen^a, Shanshan Li^a, Xiaojun Wang^{b†}

a. School of Management and Economics, University of Electronic Science and Technology of China, Chengdu, 611731, China, E-mail: xchenxchen@263.net (Xu Chen); asyshanshan@163.com (Shanshan Li)

b. Department of Management, University of Bristol, Bristol, BS8 1TZ, U.K. E-mail: xiaojun.wang@bristol.ac.uk

† Corresponding author. E-mail: xiaojun.wang@bristol.ac.uk, Tel: +44 117 3940532 (Xiaojun Wang)

Abstract: This paper considers a two-echelon pharmaceutical supply chain comprising two pharmaceutical manufacturers and a pharmacy. We derive optimal decisions for three different supply chain power structures considering two scenarios: one scenario featuring quality regulation, and one without. By comparing the equilibriums of the two regulatory scenarios under different power structures, we then evaluate the effects of quality regulation and power structure on pharmaceutical firms' decisions, profits and social welfare. Our results show that the product differentiation between two pharmaceutical manufacturers will be reduced through quality regulation, serving to intensify price competition between them. This has a negative impact on the two pharmaceutical manufacturers but a positive effect on the pharmacy's profit. However, an appropriate level of minimum quality standards can enhance social welfare and the economic performance of the whole pharmaceutical supply chain, resulting in a win-win outcome. In addition, our results demonstrate that the balanced power structure has a positive effect on the pharmaceutical supply chain's economic performance and social welfare.

Keywords: pharmaceutical supply chain; quality regulation; market structure; social welfare.

1 Introduction

There has been significant growth in the global pharmaceutical sector in recent years, with the global market valued at about \$1.2 trillion in 2018 (Mikulic 2019). This rapid growth is set to continue in the foreseeable future owing to changing lifestyles, personalised treatments, an aging population, and adoption of new technologies within the pharmaceutical industry. Meanwhile, the pharmaceutical market plays a key role for national healthcare systems in most countries around the world, as it affects how individuals access medications and how much they pay. As a result, the pharmaceutical market is heavily regulated in many developed and developing countries owing to the unique nature of pharmaceutical products and their critical role in meeting global health challenge (Yu et al. 2010; Pezzola and Sweet 2016; Bisceglia et al. 2018). While prices are regulated to ensure affordability and accessibility (Chen et al. 2019b), the quality of both new and existing pharmaceutical products is regulated to improve health status of the population, as the public health impact of substandard medicine is potentially severe (Cockburn et al. 2005; Bennett and Yin 2019). For instance, the World Health Organisation (WHO 2019) develops international standards for the manufacturing and regulation of health products and supports member states in regulation, safety and quality assurance of medicines.

For pharmaceutical firms, product quality is essential in developing and protecting company reputation, serving to enhance a firm's competitive advantage. Meanwhile, pharmaceutical firms are under increasing pressure from consumers and governments to reduce the prices of their drugs (Nagurney et al. 2013). Therefore, it is important for pharmaceutical companies to understand the impact of regulatory requirements in terms of quality standards on their supply chain decisions, in particular the trade-offs between cost and quality, as both are vital during market competition. Quality regulation is critically important for the pharmaceutical market. However, little attention has been paid to the ways in which pharmaceutical firms behave with respect to quality regulation and how their corresponding decisions affect the performance of a pharmaceutical supply chain. Studies by Nagurney et al. (2013, 2014) and Nagurney and Li (2014) are among the few to investigate price and quality competition within the pharmaceutical supply chain. However, their research does not consider power relationships and social performance. Our research aims to address this research gap by incorporating both factors in our investigation of the effects of quality regulation on

pharmaceutical supply chain decisions and performance. We examine the following three research questions:

(1) How does the regulatory requirement for minimum quality standards affect pharmaceutical supply chain firms' decisions and profitability?

(2) How can policy makers develop an appropriate quality standard to improve the economic performance of the pharmaceutical supply chain and social welfare?

(3) To what extent does the supply chain power structure affect the decisions and performance of the pharmaceutical supply chain under quality regulations?

This study makes several key contributions. First, it complements the existing studies on price and quality competition in the pharmaceutical supply chain through a comprehensive examination of the effects of quality regulation and supply chain power relationships on pharmaceutical firms' operational decisions and the consequential economic and social performance of the supply chain. In contrast to the relevant studies (e.g., Natterney et al. 2013, 2014; Natterney and Li 2014) that focus on the upstream of the pharmaceutical supply chain, we concentrate on the downstream. In this scenario, the downstream consists of two competing pharmaceutical manufacturers and one pharmacy. In addition, we consider power relationships, an important feature of the pharmaceutical supply chain when examining quality regulation effects (Rossetti et al. 2012; Chen et al. 2019a,b). Second, this research offers a novel approach for evaluating regulatory policies on quality standards of pharmaceutical products by modelling the decision behaviour of the pharmaceutical supply chain and the associated economic and social performance of the supply chain. Such an approach enables regulators to develop appropriate quality regulations to improve the sustainability of the pharmaceutical supply chain, thereby safeguarding social welfare and pharmaceutical firms' profitability. Furthermore, insights derived from the analytical results provide important managerial implications that support pharmaceutical firms in making informed strategic and operational decisions to sustain market competitiveness.

The rest of this paper is organised as follows. A survey of related literature is presented in Section 2. The models and equilibrium analysis are provided in Section 3. Section 4 investigates the effects of quality regulation on supply chain decisions, profits and social welfare. In Section 5, the effects of supply chain power structures on decisions, profits and social welfare are discussed. Numerical

analysis is discussed in Section 6. Finally, concluding remarks are offered in Section 7, outlining the main research findings and suggestions for future research.

2 Literature review

With distinctive features including high costs of R&D, complexity in supply and distribution and dominance of several multinational firms, the pharmaceutical supply chain has attracted growing attention among academics, as demonstrated through recent reviews by Rossetti et al. (2012), Dobrzykowski et al. (2014), Narayana et al. (2014) and Settanni et al. (2017). In accordance with the focus of this paper, the review of the relevant literature mainly concentrates on three relevant research streams: (i) price and quality competition in general; (ii) price and quality competition in the pharmaceutical supply chain; and (iii) the effects of quality standards on pharmaceutical supply chain decisions and performance.

Academics and practitioners have increasingly devoted their attention to incorporating quality in supply chain research, as product quality is imperative to maintaining and improving firms' competitive advantage and reputation. Saberi et al. (2014) used the game theoretical model to study quality competition among Internet service providers and proposed an algorithm that yields closed-form expressions for prices and quality levels. Li and Nagurney (2015) proposed a general multitiered supply chain network equilibrium model to illustrate the competitive behaviour of the two tiers of supply chain members regarding their quantity and quality decisions. Panagiotidou et al. (2017) analysed the effect of the returns classification process under partial quality information on the reverse supply chain operations and profitability in a manufacturing/remanufacturing hybrid facility. Kurokawa and Matsubayashi (2018) examined price and quality decisions in a duopoly model of vertical differentiation considering firms' quality repositioning costs, which are dependent on their core products' quality levels. Their research determined how equilibrium outcomes and firms' performance are affected by the relationship between firms' quality positions and repositioning costs.

In the context of the pharmaceutical industry, Masoumi et al. (2012) proposed a generalised network oligopoly model for pharmaceutical supply chain competition which considered product perishability, brand differentiation and discarding costs. Their work evaluated the effects of patent rights expiration and generic drug competition through a case study of cholesterol-lowering drugs.

Bisceglia et al. (2018) proposed a sequential game model in which the regulator controls the price as a unique instrument to affect both quality and interregional patient flow. Their model is particularly useful when studying markets in which prices are regulated by authorities and pharmaceutical producers, or where health service providers compete in terms of the quality of their product or service. Chen et al. (2019b) assessed the impact of a price cap regulation on pharmaceutical firms' pricing decisions as well as the pharmaceutical supply chain's economic performance by comparing model equilibriums under different price cap regulations. Bennett and Yin (2019) examined whether markets can overcome asymmetric information surrounding quality in a scenario without regulation. They found that chain entry can result in higher quality and lower prices for incumbent pharmacies in the overall market.

The most relevant stream of literature concentrates on the effect of the regulatory requirements for quality standards of pharmaceutical products on supply chain decisions. Within this stream, Nagurney et al.'s (2013) study used a game theory approach to incorporate quality concerns into their development of a pharmaceutical supply model, in the context of global outsourcing. By modelling the behaviours of a pharmaceutical firm and its potential contractors, Nagurney et al. proposed dynamic adjustment processes for the evolution of prices, quality levels and product flows, as well as reporting stability analysis results. Covering product categories like food and pharmaceuticals, Nagurney and Li (2014) proposed a supply chain network equilibrium model in which firms compete in terms of product quantity and quality, with information asymmetry in quality. Based on this line of research, Nagurney et al. (2014) developed a spatial price equilibrium model with information asymmetry in quality and illustrated the effects of imposing minimum quality standards as a policy instrument on equilibrium product shipments, product prices and average quality levels.

Furthermore, like many other policies, the successful implementation of quality standards requires supply chain coordination to achieve system-wide win-win outcomes (Banerjee 1986; Banerjee and Kim 1995; Welling and Kamann 2011). Using game theoretical models, Modak et al. (2016) analysed the effect of imperfect product quality on optimal decisions and depicted the hybrid contract mechanism which is designed to coordinate three-echelon supply chains. Chen et al. (2017) proposed a two-part tariff revenue sharing contract to coordinate supply chain sustainability decisions considering the supply chain power relationship. Sher et al. (2018) developed a supply chain

coordination mechanism for common items subject to failure in the electronics, defence, and medical industries. Their mechanism was designed for supply chains consisting of multiple buyers and a single supplier. Raza (2018) used a revenue-sharing contract to coordinate a single manufacturer-retailer supply chain for pricing inventory and corporate social responsibility investment decisions.

Despite a growing number of studies emphasising price and quality competition in the pharmaceutical supply chain and the related regulatory impacts, our research is different in the following respects. First, compared to the previous studies (Naturney et al. 2013, 2014; Nagurney and Li 2014) which concentrate on the upstream stage of the pharmaceutical supply chain, we develop our model in the context of the downstream stage, including two competing pharmaceutical manufacturers and one pharmacy. Second, the pharmaceutical supply chain is characterised by the dominance of a few multinational pharmaceutical manufacturers and several chains of pharmacies (Rossetti et al. 2011; Chen et al. 2019a, b). In contrast to the relevant studies (Naturney et al. 2013; 2014; Nagurney and Li 2014), we examine the impact of supply chain power structures on the pharmaceutical supply chain firms' decisions regarding quality and prices as well as associated performance. Third, given the ever-increasing awareness of sustainability in terms of the pharmaceutical supply chain among government, industry and the general public (Xie and Breen 2012; Uthayakumar and Priyan 2013; Zahir et al. 2017), we evaluate the social welfare of the pharmaceutical supply chain in addition to the economic performance of pharmaceutical firms.

3 Models and equilibrium analysis

3.1 Model formulation and assumptions

We consider a two-echelon pharmaceutical supply chain that is composed of two pharmaceutical manufacturers and a pharmacy. Pharmaceutical manufacturer 1 produces a better-quality product than manufacturer 2. Without loss of generality, we normalise that the quality of product H to one and denote by $0 < \gamma \leq 1$ the relative quality of product L. Pharmaceutical manufacturer 1's quality investment in product H is $\frac{1}{2}\alpha$ and pharmaceutical manufacturer 2's quality investment in product L is $\frac{1}{2}\alpha\gamma^2$ (Tsay and Agrawal 2000; Yan and Pei 2009; Pu et al. 2017). The pharmacy purchases

medical products from the two pharmaceutical manufacturers and then sells them to consumers. Relevant parameters and variables are defined as summarised in Table 1.

Table 1 Notations

Notation	Descriptions
w_H, w_L	Unit wholesale price of product H and product L, respectively.
q_H, q_L	Pharmacy's order quantities for product H and product L, respectively.
p_H, p_L	Pharmacy's unit retail price of product H and product L, respectively, $p_H > w_H > 0$, $p_L > w_L > 0$.
v	Consumer's valuation per unit of product quality, $v \sim U[0,1]$.
γ	Relative quality of product L, $0 < \gamma \leq 1$.
β	Minimum quality standards (MQS) for pharmaceutical products, $\gamma < \beta \leq 1$.
α	Quality investment cost coefficient of pharmaceutical manufacturers.
$\pi_{MH}(w_H), \pi_{ML}(w_L, \gamma)$	Pharmaceutical manufacturer 1's profit and manufacturer 2's profit in the MS, PS and VN models, respectively.
$\pi_R(q_H, q_L)$	Pharmacy's profit in MS, PS and VN models.
π	Supply chain's profit in the MS, PS and VN models, $\pi = \pi_{MH}(w_H) + \pi_{ML}(w_L, \gamma) + \pi_R(q_H, q_L)$.
C_s	Patient surplus.
W_s	Social welfare, $W_s = C_s + \pi_{MH}(w_H) + \pi_{ML}(w_L, \gamma) + \pi_R(q_H, q_L)$.

Regarding demand, we assume that potential consumers are continuous and total demand is one. Each consumer purchases at most one unit of either product H or product L. Consumers reserve heterogeneous valuation v for each unit of product quality and we assume that v is uniformly distributed on $[0,1]$. For any given prices, p_H and p_L for products H and L respectively, the net utility of a consumer with valuation v can be stated as follows:

$$u = \begin{cases} v - p_H, & \text{if buying product H;} \\ \gamma v - p_L, & \text{if buying product L;} \\ 0, & \text{if not buying at all.} \end{cases} \quad (1)$$

When the price of product L is low enough relative to the price of product H, that is, $\gamma p_H > p_L$, the demands for both products are positive. Consumers with $v \in [\frac{p_H - p_L}{1 - \gamma}, 1]$ buy product H, consumers with $v \in [\frac{p_L}{\gamma}, \frac{p_H - p_L}{1 - \gamma}]$ buy product L, while consumers with $v \in [0, \frac{p_L}{\gamma}]$ buy nothing. The demands for product H and product L are $q_H = 1 - \frac{p_H - p_L}{1 - \gamma}$ and $q_L = \frac{p_H - p_L}{1 - \gamma} - \frac{p_L}{\gamma}$ respectively.

The inverse demand functions for products H and L are expressed as follows:

$$p_H = 1 - q_H - \gamma q_L \quad (2)$$

$$p_L = \gamma(1 - q_H - q_L) \quad (3)$$

This type of demand function is commonly used to represent vertically differentiated products in the marketing, economics, and operations literature (e.g., Yehezkel 2008; Chen et al. 2016; Luo et al. 2018).

To simplify the calculation, we assume that the marginal cost of products H and L is 0 (Valletti 2000; Wang et al. 2013). Based on the aforementioned assumptions, the model framework is described in Figure 1.

Figure 1. The model framework

Pharmaceutical manufacturer 1's profit $\pi_{MH}(w_H)$ is:

$$\pi_{MH}(w_H) = w_H q_H - \frac{1}{2} \alpha \quad (4)$$

The first part of the formula represents pharmaceutical manufacturer 1's profit from supplying product H to the pharmacy, and the second part indicates pharmaceutical manufacturer 1's investment in the product.

Similarly, pharmaceutical manufacturer 2's profit $\pi_{ML}(w_L, \gamma)$ is:

$$\pi_{ML}(w_L, \gamma) = w_L q_L - \frac{1}{2} \alpha \gamma^2 \quad (5)$$

The first part of the formula represents pharmaceutical manufacturer 2's profit from supplying product L to the pharmacy, and the second part indicates pharmaceutical manufacturer 2's investment in product quality.

Pharmacy's profit $\pi_R(q_H, q_L)$ is:

$$\pi_R(q_H, q_L) = (p_H q_H - w_H q_H) + (p_L q_L - w_L q_L) \quad (6)$$

The first part of the formula represents the profit from selling product H and the second part represents the profit from selling product L.

The social welfare consists of the patient surplus, the pharmaceutical manufacturer's profit and the pharmacy's profit (Jin et al. 2015; Chen et al. 2019b). With reference to the previous literature (Cowan 1998; Jin et al. 2015; Chen et al. 2019b), the patient surplus C_s is:

$$C_s = \int_0^{1-p_H-\gamma q_L} (1-x-\gamma q_L-p_H) dx + \int_0^{1-q_H-\frac{p_L}{\gamma}} [\gamma(1-q_H-y)-p_L] dy = \frac{q_H^2}{2} + \frac{\gamma q_L^2}{2} \quad (7)$$

The first part of the formula represents the patient surplus for product H and the second part indicates the patient surplus for product L.

3.2 The base model

This section studies the optimal decisions of the pharmaceutical manufacturers and pharmacy under different channel power structures for the base model that do not have quality standard requirements. Under these conditions,, we built the Pharmaceutical Manufacturer Stackelberg (MS), Pharmacy Stackelberg (PS) and Vertical Nash (VN) models.

3.2.1 Pharmaceutical manufacturer Stackelberg (MS) model

In the MS model, the pharmaceutical manufacturer is the Stackelberg leader while the pharmacy is the follower with respect to deciding prices. This type of supply chain power structure is common as large pharmaceutical firms (e.g., Johnson & Johnson) often take a leading role in dealing with downstream pharmacies (Chen et al. 2019b). The decision sequence of the pharmaceutical manufacturers and pharmacy is as follows. During the first stage, manufacturer 2 decides its quality level (γ) for product L. At the second stage, manufacturer 1 decides its wholesale price (w_H) for product H and pharmaceutical manufacturer 2 decides its wholesale price (w_L) for product L independently and simultaneously. In the third stage, the pharmacy decides its order quantities (q_H and q_L) for product H and product L, respectively.

Thus, the decision process of the MS model can be described as

$$\max_{\gamma} \pi_{ML}(w_L, \gamma) \rightarrow \begin{cases} \max_{w_H} \pi_{MH}(w_H) \\ \max_{w_L} \pi_{ML}(w_L, \gamma) \end{cases} \rightarrow \max_{q_H, q_L} \pi_R(q_H, q_L).$$

3.2.2 Pharmacy Stackelberg (PS) model

In the PS model, the pharmacy is the Stackelberg leader while the pharmaceutical manufacturers are the followers in deciding prices. This type of power structure is applicable when smaller pharmaceutical firms deal with large pharmacy chains like CVS Health in the United States and Boots in the United Kingdom. The decision sequence of the pharmaceutical manufacturers and pharmacy is

as follows. During the first stage, manufacturer 2 decides its quality level (γ) for product L. At the second stage, the pharmacy decides its order quantities (q_H and q_L) for product H and product L, respectively. In the third stage, manufacturer 1 decides its wholesale price (w_H) for product H and manufacturer 2 decides its wholesale price (w_L) for product L independently and simultaneously.

Thus, the process of the PS model can be described as

$$\max_{\gamma} \pi_{ML}(w_L, \gamma) \rightarrow \max_{q_H, q_L} \pi_R(q_H, q_L) \rightarrow \begin{cases} \max_{w_H} \pi_{MH}(w_H) \\ \max_{w_L} \pi_{ML}(w_L, \gamma). \end{cases}$$

3.2.3 Vertical Nash (VN) model

In the VN model, the pharmaceutical manufacturers and pharmacy make their pricing decisions simultaneously. This type of power structure applies to the relationship between large pharmaceutical firms and national pharmacy chains. The decision sequence of the pharmaceutical manufacturers and pharmacy is as follows. During the first stage, manufacturer 2 decides its quality level (γ) for product L. At the second stage, manufacturer 1 decides its wholesale price (w_H) for product H, manufacturer 2 decides its wholesale price (w_L) for product L and the pharmacy decides its order quantities (q_H and q_L) for product H and product L independently and simultaneously.

Thus, the process of the VN model can be described as

$$\max_{\gamma} \pi_{ML}(w_L, \gamma) \rightarrow \begin{cases} \max_{w_H} \pi_{MH}(w_H) \\ \max_{w_L} \pi_{ML}(w_L, \gamma) \\ \max_{q_H, q_L} \pi_R(q_H, q_L). \end{cases}$$

3.3 Quality regulation model

In the quality regulation model, there are regulatory requirements regarding minimum quality standards (β) for pharmaceutical products. This section studies the optimal decisions of pharmaceutical manufacturers and pharmacy under different channel power structures in the quality regulation model. In particular, we build MS, PS and VN models.

3.3.1 Pharmaceutical manufacturer Stackelberg (MS) model

The MS model includes three stages. During the first stage, manufacturer 2 decides on a quality level (γ) for product L considering a minimum quality standard (MQS; β). At the second stage, manufacturer 1 decides its wholesale price (w_H) for product H and manufacturer 2 decides its wholesale price (w_L) for product L independently and simultaneously. In the third stage, the pharmacy

decides its order quantities (q_H and q_L) for product H and product L, respectively.

Thus, the process of the MS model can be described as

$$\begin{array}{l} \max_{\gamma} \pi_{ML}(w_L, \gamma) \\ s. t. \beta \leq \gamma \leq 1 \end{array} \rightarrow \begin{cases} \max_{w_H} \pi_{MH}(w_H) \\ \max_{w_L} \pi_{ML}(w_L, \gamma) \end{cases} \rightarrow \max_{q_H, q_L} \pi_R(q_H, q_L).$$

3.3.2 Pharmacy Stackelberg (PS) model

The PS model features three stages. During the first stage, manufacturer 2 decides on a quality level for product L (γ) considering the MQS (β). At the second stage, the pharmacy decides its order quantities (q_H and q_L) for product H and product L, respectively. In the third stage, manufacturer 1 decides its wholesale price (w_H) for product H and manufacturer 2 decides its wholesale price (w_L) for product L independently and simultaneously.

Thus, the process of the PS model can be described as

$$\begin{array}{l} \max_{\gamma} \pi_{ML}(w_L, \gamma) \\ s. t. \beta \leq \gamma \leq 1 \end{array} \rightarrow \max_{q_H, q_L} \pi_R(q_H, q_L) \rightarrow \begin{cases} \max_{w_H} \pi_{MH}(w_H) \\ \max_{w_L} \pi_{ML}(w_L, \gamma) \end{cases}$$

3.3.3 Vertical Nash (VN) model

The VN model includes two stages. During the first stage, manufacturer 2 decides on a quality level for product L (γ) considering the MQS (β). At the second stage, manufacturer 1 decides its wholesale price (w_H) for product H, manufacturer 2 decides its wholesale price (w_L) for product L and the pharmacy decides its order quantities (q_H and q_L) for product H and product L independently and simultaneously.

Thus, the process of the VN model can be described as

$$\begin{array}{l} \max_{\gamma} \pi_{ML}(w_L, \gamma) \\ s. t. \beta \leq \gamma \leq 1 \end{array} \rightarrow \begin{cases} \max_{w_H} \pi_{MH}(w_H) \\ \max_{w_L} \pi_{ML}(w_L, \gamma) \\ \max_{q_H, q_L} \pi_R(q_H, q_L) \end{cases}$$

The optimal quality (γ) for product L, unit wholesale prices (w_H, w_L) and unit retail prices (p_H, p_L) for products H and L and the pharmacy's optimal order quantities (q_H, q_L) are presented in Table 2. The derivation of these optimal solutions is provided in the appendix.

Table 2. Optimal solutions for six models

Models	γ^{ij}	w_H^{ij}	w_L^{ij}	q_H^{ij}	q_L^{ij}	p_H^{ij}	p_L^{ij}
--------	---------------	------------	------------	------------	------------	------------	------------

MS	NMS ($ij = nm$)	γ_0	$\frac{2(1-\gamma_0)}{4-\gamma_0}$	$\frac{(1-\gamma_0)\gamma_0}{4-\gamma_0}$	$\frac{1}{4-\gamma_0}$	$\frac{1}{8-2\gamma_0}$	$\frac{3(2-\gamma_0)}{2(4-\gamma_0)}$	$\frac{\gamma_0(5-2\gamma_0)}{2(4-\gamma_0)}$
	RMS ($ij = rm$)	β	$\frac{2(1-\beta)}{4-\beta}$	$\frac{(1-\beta)\beta}{4-\beta}$	$\frac{1}{4-\beta}$	$\frac{1}{8-2\beta}$	$\frac{3(2-\beta)}{2(4-\beta)}$	$\frac{\beta(5-2\beta)}{2(4-\beta)}$
PS	NPS ($ij = np$)	γ_1	$\frac{1-\gamma_1}{4-\gamma_1}$	$\frac{(1-\gamma_1)\gamma_1}{2(4-\gamma_1)}$	$\frac{1}{4-\gamma_1}$	$\frac{1}{8-2\gamma_1}$	$\frac{3(2-\gamma_1)}{2(4-\gamma_1)}$	$\frac{\gamma_1(5-2\gamma_1)}{2(4-\gamma_1)}$
	RPS ($ij = rp$)	β	$\frac{1-\beta}{4-\beta}$	$\frac{(1-\beta)\beta}{2(4-\beta)}$	$\frac{1}{4-\beta}$	$\frac{1}{8-2\beta}$	$\frac{3(2-\beta)}{2(4-\beta)}$	$\frac{\beta(5-2\beta)}{2(4-\beta)}$
VN	NVN ($ij = nv$)	γ_2	$\frac{3(1-\gamma_2)}{9-\gamma_2}$	$\frac{(1-\gamma_2)\gamma_2}{9-\gamma_2}$	$\frac{3}{9-\gamma_2}$	$\frac{1}{9-\gamma_2}$	$\frac{2(3-\gamma_2)}{9-\gamma_2}$	$\frac{(5-\gamma_2)\gamma_2}{9-\gamma_2}$
	RVN ($ij = rv$)	β	$\frac{3(1-\beta)}{9-\beta}$	$\frac{(1-\beta)\beta}{9-\beta}$	$\frac{3}{9-\beta}$	$\frac{1}{9-\beta}$	$\frac{2(3-\beta)}{9-\beta}$	$\frac{(5-\beta)\beta}{9-\beta}$

4 Effects of quality regulation

In this section, we discuss the effects of the regulatory requirements of MQS on the pharmaceutical supply chain's operational decisions, profits and social welfare.

4.1 The effect of quality regulations on operational decisions

Regarding the effect of quality regulations on operational decisions of the pharmaceutical supply chain, we present the following lemma.

Lemma 1: (1) If $0 < \alpha < \alpha_1^j$ or $\alpha > \alpha_1^j$ and $\beta_1^j < \beta < 1$, then $w_L^{rj} < w_L^{nj}$; otherwise, $w_L^{rj} > w_L^{nj}$.

(2) $q_H^{rj} > q_H^{nj}$, $q_L^{rj} > q_L^{nj}$.

(3) $p_H^{rj} < p_H^{nj}$, $p_L^{rj} > p_L^{nj}$.

Part (1) of this lemma means that if the level of the MQS is higher than the optimal quality level ($\beta > \gamma^{nj}$) in the unregulated market, the optimal wholesale price of product H will decrease as a consequence of the quality regulations. However, the optimal wholesale price of product L depends on the quality investment cost coefficient and the level of the MQS. More specifically, if the quality investment cost coefficient is lower than one threshold ($\alpha < \alpha_1^j$), or if the quality investment cost coefficient is higher and the level of the MQS is higher ($\alpha > \alpha_1^j$ and $\beta > \beta_1^j$), the optimal wholesale price of product L will decrease under the quality regulations. In contrast, the optimal wholesale price of product L will increase under the regulation. This can be explained by the fact that the MQS results

in higher quality for product L. When the quality investment cost coefficient is lower, pharmaceutical manufacturer 2 invests in quality to improve the quality level of product L. With less product differentiation, the price competition between pharmaceutical manufacturers 1 and 2 intensifies, which leads to a reduction of the wholesale prices for products H and L. Meanwhile, as the quality investment cost coefficient and the MQS increase, the heterogeneity between product H and product L diminishes. Consequently, there is an intensification of market competition, which leads to a decrease in the wholesale prices for products H and L. However, where the quality investment cost coefficient is high and the MQS is low, manufacturer 2 will charge a higher wholesale price to maximise its own profit. Part (2) of the lemma indicates that the order quantities of products H and L rise under the quality regulations, and part (3) of this lemma shows that the optimal retail price of product H decreases whereas the optimal retail price of product L increases under the regulations. This result is contrary to the finding of Nagurney et al. (2014) that both the average quality and prices increase with the market demand after the imposition of minimum quality standards. Intuitively, the quality regulations for pharmaceutical products will force pharmaceutical manufacturers, particularly those with lower quality standards, to invest in improving their product quality to meet regulatory requirements. The improved quality levels will boost customer demand and pharmaceutical firms will also raise retail prices to pass on quality improvement costs to consumers. While the MQS does not have much impact on the quality level of products made by manufacturers with high quality standards, intensified market competition (owing to an improved quality level in competitors' products) will force them to reduce their retail prices. Consequently, the demand for their pharmaceutical products will also rise under the quality regulations.

4.2 The effect of quality regulations on profits

Now, we examine the effect of quality regulations on the economic performance of the pharmaceutical supply chain, and derive the following proposition.

Proposition 1: (1) $\pi_{MH}^{rj}(w_H) < \pi_{MH}^{nj}(w_H)$, $\pi_{ML}^{rj}(w_L, \gamma) < \pi_{ML}^{nj}(w_L, \gamma)$, $\pi_R^{rj}(q_H, q_L) > \pi_R^{nj}(q_H, q_L)$.

(2) If $0 < \alpha < \alpha_2^j$ or $\alpha > \alpha_2^j$ and $\gamma^{nj} < \beta < \beta_2^j$, then $\pi^{rj} > \pi^{nj}$. Otherwise, $\pi^{rj} < \pi^{nj}$.

Part (1) of the proposition indicates that under the quality regulations, the profits of

pharmaceutical manufacturers 1 and 2 will decrease, while the pharmacy's profit will always increase. The quality regulations require manufacturer 2 to enhance the quality of product L. As a result, the quality regulation intensifies market competition based on the diminished quality differentiation between products H and L. The intensified market competition will force the two pharmaceutical manufacturers to engage in fierce price competition in order to win customer demand, impacting their profits negatively. However, the pharmacy will benefit from the intensified market competition between the pharmaceutical manufacturers. As illustrated in Lemma 1, the demand for both products H and L increases under the quality regulations, and this contributes to a profit increase for the pharmacy.

Part (2) of the proposition refers to how the quality regulations will have a negative impact on the pharmaceutical supply chain's economic performance in general. The total profit of the whole pharmaceutical supply chain will only rise under the quality regulations when the quality investment cost coefficient and the level of the MQS meet certain conditions specified in Proposition 1. Intuitively, manufacturer 2 has an obligation under the regulations to invest in quality to meet the MQS. Although the improved quality level of product L will increase its demand, improved quality also intensifies market competition based on diminishing product differentiation between the two pharmaceutical manufacturers, thereby damaging profitability of pharmaceutical manufacturers. The quality regulation will only have a positive impact on the total profit of the pharmaceutical supply chain if the quality investment cost coefficient is lower than one threshold ($\alpha < \alpha_2^j$), or if the quality investment cost coefficient is higher yet the levels of the MQS are lower ($\alpha > \alpha_2^j$ and $\beta < \beta_2^j$). In the first case, manufacturer 2 does not have much incentive to improve the quality beyond the level specified by the MQS. In the second case, it also requires major investment from manufacturer 2 to bridge the gap between the quality levels specified by the MQS and product H. Under these conditions, there is sufficient quality differentiation between products H and L to avoid a fierce price competition between the two manufacturers. Therefore, regulatory requirements for the MQS have a significant impact on the performance of the pharmaceutical supply chain.

4.3 The effect of quality regulations on social welfare

In light of growing concern on sustainability, it is important for policy makers to consider both

economic and social factors in the development of quality regulations for pharmaceutical products. Therefore, we analyse the effect of quality regulations on social welfare, and propose the following.

Proposition 2: *If $0 < \alpha < \alpha_3^j$ or $\alpha > \alpha_3^j$ and $\gamma^{nj} < \beta < \beta_3^j$, then $W_s^{rj} > W_s^{nj}$. Otherwise, $W_s^{rj} < W_s^{nj}$.*

This proposition shows whether the quality regulations have a positive or negative impact on social welfare as determined by the quality investment cost coefficient and level of MQS. Such a proposition is consistent with the fact that social welfare consists of the patient surplus and pharmaceutical supply chain's profit. The patient surplus is dependent on retail prices and quality levels of products H and L. As shown in Lemma 1, the retail price of product H decreases under the quality regulations, and manufacturer 2 increases the retail price of product L because of higher quality levels. As discussed in Proposition 1, the impact of the quality regulations on supply chain profit is determined by the quality investment cost coefficient and the level of the MQS. Combining these factors, the social welfare will rise under the quality regulations if the quality investment cost coefficient is lower than one threshold ($\alpha < \alpha_3^j$), or if the quality investment cost coefficient is higher and the levels of the MQS are lower ($\alpha > \alpha_3^j$ and $\beta < \beta_3^j$). Otherwise, the quality regulations will harm social welfare.

Based on Propositions 1 and 2, we have the following proposition.

Proposition 3: *If $0 < \alpha < \alpha_2^j$ or $\alpha > \alpha_2^j$ and $\gamma^{nj} < \beta < \beta_2^j$, then $\pi^{rj} > \pi^{nj}$ and $W_s^{rj} > W_s^{nj}$.*

This means that quality regulation can enhance the profit and social welfare of the pharmaceutical supply chain under certain conditions specified in Proposition 3. For more clarity, we illustrate Propositions 2 and 3 in Figure 2. In region I, the whole pharmaceutical supply chain will be worse off financially under the quality regulations, despite an improvement in social welfare. In region II, both the economic performance and social welfare of the pharmaceutical supply chain will be enhanced under the quality regulations. Hence, in this case, the supply chain and government can achieve a win-win outcome. Meanwhile, the pharmacy and pharmaceutical manufacturers can achieve Pareto improvement through coordination mechanisms, such as revenue-sharing or cost-

sharing contracts. Therefore, from the government's perspective, a proper range of MQS can be designed to improve social welfare as well as to ensure the profitability of pharmaceutical firms.

Figure 2. Quality regulation strategy

4.4 Revenue-sharing contract

Based on region II in Figure 2, we hypothesise that the economic performance of the pharmaceutical supply chain will be enhanced under the quality regulations. However, to ensure that the pharmacy and pharmaceutical manufacturers achieve Pareto improvement, coordination mechanisms are necessary. A revenue-sharing contract is a common coordination mechanism in supply chains (Cachon and Lariviere 2005; Raza 2018). We assume that the pharmacy shares a part of the revenue gained from sales of product H ($\theta_H p_H q_H$) with pharmaceutical manufacturer 1 and a part of the revenue gained from sales of product L ($\theta_L p_L q_L$) with pharmaceutical manufacturer 2. θ_H ($0 < \theta_H < 1$) and θ_L ($0 < \theta_L < 1$) represent these two revenue-sharing ratios respectively. To coordinate the pharmaceutical supply chain through the revenue-sharing contract, the following proposition is obtained.

Proposition 4: *Through a revenue-sharing contract, the pharmaceutical supply chain can achieve Pareto improvement with $\theta_H^m = \frac{4(\beta-\gamma_0)[8+\beta+(1-\beta)\gamma_0]}{3(2-\beta)(4-\gamma_0)^2}$ and $\theta_L^m = \frac{-2F_2(\beta)}{\beta(5-2\beta)(4-\gamma_0)^2}$ in the MS power structure, $\theta_H^p = \frac{2(\beta-\gamma_1)[8+\beta+(1-\beta)\gamma_1]}{3(2-\beta)(4-\gamma_1)^2}$ and $\theta_L^p = \frac{-F_6(\beta)}{\beta(5-2\beta)(4-\gamma_1)^2}$ in the PS power structure and $\theta_H^v = \frac{3(\beta-\gamma_2)[63+\beta+(1-\beta)\gamma_2]}{2(3-\beta)(9-\gamma_2)^2}$ and $\theta_L^v = \frac{-F_9(\beta)}{2\beta(5-\beta)(9-\gamma_2)^2}$ in the VN power structure.*

Proposition 4 indicates that, through the revenue-sharing contract, the profits of pharmaceutical

manufacturers 1 and 2 and the pharmacy can be increased under the quality regulation, which means the pharmaceutical supply chain can achieve Pareto improvement. In addition, the optimal revenue-sharing ratios are influenced by the supply chain power structure. Under the quality regulation, pharmaceutical manufacturers will suffer profit reduction, which consequently decreases pharmaceutical manufacturers' incentive to supply these regulated drugs. More seriously, if the pharmaceutical manufacturers cannot bear the loss imposed by the quality regulation, there is a risk of supply shortage for the regulated drugs. Therefore, to avoid shortages, the pharmacy may redistribute its revenue to pharmaceutical manufacturers to compensate them and ensure the supply of drugs. Revenue-sharing contracts can protect the essential economic benefit of pharmaceutical firms, therefore mitigating the risk of policy failure and improving the sustainability of the pharmaceutical sector.

5 Effects of the supply chain power structure

Owing to the importance of power relationships in supply chain research (Shi et al. 2013; Chen and Wang et al. 2015; Chen et al. 2017), here, we analyse the effects of the supply chain power structure on supply chain decisions, profits and social welfare.

5.1 The effect of supply chain power structure on decisions

Regarding the effect of supply chain power structure on pharmaceutical firms' operational decisions, we derive the following lemma.

Lemma 2: *For the base model, (1) $\gamma^{nm} > \gamma^{np} > \gamma^{nv}$. (2) $w_H^{nm} > w_H^{nv} > w_H^{np}$, $w_L^{nm} > w_L^{np} > w_L^{nv}$. (3) $q_H^{nv} > q_H^{nm} > q_H^{np}$, $q_L^{nm} > q_L^{np} > q_L^{nv}$. (4) $p_H^{np} > p_H^{nm} > p_H^{nv}$, $p_L^{nm} > p_L^{np} > p_L^{nv}$.*

For the quality regulation model, (1) $\gamma^{rm} = \gamma^{rp} = \gamma^{rv}$. (2) $w_H^{rm} > w_H^{rv} > w_H^{rp}$, $w_L^{rm} > w_L^{rp} > w_L^{rv}$. (3) $q_H^{rv} > q_H^{rm} = q_H^{rp}$, $q_L^{rm} = q_L^{rp} > q_L^{rv}$. (4) $p_H^{rm} = p_H^{rp} > p_H^{rv}$, $p_L^{rm} = p_L^{rp} > p_L^{rv}$.

The first part of Lemma 2 shows that in the base model, the optimal quality level of product L is highest when pharmaceutical manufacturers have dominant power over the pharmacy. Meanwhile, the wholesale and retail prices are also highest while the demand for Product L is greatest. In contrast, although the wholesale price for product H is also highest in the manufacturer-dominated power structure, the demand for product H is lower than that in the balanced power structure, whereas the

retail price of product H is lower than that in the pharmacy-dominated power structure. This is consistent with previous studies whereby pharmaceutical manufacturers can set higher wholesale prices when they have dominant power in the supply chain and the balanced power structure leads to the lowest retail prices for both products (Shi et al. 2013; Chen and Wang 2015). However, the high wholesale prices do not necessarily translate into higher retailer prices for product H, as product differentiation and market competition have more of an influence in this case.

The second part of Lemma 2 indicates that in the quality regulation model, the optimal quality level of product L is the same under three different power structures based on the MQS. The difference in the wholesale prices of products H and L follows the same order as compared to the base model. Interestingly, the retail prices and product demand of products H and L, respectively, are the same when there is an imbalanced supply chain power structure. In addition, the intense competition in a balanced power structure results in lower retail prices for product H, which is beneficial for customers and in turn triggers increased product demand. As in the case of the base model, the retail prices of both products are lowest and the demand for product H is highest. Again, an exception is the demand for product L, which is lowest in the Vertical Nash model, as product quality levels play a role in such a scenario.

5.2 The effect of supply chain power structure on profits

Regarding the effect of supply chain structure on individual and collective performances of pharmaceutical firms, we propose the following proposition.

Proposition 5: *For the base model, (1) $\pi_{MH}^{nm}(w_H) > \pi_{MH}^{nv}(w_H) > \pi_{MH}^{np}(w_H)$, $\pi_{ML}^{nm}(w_L, \gamma) > \pi_{ML}^{np}(w_L, \gamma) > \pi_{ML}^{nv}(w_L, \gamma)$. (2) $\pi_R^{np}(q_H, q_L) > \pi_R^{nv}(q_H, q_L) > \pi_R^{nm}(q_H, q_L)$. (3) $\pi^{nv} > \pi^{nm} > \pi^{np}$.*

For the quality regulation model, (1) $\pi_{MH}^{rm}(w_H) > \pi_{MH}^{rv}(w_H) > \pi_{MH}^{rp}(w_H)$, $\pi_{ML}^{rm}(w_L, \gamma) > \pi_{ML}^{rp}(w_L, \gamma) > \pi_{ML}^{rv}(w_L, \gamma)$. (2) $\pi_R^{rp}(q_H, q_L) > \pi_R^{rv}(q_H, q_L) > \pi_R^{rm}(q_H, q_L)$. (3) $\pi^{rv} > \pi^{rm} = \pi^{rp}$.

According to Proposition 5, the supply chain power structure has the same effect on the individual economic performance of the pharmaceutical manufacturers as it does on the pharmacy. Manufacturer 1 and the pharmacy can gain the most profit when they have dominant power in the supply chain. This is then followed by a balanced power structure. Intuitively, the economic

performance of each member in the supply chain is at its worst when that member has less power in the chain. These findings are in line with previous studies on supply chain power relationships (Shi et al. 2013; Chen and Wang 2015; Chen et al. 2017). Although pharmaceutical manufacturer 2, as expected, performs best financially when manufacturers are the dominant players in the supply chain, the balanced power structure delivers worse economic performance than the PS model. This can be explained by the fact that a balanced power structure often intensifies competition, which can have a negative impact on pharmaceutical manufacturers, as discussed in Proposition 2. Despite a negative effect of intensified market competition on the profit of manufacturer 2, the balanced power structure will lead to improved performance of the pharmaceutical supply chain overall. One difference between the effects of the two models' supply chain power structures is that the two imbalanced power structures produce the same results under the quality regulations, whereas the pharmaceutical manufacturer-dominated supply chain produces better collective performance than that of a pharmacy-dominated supply chain.

5.3 The effect of supply chain power structure on social welfare

Regarding the effect of supply chain structure on social welfare, we derive the following proposition.

Proposition 6: *In the model, $W_s^{nv} > W_s^{nm} > W_s^{np}$.*

In the quality regulation model, $W_s^{rv} > W_s^{rm} = W_s^{rp}$.

According to Proposition 6m the effect of the supply chain power structure on social welfare is similar to its effect on the total profit of the entire pharmaceutical supply chain. This applies to both the base model and quality regulation model. The reason is that both the supply chain profit and patient surplus contribute to social welfare. A balanced supply chain power structure will raise the collective profit of the pharmaceutical supply chain, meanwhile benefitting consumers because of lower retail prices.

6 Numerical analysis

In this section, numerical examples are provided to analyse how the model performances are affected by some parameters. First, sensitivity analysis is provided to examine the effect of minimum quality standards (β) on manufacturer 1's profit, manufacturer 2's profit, the pharmacy's profit and the supply chain's profit under different channel power structures and under the quality regulation model. We

specify that $\alpha = 0.01$, then derive the profits of the two manufacturers and pharmacy as shown in Figures 3-5.

Figure 3. Effect of Minimum quality standards (β) on manufacturer 1's profit

Figure 4. Effect of Minimum quality standards (β) on manufacturer 2's profit

Figure 5. Effect of Minimum quality standards (β) on pharmacy's profit

According to Figures 3-5, if the level of the MQS is higher than the optimal quality level in the

unregulated market, the profits of pharmaceutical manufacturers 1 and 2 will decrease while the pharmacy's profit will always increase. In addition, manufacturer 1 and the pharmacy can gain the most profit when they have dominant power in the supply chain. A symmetrical power structure provides the second highest profits for manufacturer 1 and the pharmacy. . Intuitively, they have the worst economic performance when they have less power in the supply chain. Manufacturer 2 stands to gain the most profit in a situation where manufacturers are the dominant players in the supply chain, and interestingly, its economic performance is worse in the symmetrical power structure than that in the PS model.

Now we specify that $\alpha = 0.01$ ($0 < \alpha < \alpha_2^j$) and $\alpha = 0.12$ ($\alpha > \alpha_2^j$), then derive the total supply chain profit as shown in Figures 6-7. The analysis results indicate that the effect of minimum quality standards (β) on the supply chain profit is related to the quality investment cost coefficient (α). If the quality investment cost coefficient is low, the supply chain profit will increase. The implication is clear. A low cost of quality improvement will certainly bring economic benefit to the supply chain. Besides, a symmetric power structure results in the best economic performance for the supply chain, which is in line with the findings of the existing literature on supply chain power relationships (Shi et al. 2013; Chen and Wang 2015; Chen et al. 2017).

Figure 6. Effect of Minimum quality standards (β) on supply chain's profit ($0 < \alpha < \alpha_2^j$)

Figure 7. Effect of Minimum quality standards (β) on supply chain's profit ($\alpha > \alpha_2^j$)

7 Conclusions and suggestions for future research

In this paper, we studied a two-echelon pharmaceutical supply chain consisting of two pharmaceutical manufacturers and a pharmacy. Customers were heterogeneous in their valuation of two products produced by manufacturers 1 and 2. Based on consumers' net utility, we segmented the market and derived demand functions for products H and L, respectively. Through the comparison of equilibriums of the base model and quality regulation model under three different supply chain power structures, we analysed the effects of the quality regulation and supply chain power relationships on optimal operational decisions, individual and collective economic performance, and social welfare. The main findings were as follows.

Under the quality regulations, the retail price of product H will always decrease and the retail price of product L will increase because of the improved quality level, which is beneficial to consumers and consequently triggers demand increases for both products. However, with diminishing product differentiation, the competition between the two pharmaceutical manufacturers intensifies. This has a negative effect on the two manufacturers' profits but a positive effect on the pharmacy's profit. Nevertheless, the pharmaceutical supply chain's total profit and social welfare can improve simultaneously if the quality regulations can be appropriately designed. This means that a proper range of MQS can deliver a win-win outcome for both the pharmaceutical supply chain and society. Meanwhile, the pharmacy and the pharmaceutical manufacturers can achieve Pareto improvement

through coordination mechanisms, such as revenue-sharing or cost-sharing contracts.

Moreover, supply chain power relationships have a great influence on the operational decisions, profits and social welfare of the pharmaceutical supply chain. A balanced supply chain power structure often intensifies the competition, which leads to relatively lower retail prices than would be the case in imbalanced power structures, whether or not there is quality regulation. Pharmaceutical manufacturer 1 and the pharmacy will gain the most profits when they hold dominant power in the supply chain and gain the fewest profits when they have less power, which is consistent with the existing literature (Shi et al. 2013; Chen and Wang 2015; Chen et al. 2017). However, this is not the case for pharmaceutical manufacturer 2, which will perform better when it has less power than it would have within the balanced power structure. In this case, power structure and/or diminishing product differentiation intensifies competition, which negatively affects the profit of manufacturer 2. In contrast, a balanced power structure creates positive impacts, both in terms of the total profit of the pharmaceutical supply chain and social welfare.

This research has certain limitations, the approach to which may lead to several future research directions. First, this study adopted a linear-inverse demand function. Although this form of deterministic demand function has the advantage of being analytically tractable and is widely used in the existing literature (Chen et al. 2016), one future extension would be to employ a stochastic demand function in order to assess how the research findings might be affected by different demand functions. Second, to simplify the calculations, we adopted the assumption that the marginal cost of products H and L is 0. In practice, pharmaceutical manufacturers could incur different marginal costs. Thus, one future extension would be to consider this additional cost factor and evaluate how different marginal costs would affect the research findings. In addition, our model analyses a supply chain structure with two competing pharmaceutical manufacturers and one common pharmacy. As the effects of the quality regulations on the pharmaceutical supply chain's decisions and performances are significantly influenced by an intensified competition between the two manufacturers, one important future extension would be to consider a scenario featuring multiple pharmaceutical manufacturers and multiple pharmacies (Choi 1996). Finally, this research focuses mainly on the economic and social aspects of the pharmaceutical supply chain. One valuable future extension would be to incorporate environmental impact into the evaluation of sustainability performance. This would require

embedding environmental aspects in the modelling, and would certainly contribute to developing a more sustainable pharmaceutical supply chain.

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Appendix

Proof of Table 2

No quality regulation model

MS model

From formula (6), we get that $\frac{\partial \pi_R(q_H, q_L)}{\partial q_H} = 1 - 2q_H - 2\gamma q_L - w_H$ and $\frac{\partial \pi_R(q_H, q_L)}{\partial q_L} = \gamma - 2\gamma q_H - 2\gamma q_L - w_L$.

Then $\frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H^2} = -2 < 0$, $\frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L^2} = -2\gamma$ and $\frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H \partial q_L} = \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L \partial q_H} = -2\gamma$. So the Hessian matrix is

$$\begin{vmatrix} \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H^2} & \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H \partial q_L} \\ \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L \partial q_H} & \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L^2} \end{vmatrix} = 4(1 - \gamma)\gamma > 0. \text{ Then } \pi_R(q_H, q_L) \text{ is jointly concave in } q_H \text{ and } q_L. \text{ Set } \frac{\partial \pi_R(q_H, q_L)}{\partial q_H} =$$

$\frac{\partial \pi_R(q_H, q_L)}{\partial q_L} = 0$, we get $q_H = \frac{-1 + \gamma + w_H - w_L}{2(-1 + \gamma)}$ and $q_L = \frac{\gamma w_H - w_L}{2\gamma - 2\gamma^2}$. Replace q_H and q_L into formula (4) and (5), we get

that $\frac{d\pi_{MH}(w_H)}{dw_H} = \frac{1 - \gamma - 2w_H + w_L}{2 - 2\gamma}$ and $\frac{d\pi_{ML}(w_L, \gamma)}{dw_L} = \frac{\gamma w_H - 2w_L}{2\gamma - 2\gamma^2}$. Then, $\frac{d^2 \pi_{MH}(w_H)}{d(w_H)^2} = \frac{1}{-1 + \gamma} < 0$ and $\frac{d^2 \pi_{ML}(w_L, \gamma)}{d(w_L)^2} =$

$\frac{1}{(-1 + \gamma)\gamma} < 0$. Then $\pi_{MH}(w_H)$ is concave in w_H and $\pi_{ML}(w_L, \gamma)$ is concave in w_L . Set $\frac{d\pi_{MH}(w_H)}{dw_H} = \frac{d\pi_{ML}(w_L, \gamma)}{dw_L} =$

0, we get $w_H = \frac{2 - 2\gamma}{4 - \gamma}$ and $w_L = \frac{(1 - \gamma)\gamma}{4 - \gamma}$. Replace w_H and w_L into formula (5), we get $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} =$

$\frac{-4 + (7 + 128\alpha)\gamma - 96\alpha\gamma^2 + 24\alpha\gamma^3 - 2\alpha\gamma^4}{2(-4 + \gamma)^3}$ and $\frac{d^2 \pi_{ML}(w_L, \gamma)}{d\gamma^2} = -\frac{8 + \alpha(-4 + \gamma)^4 + 7\gamma}{(-4 + \gamma)^4} < 0$. Then $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma}$ decreases in γ and

$\pi_{ML}(w_L, \gamma)$ is concave in γ . Set $\gamma = 0$, we get $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{1}{32} > 0$. Set $\gamma = 1$, we get $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = -\frac{1}{18} - \alpha <$

0. Therefore, there exists unique $\gamma = \gamma_0$, which makes $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = 0$. Set $h = -4 + (7 + 128\alpha)\gamma_0 - 96\alpha\gamma_0^2 +$

$24\alpha\gamma_0^3 - 2\alpha\gamma_0^4$, we get $h = 0$. Replace γ into w_H , w_L , q_H and q_L , we get $w_H = \frac{2(1 - \gamma_0)}{4 - \gamma_0}$, $w_L = \frac{(1 - \gamma_0)\gamma_0}{4 - \gamma_0}$, $q_H =$

$\frac{1}{4 - \gamma_0}$ and $q_L = \frac{1}{8 - 2\gamma_0}$. Replace γ , q_H and q_L into formula (2) and (3), we get $p_H = \frac{3(2 - \gamma_0)}{2(4 - \gamma_0)}$ and $p_L = \frac{\gamma_0(5 - 2\gamma_0)}{2(4 - \gamma_0)}$.

PS model

From formula (2) and (3), we get $q_H = 1 - \frac{p_H - p_L}{1 - \gamma}$ and $q_L = \frac{p_H - p_L}{1 - \gamma} - \frac{p_L}{\gamma}$. Set $p_H = w_H + m$ and $p_L = w_L + n$,

we get $q_H = 1 - \frac{w_H + m - w_L - n}{1 - \gamma}$ and $q_L = \frac{w_H + m - w_L - n}{1 - \gamma} - \frac{w_L + n}{\gamma}$. Replace q_H and q_L into formula (4) and (5), we

get $\frac{d\pi_{MH}(w_H)}{dw_H} = \frac{-1 + m - n + \gamma + 2w_H - w_L}{-1 + \gamma}$, $\frac{d\pi_{ML}(w_L, \gamma)}{dw_L} = \frac{n - m\gamma - \gamma w_H + 2w_L}{(-1 + \gamma)\gamma}$. Then $\frac{d^2 \pi_{MH}(w_H)}{d(w_H)^2} = \frac{2}{-1 + \gamma} < 0$, $\frac{d^2 \pi_{ML}(w_L, \gamma)}{d(w_L)^2} =$

$\frac{2}{(-1 + \gamma)\gamma} < 0$. Then $\pi_{MH}(w_H)$ is concave in w_H and $\pi_{ML}(w_L, \gamma)$ is concave in w_L . Set $\frac{d\pi_{MH}(w_H)}{dw_H} = \frac{d\pi_{ML}(w_L, \gamma)}{dw_L} =$

0, we get $w_H = (1 - \gamma)q_H$ and $w_L = (1 - \gamma)\gamma q_L$. Replace w_H and w_L into formula (6), we get $\frac{\partial \pi_R(q_H, q_L)}{\partial q_H} =$

$1 + 2(-2 + \gamma)q_H - 2\gamma q_L$ and $\frac{\partial \pi_R(q_H, q_L)}{\partial q_L} = \gamma(1 - 2q_H + 2(-2 + \gamma)q_L)$. Then $\frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H^2} = 2(-2 + \gamma) < 0$,

$\frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L^2} = 2(-2 + \gamma)\gamma$ and $\frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H \partial q_L} = \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L \partial q_H} = -2\gamma$. So the Hessian matrix is

$$\begin{vmatrix} \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H^2} & \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H \partial q_L} \\ \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L \partial q_H} & \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L^2} \end{vmatrix} = 4\gamma(4 - 5\gamma + \gamma^2) > 0. \text{ Then } \pi_R(q_H, q_L) \text{ is jointly concave in } q_H \text{ and } q_L. \text{ Set}$$

$$\frac{\partial \pi_R(q_H, q_L)}{\partial q_H} = \frac{\partial \pi_R(q_H, q_L)}{\partial q_L} = 0, \text{ we get } q_H = \frac{1}{4-\gamma} \text{ and } q_L = \frac{1}{8-2\gamma}. \text{ Then } w_H = \frac{1-\gamma}{4-\gamma} \text{ and } w_L = \frac{(1-\gamma)\gamma}{2(4-\gamma)}. \text{ Replace}$$

$$w_H, w_L, q_H \text{ and } q_L \text{ into formula (5), we get } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{-4+(7+256\alpha)\gamma-192\alpha\gamma^2+48\alpha\gamma^3-4\alpha\gamma^4}{4(-4+\gamma)^3} \text{ and } \frac{d^2\pi_{ML}(w_L, \gamma)}{d\gamma^2} =$$

$$-\frac{8+2\alpha(-4+\gamma)^4+7\gamma}{2(-4+\gamma)^4} < 0. \text{ Then } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} \text{ decreases in } \gamma \text{ and } \pi_{ML}(w_L, \gamma) \text{ is concave in } \gamma. \text{ Set } \gamma = 0, \text{ we get}$$

$$\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{1}{64} > 0. \text{ Set } \gamma = 1, \text{ we get } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = -\frac{1}{36} - \alpha < 0. \text{ Therefore, there exists unique } \gamma = \gamma_1, \text{ which}$$

$$\text{makes } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = 0. \text{ Set } e = -4 + (7 + 256\alpha)\gamma_1 - 192\alpha\gamma_1^2 + 48\alpha\gamma_1^3 - 4\alpha\gamma_1^4, \text{ we get } e = 0. \text{ Replace } \gamma$$

$$\text{into } w_H, w_L, q_H \text{ and } q_L, \text{ we get } w_H = \frac{1-\gamma_1}{4-\gamma_1}, w_L = \frac{(1-\gamma_1)\gamma_1}{2(4-\gamma_1)}, q_H = \frac{1}{4-\gamma_1} \text{ and } q_L = \frac{1}{8-2\gamma_1}. \text{ Replace } \gamma, q_H \text{ and}$$

$$q_L \text{ into formula (2) and (3), we get } p_H = \frac{3(2-\gamma_1)}{2(4-\gamma_1)} \text{ and } p_L = \frac{\gamma_1(5-2\gamma_1)}{2(4-\gamma_1)}.$$

VN model

$$\text{From formula (2) and (3), we get } q_H = 1 - \frac{p_H - p_L}{1-\gamma} \text{ and } q_L = \frac{p_H - p_L}{1-\gamma} - \frac{p_L}{\gamma}. \text{ Set } p_H = w_H + m \text{ and } p_L = w_L + n,$$

$$\text{we get } q_H = 1 - \frac{w_H + m - w_L - n}{1-\gamma} \text{ and } q_L = \frac{w_H + m - w_L - n}{1-\gamma} - \frac{w_L + n}{\gamma}. \text{ Replace } q_H \text{ and } q_L \text{ into formula (4) and (5), we}$$

$$\text{get } \frac{d\pi_{MH}(w_H)}{dw_H} = \frac{-1+m-n+\gamma+2w_H-w_L}{-1+\gamma}, \frac{d\pi_{ML}(w_L, \gamma)}{dw_L} = \frac{n-m\gamma-\gamma w_H+2w_L}{(-1+\gamma)\gamma}. \text{ Then } \frac{d^2\pi_{MH}(w_H)}{d(w_H)^2} = \frac{2}{-1+\gamma} < 0, \frac{d^2\pi_{ML}(w_L, \gamma)}{d(w_L)^2} =$$

$$\frac{2}{(-1+\gamma)\gamma} < 0. \text{ Then } \pi_{MH}(w_H) \text{ is concave in } w_H \text{ and } \pi_{ML}(w_L, \gamma) \text{ is concave in } w_L. \text{ From formula (6), we get that}$$

$$\frac{\partial \pi_R(q_H, q_L)}{\partial q_H} = 1 - 2q_H - 2\gamma q_L - w_H \text{ and } \frac{\partial \pi_R(q_H, q_L)}{\partial q_L} = \gamma - 2\gamma q_H - 2\gamma q_L - w_L. \text{ Then } \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H^2} = -2 < 0,$$

$$\frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L^2} = -2\gamma \text{ and } \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H \partial q_L} = \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L \partial q_H} = -2\gamma. \text{ So the Hessian matrix is } \begin{vmatrix} \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H^2} & \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_H \partial q_L} \\ \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L \partial q_H} & \frac{\partial^2 \pi_R(q_H, q_L)}{\partial q_L^2} \end{vmatrix} =$$

$$4(1-\gamma)\gamma > 0. \text{ Then } \pi_R(q_H, q_L) \text{ is jointly concave in } q_H \text{ and } q_L. \text{ Set } \frac{d\pi_{MH}(w_H)}{dw_H} = \frac{d\pi_{ML}(w_L, \gamma)}{dw_L} = \frac{\partial \pi_R(q_H, q_L)}{\partial q_H} =$$

$$\frac{\partial \pi_R(q_H, q_L)}{\partial q_L}, \text{ we get } w_H = \frac{3(-1+\gamma)}{-9+\gamma}, w_L = \frac{(-1+\gamma)\gamma}{-9+\gamma}, q_H = -\frac{3}{-9+\gamma} \text{ and } q_L = \frac{1}{9-\gamma}. \text{ Replace } w_H, w_L, q_H \text{ and } q_L \text{ into}$$

$$\text{formula (5), we get } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{-9+(17+729\alpha)\gamma-243\alpha\gamma^2+27\alpha\gamma^3-\alpha\gamma^4}{(-9+\gamma)^3} \text{ and } \frac{d^2\pi_{ML}(w_L, \gamma)}{d\gamma^2} = -\alpha - \frac{2(63+17\gamma)}{(-9+\gamma)^4} < 0. \text{ Then}$$

$$\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} \text{ decreases in } \gamma \text{ and } \pi_{ML}(w_L, \gamma) \text{ is concave in } \gamma. \text{ Set } \gamma = 0, \text{ we get } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{1}{81} > 0. \text{ Set } \gamma = 1,$$

$$\text{we get } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = -\frac{1}{64} - \alpha < 0. \text{ Therefore, there exists unique } \gamma = \gamma_2, \text{ which makes } \frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = 0. \text{ Set } k =$$

$$-9 + (17 + 729\alpha)\gamma - 243\alpha\gamma^2 + 27\alpha\gamma^3 - \alpha\gamma^4, \text{ we get } k = 0. \text{ Replace } \gamma \text{ into } w_H, w_L, q_H \text{ and } q_L, \text{ we get}$$

$$w_H = \frac{3(1-\gamma_2)}{9-\gamma_2}, w_L = \frac{(1-\gamma_2)\gamma_2}{9-\gamma_2}, q_H = \frac{3}{9-\gamma_2} \text{ and } q_L = \frac{1}{9-\gamma_2}. \text{ Replace } \gamma, q_H \text{ and } q_L \text{ into formula (2) and (3), we get}$$

$$p_H = \frac{2(3-\gamma_2)}{9-\gamma_2} \text{ and } p_L = \frac{(5-\gamma_2)\gamma_2}{9-\gamma_2}.$$

Quality regulation model

MS model

Similarly to no quality regulation model, we get the values of w_H , w_L , q_H and q_L . Considering the minimum quality standards (MQS) for medicines, we get $\gamma = \beta$. Replace γ into w_H , w_L , q_H and q_L , we get $w_H = \frac{2(1-\beta)}{4-\beta}$, $w_L = \frac{(1-\beta)\beta}{4-\beta}$, $q_H = \frac{1}{4-\beta}$ and $q_L = \frac{1}{8-2\beta}$. Replace γ , q_H and q_L into formula (2) and (3), we get $p_H = \frac{3(2-\beta)}{2(4-\beta)}$ and $p_L = \frac{\beta(5-2\beta)}{2(4-\beta)}$.

PS model

Similarly to no quality regulation model, we get the values of w_H , w_L , q_H and q_L . Considering the minimum quality standards (MQS) for medicines, we get $\gamma = \beta$. Replace γ into w_H , w_L , q_H and q_L , we get $w_H = \frac{1-\beta}{4-\beta}$, $w_L = \frac{(1-\beta)\beta}{2(4-\beta)}$, $q_H = \frac{1}{4-\beta}$ and $q_L = \frac{1}{8-2\beta}$. Replace γ , q_H and q_L into formula (2) and (3), we get $p_H = \frac{3(2-\beta)}{2(4-\beta)}$ and $p_L = \frac{\beta(5-2\beta)}{2(4-\beta)}$.

VN model

Similarly to no quality regulation model, we get the values of w_H , w_L , q_H and q_L . Considering the minimum quality standards (MQS) for medicines, we get $\gamma = \beta$. Replace γ into w_H , w_L , q_H and q_L , we get $w_H = \frac{3(1-\beta)}{9-\beta}$, $w_L = \frac{(1-\beta)\beta}{9-\beta}$, $q_H = \frac{3}{9-\beta}$ and $q_L = \frac{1}{9-\beta}$. Replace γ , q_H and q_L into formula (2) and (3), we get $p_H = \frac{2(3-\beta)}{9-\beta}$ and $p_L = \frac{(5-\beta)\beta}{9-\beta}$.

Proof of Lemma 1

MS model

(1) For unit wholesale price of product H, we get $w_H^r - w_H^n = \frac{6(\beta-\gamma_0)}{(4-\beta)(-4+\gamma_0)} < 0$, so $w_H^r < w_H^n$.

For unit wholesale price of product L, we get $w_L^r - w_L^n = \frac{1}{(4-\beta)(4-\gamma_0)} [\beta^2(-4+\gamma_0) - 4\gamma_0 + 4\gamma_0^2 + \beta(4-\gamma_0^2)]$. Set $L_1(\beta) = \beta^2(-4+\gamma_0) - 4\gamma_0 + 4\gamma_0^2 + \beta(4-\gamma_0^2)$, $L_1(\beta)$ is concave in β . Set $L_1(\beta) = 0$, we get $\beta_{11} = \frac{4(1-\gamma_0)}{4-\gamma_0}$ and $\beta_{12} = \gamma_0$. we should compare β_{11} with γ_0 and 1. Compare β_{11} with 1, we get $\beta_{11} - 1 = \frac{3\gamma_0}{-4+\gamma_0} < 0$, so $\beta_{11} < 1$. Compare β_{11} with γ_0 , we get $\beta_{11} - \gamma_0 = \frac{4-8\gamma_0+\gamma_0^2}{4-\gamma_0}$. Set $L_2(\gamma_0) = 4 - 8\gamma_0 + \gamma_0^2$, $L_2(\gamma_0)$ is convex in γ_0 . Set $L_2(\gamma_0) = 0$, we get $\gamma_{01} = 2(2-\sqrt{3})$ and $\gamma_{02} = 2(2+\sqrt{3})$. Replace $\gamma = \gamma_{01}$ into $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma}$, we get $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{1}{24}(7-4\sqrt{3}) + 2(-2+\sqrt{3})\alpha$. Set $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = 0$, we get $\alpha_1 = \frac{7-4\sqrt{3}}{48(2-\sqrt{3})}$. If $\alpha < \alpha_1$, then $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} > 0$ and $\gamma_{01} < \gamma_0$, then $\beta_{11} < \gamma_0$, then $w_L^r < w_L^n$. If $\alpha > \alpha_1$, then $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} < 0$ and

$\gamma_{01} > \gamma_0$, then $\beta_{11} > \gamma_0$. Then if $\gamma_0 < \beta < \beta_{11}$, $w_L^r > w_L^n$; if $\beta > \beta_{11}$, $w_L^r < w_L^n$. Therefore, if $0 < \alpha < \alpha_1$ or $\alpha > \alpha_1$ and $\beta_{11} < \beta < 1$, then $w_L^r < w_L^n$. Otherwise, $w_L^r > w_L^n$.

Therefore, if $0 < \alpha < \alpha_1$ or $\alpha > \alpha_1$ and $\beta_1 < \beta < 1$, then $w_L^r < w_L^n$. Otherwise, $w_L^r > w_L^n$. Where $\alpha_1 = \frac{7-4\sqrt{3}}{48(2-\sqrt{3})}$ and $\beta_1 = \frac{4(1-\gamma_0)}{4-\gamma_0}$.

(2) For the optimal order quantity of product H, we get $q_H^r - q_H^n = \frac{\beta-\gamma_0}{(-4+\beta)(-4+\gamma_0)} > 0$, so $q_H^r > q_H^n$.

For the optimal order quantity of product L, we get $q_L^r - q_L^n = \frac{\beta-\gamma_0}{2(-4+\beta)(-4+\gamma_0)} > 0$, so $q_L^r > q_L^n$.

(3) For unit retail price of product H, we get $p_H^r - p_H^n = -\frac{3(\beta-\gamma_0)}{(4-\beta)(4-\gamma_0)} < 0$, so $p_H^r < p_H^n$.

For unit retail price of product L, we get $p_L^r - p_L^n = \frac{1}{(-4+\beta)(-4+\gamma_0)} [\beta^2(-4+\gamma_0) - 10\gamma_0 + 4\gamma_0^2 + \beta(10 - \gamma_0^2)]$. Set $L_3(\beta) = \beta^2(-4+\gamma_0) - 10\gamma_0 + 4\gamma_0^2 + \beta(10 - \gamma_0^2)$, $L_3(\beta)$ is concave in β . Set $L_3(\beta) = 0$, we get $\beta_{31} = \frac{2(5-2\gamma_0)}{4-\gamma_0}$ and $\beta_{32} = \gamma_0$. we should compare β_{31} with γ_0 and 1. Compare β_{31} with 1, we get $\beta_{31} - 1 = \frac{3(2-\gamma_0)}{4-\gamma_0} > 0$, so $\gamma_0 < 1 < \beta_{31}$. Therefore, $p_L^r > p_L^n$.

PS model

(1) For unit wholesale price of product H, we get $w_H^r - w_H^n = -\frac{3(\beta-\gamma_1)}{(-4+\beta)(-4+\gamma_1)}$, so $w_H^r < w_H^n$.

For unit wholesale price of product L, we get $w_L^r - w_L^n = \frac{1}{2(-4+\beta)(-4+\gamma_1)} [\beta^2(-4+\gamma_1) - 4\gamma_1 + 4\gamma_1^2 + \beta(4 - \gamma_1^2)]$. Set $L_4(\beta) = \beta^2(-4+\gamma_1) - 4\gamma_1 + 4\gamma_1^2 + \beta(4 - \gamma_1^2)$, $L_4(\beta)$ is concave in β . Set $L_4(\beta) = 0$, we get $\beta_{11} = \frac{4(1-\gamma_1)}{4-\gamma_1}$ and $\beta_{12} = \gamma_1$. we should compare β_{11} with γ_1 and 1. Compare β_{11} with 1, we get $\beta_{11} - 1 = \frac{3\gamma_1}{-4+\gamma_1} < 0$, so $\beta_{11} < 1$. Compare β_{11} with γ_1 , we get $\beta_{11} - \gamma_1 = \frac{4-8\gamma_1+\gamma_1^2}{4+\gamma_1}$. Set $L_5(\gamma_1) = 4 - 8\gamma_1 + \gamma_1^2$, $L_5(\gamma_1)$

is convex in γ_1 . Set $L_5(\gamma_1) = 0$, we get $\gamma_{11} = 2(2 - \sqrt{3})$ and $\gamma_{12} = 2(2 + \sqrt{3})$. Replace $\gamma = \gamma_{11}$ into $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma}$, we get $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{1}{24} (7 - 4\sqrt{3}) + 2(-2 + \sqrt{3})\alpha$. Set $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = 0$, we get $\alpha_1 = \frac{7-4\sqrt{3}}{96(2-\sqrt{3})}$. If $\alpha <$

α_1 , then $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} > 0$ and $\gamma_{11} < \gamma_1$, then $\beta_{11} < \gamma_1$, then $w_L^r < w_L^n$. If $\alpha > \alpha_1$, then $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} < 0$ and $\gamma_{11} > \gamma_1$, then $\beta_{11} > \gamma_1$. Then if $\gamma_1 < \beta < \beta_{11}$, $w_L^r > w_L^n$; if $\beta > \beta_{11}$, $w_L^r < w_L^n$. Therefore, if $0 < \alpha < \alpha_1$ or $\alpha > \alpha_1$ and $\beta_{11} < \beta < 1$, then $w_L^r < w_L^n$. Otherwise, $w_L^r > w_L^n$.

Therefore, if $0 < \alpha < \alpha_1$ or $\alpha > \alpha_1$ and $\beta_1 < \beta < 1$, then $w_L^r < w_L^n$. Otherwise, $w_L^r > w_L^n$. Where $\alpha_1 = \frac{7-4\sqrt{3}}{96(2-\sqrt{3})}$ and $\beta_1 = \frac{4(1-\gamma_1)}{4-\gamma_1}$.

(2) For the optimal order quantity of product H, we get $q_H^r - q_H^n = \frac{\beta-\gamma_1}{(-4+\beta)(-4+\gamma_1)} > 0$, so $q_H^r > q_H^n$.

For the optimal order quantity of product L, we get $q_L^r - q_L^n = \frac{\beta-\gamma_1}{2(-4+\beta)(-4+\gamma_1)} > 0$, so $q_L^r > q_L^n$.

(3) For unit retail price of product H, we get $p_H^r - p_H^n = -\frac{3(\beta-\gamma_1)}{(4-\beta)(4-\gamma_1)} < 0$, so $p_H^r < p_H^n$.

For unit retail price of product L, we get $p_L^r - p_L^n = \frac{1}{(-4+\beta)(-4+\gamma_1)} [\beta^2(-4+\gamma_1) - 10\gamma_1 + 4\gamma_1^2 + \beta(10 - \gamma_1^2)]$. Set $L_6(\beta) = \beta^2(-4+\gamma_1) - 10\gamma_1 + 4\gamma_1^2 + \beta(10 - \gamma_1^2)$, $L_6(\beta)$ is concave in β . Set $L_6(\beta) = 0$, we get $\beta_{31} = \frac{2(5-2\gamma_1)}{4-\gamma_1}$ and $\beta_{32} = \gamma_1$. we should compare β_{31} with γ_1 and 1. Compare β_{31} with 1, we get $\beta_{31} - 1 = \frac{3(2-\gamma_1)}{4-\gamma_1} > 0$, so $\gamma_1 < 1 < \beta_{31}$. Therefore, $p_L^r > p_L^n$.

VN model

(1) For unit wholesale price of product H, we get $w_H^r - w_H^n = -\frac{24(\beta-\gamma_2)}{(-9+\beta)(-9+\gamma_2)} < 0$, so $w_H^r < w_H^n$.

For unit wholesale price of product L, we get $w_L^r - w_L^n = \frac{\beta^2(-9+\gamma_2) - 9\gamma_2 + 9\gamma_2^2 + \beta(9-\gamma_2^2)}{(-9+\beta)(-9+\gamma_2)}$. Set $L_7(\beta) = \beta^2(-9 + \gamma_2) - 9\gamma_2 + 9\gamma_2^2 + \beta(9 - \gamma_2^2)$, $L_7(\beta)$ is concave in β . Set $L_7(\beta) = 0$, we get $\beta_{11} = \frac{9(1-\gamma_2)}{9-\gamma_2}$ and $\beta_{12} = \gamma_2$. we should compare β_{11} with γ_2 and 1. Compare β_{11} with 1, we get $\beta_{11} - 1 = \frac{8\gamma_2}{-9+\gamma_2} < 0$, so $\beta_{11} < 1$. Compare β_{11} with γ_2 , we get $\beta_{11} - \gamma_2 = \frac{9-18\gamma_2+\gamma_2^2}{9-\gamma_2}$. Set $L_8(\gamma_2) = 9 - 18\gamma_2 + \gamma_2^2$, $L_8(\gamma_2)$ is convex in γ_2 . Set $L_8(\gamma_2) = 0$, we get $\gamma_{21} = 3(3 - 2\sqrt{2})$ and $\gamma_{22} = 3(3 + 2\sqrt{2})$. Replace $\gamma = \gamma_{21}$ into $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma}$, we get $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{17}{72} - \frac{1}{3\sqrt{2}} - 9\alpha + 6\sqrt{2}\alpha$. Set $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = 0$, we get $\alpha_1 = \frac{17-12\sqrt{2}}{216(3-2\sqrt{2})}$. If $\alpha < \alpha_1$, then $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} > 0$ and $\gamma_{21} < \gamma_2$, then $\beta_{11} < \gamma_2$, then $w_L^r < w_L^n$. If $\alpha > \alpha_1$, then $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} < 0$ and $\gamma_{21} > \gamma_2$, then $\beta_{11} > \gamma_2$. Then if $\gamma_2 < \beta < \beta_{11}$, $w_L^r > w_L^n$; if $\beta > \beta_{11}$, $w_L^r < w_L^n$. Therefore, if $0 < \alpha < \alpha_1$ or $\alpha > \alpha_1$ and $\beta_{11} < \beta < 1$, then $w_L^r < w_L^n$. Otherwise, $w_L^r > w_L^n$. Therefore, if $0 < \alpha < \alpha_1$ or $\alpha > \alpha_1$ and $\beta_1 < \beta < 1$, then $w_L^r < w_L^n$. Otherwise, $w_L^r > w_L^n$. Where $\alpha_1 = \frac{17-12\sqrt{2}}{216(3-2\sqrt{2})}$ and $\beta_1 = \frac{9(1-\gamma_2)}{9-\gamma_2}$.

(2) For the optimal order quantity of product H, we get $q_H^r - q_H^n = \frac{3(\beta-\gamma_2)}{(-9+\beta)(-9+\gamma_2)} > 0$, so $q_H^r > q_H^n$.

For the optimal order quantity of product L, we get $q_L^r - q_L^n = \frac{\beta-\gamma_2}{(-9+\beta)(-9+\gamma_2)} > 0$, so $q_L^r > q_L^n$.

(3) For unit retail price of product H, we get $p_H^r - p_H^n = -\frac{12(\beta-\gamma_2)}{(9-\beta)(9-\gamma_2)} < 0$, so $p_H^r < p_H^n$.

For unit retail price of product L, we get $p_L^r - p_L^n = \frac{1}{(-9+\beta)(-9+\gamma_2)} [\beta^2(-9 + \gamma_2) - 45\gamma_2 + 9\gamma_2^2 + \beta(45 - \gamma_2^2)]$. Set $L_9(\beta) = \beta^2(-9 + \gamma_2) - 45\gamma_2 + 9\gamma_2^2 + \beta(45 - \gamma_2^2)$, $L_9(\beta)$ is concave in β . Set $L_9(\beta) = 0$, we get $\beta_{31} = \frac{9(5-\gamma_2)}{9-\gamma_2}$ and $\beta_{32} = \gamma_2$. we should compare β_{31} with γ_2 and 1. Compare β_{31} with 1, we get $\beta_{31} - 1 = \frac{4(9-2\gamma_2)}{9-\gamma_2} > 0$, so $\gamma_2 < 1 < \beta_{31}$. Therefore, $p_L^r > p_L^n$.

Proof of Proposition 1

MS model

(1) For the pharmaceutical manufacturer 1, from formula (4), we get $\pi_{MH}^r(w_H) - \pi_{MH}^n(w_H) = \frac{2}{(-4+\beta)^2(-4+\gamma_0)^2} [\beta^2(-1+\gamma_0) + 8\gamma_0 + \gamma_0^2 + \beta(-8-\gamma_0^2)]$. Set $F_1(\beta) = \beta^2(-1+\gamma_0) + 8\gamma_0 + \gamma_0^2 + \beta(-8-\gamma_0^2)$,

we get $\Delta = (-8 - 2\gamma_0 + \gamma_0^2)^2 > 0$. Set $F_1(\beta) = 0$, we get $\beta_{11} = \frac{8+\gamma_0}{-1+\gamma_0}$ and $\beta_{12} = \gamma_0$. Then $\pi_{MH}^r(w_H) < \pi_{MH}^n(w_H)$.

For the pharmaceutical manufacturer 2, from formula (5), we get $\pi_{ML}^r(w_L, \gamma) - \pi_{ML}^n(w_L, \gamma) = \frac{1}{2(-4+\beta)^2(-4+\gamma_0)^2} [\beta^4(-16\alpha + 8\alpha\gamma_0 - \alpha\gamma_0^2) + \beta^3(128\alpha - 64\alpha\gamma_0 + 8\alpha\gamma_0^2) + \beta(16 - 7\gamma_0^2 - 128\alpha\gamma_0^2 + 64\alpha\gamma_0^3 -$

$8\alpha\gamma_0^4) + \beta^2(-16 - 256\alpha + 7\gamma_0 + 128\alpha\gamma_0 - 8\alpha\gamma_0^3 + \alpha\gamma_0^4) - 16\gamma_0 + 16\gamma_0^2 + 256\alpha\gamma_0^2 - 128\alpha\gamma_0^3 + 16\alpha\gamma_0^4]$.

Set $F_2(\beta) = \beta^4(-16\alpha + 8\alpha\gamma_0 - \alpha\gamma_0^2) + \beta^3(128\alpha - 64\alpha\gamma_0 + 8\alpha\gamma_0^2) + \beta(16 - 7\gamma_0^2 - 128\alpha\gamma_0^2 + 64\alpha\gamma_0^3 - 8\alpha\gamma_0^4) + \beta^2(-16 - 256\alpha + 7\gamma_0 + 128\alpha\gamma_0 - 8\alpha\gamma_0^3 + \alpha\gamma_0^4) - 16\gamma_0 + 16\gamma_0^2 + 256\alpha\gamma_0^2 - 128\alpha\gamma_0^3 + 16\alpha\gamma_0^4$, we

get $\frac{dF_2(\beta)}{d\beta} = 4\beta^3(-16\alpha + 8\alpha\gamma_0 - \alpha\gamma_0^2) + 3\beta^2(128\alpha - 64\alpha\gamma_0 + 8\alpha\gamma_0^2) + 2\beta(-16 - 256\alpha + 7\gamma_0 +$

$128\alpha\gamma_0 - 8\alpha\gamma_0^3 + \alpha\gamma_0^4) + 16 - 7\gamma_0^2 - 128\alpha\gamma_0^2 + 64\alpha\gamma_0^3 - 8\alpha\gamma_0^4$, $\frac{d^2F_2(\beta)}{d\beta^2} = 12\beta^2(-16\alpha + 8\alpha\gamma_0 - \alpha\gamma_0^2) +$

$6\beta(128\alpha - 64\alpha\gamma_0 + 8\alpha\gamma_0^2) + 2(-16 - 256\alpha + 7\gamma_0 + 128\alpha\gamma_0 - 8\alpha\gamma_0^3 + \alpha\gamma_0^4)$ and $\frac{d^3F_2(\beta)}{d\beta^3} = 24\beta(-16\alpha +$

$8\alpha\gamma_0 - \alpha\gamma_0^2) + 6(128\alpha - 64\alpha\gamma_0 + 8\alpha\gamma_0^2)$. Set $\beta = \gamma_0$, we get $\frac{d^3F_2(\beta)}{d\beta^3} = 24\alpha(-4 + \gamma_0)^2(2 - \gamma_0) > 0$,

$\frac{d^2F_2(\beta)}{d\beta^2} = -2(16 + 256\alpha - (7 + 512\alpha)\gamma_0 + 288\alpha\gamma_0^2 - 64\alpha\gamma_0^3 + 5\alpha\gamma_0^4) = -2(16 + 256\alpha - (7 + 512\alpha)\gamma_0 +$

$288\alpha\gamma_0^2 - 64\alpha\gamma_0^3 + 5\alpha\gamma_0^4) - 5h = -4(3 + 128\alpha) + 3(-7 + 128\alpha)\gamma_0 - 96\alpha\gamma_0^2 + 8\alpha\gamma_0^3 < 0$, $\frac{dF_2(\beta)}{d\beta} =$

$-(-4 + \gamma_0)(4 - (7 + 128\alpha)\gamma_0 + 96\alpha\gamma_0^2 - 24\alpha\gamma_0^3 + 2\alpha\gamma_0^4) = (-4 + \gamma_0)h = 0$ and $F_2(\beta) = 0$. Therefore, γ_0

is the smallest root and multiple roots of $F_2(\beta)$. Set $\beta = 1$, we get $\frac{d^3F_2(\beta)}{d\beta^3} = 24\alpha(-4 + \gamma_0)^2 > 0$, $\frac{d^2F_2(\beta)}{d\beta^2} =$

$2(-16 + 32\alpha + (7 - 16\alpha)\gamma_0 + 18\alpha\gamma_0^2 - 8\alpha\gamma_0^3 + \alpha\gamma_0^4) = 2(-16 + 32\alpha + (7 - 16\alpha)\gamma_0 + 18\alpha\gamma_0^2 - 8\alpha\gamma_0^3 +$

$\alpha\gamma_0^4) + h = -36 + 21\gamma_0 + \alpha(64 + 96\gamma_0 - 60\gamma_0^2 + 8\gamma_0^3)$. If $\alpha > \frac{3(12-7\gamma_0)}{4(4-\gamma_0)^2(1+2\gamma_0)}$, then $\frac{d^2F_2(\beta)}{d\beta^2} > 0$. If $\alpha <$

$\frac{3(12-7\gamma_0)}{4(4-\gamma_0)^2(1+2\gamma_0)}$, then $\frac{d^2F_2(\beta)}{d\beta^2} < 0$. $\frac{dF_2(\beta)}{d\beta} = -16(1 + 12\alpha) + 2(7 + 48\alpha)\gamma_0 - (7 + 108\alpha)\gamma_0^2 + 48\alpha\gamma_0^3 -$

$6\alpha\gamma_0^4 = -16(1 + 12\alpha) + 2(7 + 48\alpha)\gamma_0 - (7 + 108\alpha)\gamma_0^2 + 48\alpha\gamma_0^3 - 6\alpha\gamma_0^4 - 3h = -4(1 + 48\alpha) - (7 +$

$288\alpha)\gamma_0 + (-7 + 180\alpha)\gamma_0^2 - 24\alpha\gamma_0^3 < 0$, $F_2(\beta) = 9(-1 + \gamma_0)(16\alpha + (1 + 8\alpha)\gamma_0 - 7\alpha\gamma_0^2 + \alpha\gamma_0^3) < 0$.

Therefore, $F_2(\beta)$ decreases in β and $F_2(\beta) < 0$. Then $\pi_{ML}^r(w_L, \gamma) < \pi_{ML}^n(w_L, \gamma)$.

(2) For the pharmacy, from formula (6), we get $\pi_R^r(q_H, q_L) - \pi_R^n(q_H, q_L) = \frac{1}{4(-4+\beta)^2(-4+\gamma_0)^2} [\beta^2(-4 - 5\gamma_0) - 112\gamma_0 + 4\gamma_0^2 + \beta(112 + 5\gamma_0^2)]$. Set $F_3(\beta) = \beta^2(-4 - 5\gamma_0) - 112\gamma_0 + 4\gamma_0^2 + \beta(112 + 5\gamma_0^2)$, we get $\Delta =$

$(-112 + 8\gamma_0 + 5\gamma_0^2)^2 > 0$. Set $F_3(\beta) = 0$, we get $\beta_{11} = \frac{4(28-\gamma_0)}{4+5\gamma_0}$ and $\beta_{12} = \gamma_0$. Since $\gamma_0 < \beta \leq 1$, we should

compare β_{11} with these thresholds. Compare β_{11} with 1, we get $\beta_{11} - 1 = \frac{9(12-\gamma_0)}{4+5\gamma_0} > 0$. Therefore,

$$\pi_R^r(q_H, q_L) > \pi_R^n(q_H, q_L).$$

(3) For the pharmaceutical supply chain, we get $\pi^r - \pi^n = \frac{1}{4(-4+\beta)^2(-4+\gamma_0)^2} [\beta^4(-32\alpha + 16\alpha\gamma_0 - 2\alpha\gamma_0^2) + \beta^3(256\alpha - 128\alpha\gamma_0 + 16\alpha\gamma_0^2) + \beta(80 - 17\gamma_0^2 - 256\alpha\gamma_0^2 + 128\alpha\gamma_0^3 - 16\alpha\gamma_0^4) + \beta^2(-44 - 512\alpha + 17\gamma_0 + 256\alpha\gamma_0 - 16\alpha\gamma_0^3 + 2\alpha\gamma_0^4) - 80\gamma_0 + 44\gamma_0^2 + 512\alpha\gamma_0^2 - 256\alpha\gamma_0^3 + 32\alpha\gamma_0^4]$. Set $F_4(\beta) = \beta^4(-32\alpha + 16\alpha\gamma_0 - 2\alpha\gamma_0^2) + \beta^3(256\alpha - 128\alpha\gamma_0 + 16\alpha\gamma_0^2) + \beta(80 - 17\gamma_0^2 - 256\alpha\gamma_0^2 + 128\alpha\gamma_0^3 - 16\alpha\gamma_0^4) + \beta^2(-44 - 512\alpha + 17\gamma_0 + 256\alpha\gamma_0 - 16\alpha\gamma_0^3 + 2\alpha\gamma_0^4) - 80\gamma_0 + 44\gamma_0^2 + 512\alpha\gamma_0^2 - 256\alpha\gamma_0^3 + 32\alpha\gamma_0^4$, we get $\frac{dF_4(\beta)}{d\beta} = 4\beta^3(-32\alpha + 16\alpha\gamma_0 - 2\alpha\gamma_0^2) + 3\beta^2(256\alpha - 128\alpha\gamma_0 + 16\alpha\gamma_0^2) + 2\beta(-44 - 512\alpha + 17\gamma_0 + 256\alpha\gamma_0 - 16\alpha\gamma_0^3 + 2\alpha\gamma_0^4) + 80 - 17\gamma_0^2 - 256\alpha\gamma_0^2 + 128\alpha\gamma_0^3 - 16\alpha\gamma_0^4$, $\frac{d^2F_4(\beta)}{d\beta^2} = 12\beta^2(-32\alpha + 16\alpha\gamma_0 - 2\alpha\gamma_0^2) + 6\beta(256\alpha - 128\alpha\gamma_0 + 16\alpha\gamma_0^2) + 2(-44 - 512\alpha + 17\gamma_0 + 256\alpha\gamma_0 - 16\alpha\gamma_0^3 + 2\alpha\gamma_0^4)$ and $\frac{d^3F_4(\beta)}{d\beta^3} = 24\beta(-32\alpha + 16\alpha\gamma_0 - 2\alpha\gamma_0^2) + 6(256\alpha - 128\alpha\gamma_0 + 16\alpha\gamma_0^2)$. And we get four roots of $F_4(\beta)$, β_{11} , β_{12} , β_{13} and β_{14} . Set $\beta = \gamma_0$, we get $\frac{d^3F_4(\beta)}{d\beta^3} = 48\alpha(-4 + \gamma_0)^2(2 - \gamma_0) > 0$, $\frac{d^2F_4(\beta)}{d\beta^2} = -2(44 + 512\alpha - (17 + 1024\alpha)\gamma_0 + 576\alpha\gamma_0^2 - 128\alpha\gamma_0^3 + 10\alpha\gamma_0^4) = -2(44 + 512\alpha - (17 + 1024\alpha)\gamma_0 + 576\alpha\gamma_0^2 - 128\alpha\gamma_0^3 + 10\alpha\gamma_0^4) - 10h = 4(-4(3 + 64\alpha) + 3(-3 + 64\alpha)\gamma_0 - 48\alpha\gamma_0^2 + 4\alpha\gamma_0^3) < 0$, $\frac{dF_4(\beta)}{d\beta} = -(-4 + \gamma_0)(20 - (17 + 256\alpha)\gamma_0 + 192\alpha\gamma_0^2 - 48\alpha\gamma_0^3 + 4\alpha\gamma_0^4) + 2h = 3(4 - \gamma_0)^2 > 0$ and $F_4(\beta) = 0$. Therefore, γ_0 is the smallest root of $F_4(\beta)$. Set $\beta = 1$, we get $\frac{d^3F_4(\beta)}{d\beta^3} = 48\alpha(-4 + \gamma_0)^2 > 0$, $\frac{d^2F_4(\beta)}{d\beta^2} = -88 + 128\alpha + (34 - 64\alpha)\gamma_0 + 72\alpha\gamma_0^2 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4 = -88 + 128\alpha + (34 - 64\alpha)\gamma_0 + 72\alpha\gamma_0^2 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4 + 2h = 8(-12 + 6\gamma_0 + \alpha(16 + 24\gamma_0 - 15\gamma_0^2 + 2\gamma_0^3))$. Set $\frac{d^2F_4(\beta)}{d\beta^2} = 0$, we get $\alpha_{31} = \frac{6(2-\gamma_0)}{(-4+\gamma_0)^2(1+2\gamma_0)}$. If $\alpha > \alpha_{31}$, then $\frac{d^2F_4(\beta)}{d\beta^2} > 0$. If $\alpha < \alpha_{31}$, then $\frac{d^2F_4(\beta)}{d\beta^2} < 0$. $\frac{dF_4(\beta)}{d\beta} = -8(1 + 48\alpha) + 2(17 + 96\alpha)\gamma_0 - (17 + 216\alpha)\gamma_0^2 + 96\alpha\gamma_0^3 - 12\alpha\gamma_0^4 = -8(1 + 48\alpha) + 2(17 + 96\alpha)\gamma_0 - (17 + 216\alpha)\gamma_0^2 + 96\alpha\gamma_0^3 - 12\alpha\gamma_0^4 - 6h = 16 - 8\gamma_0 - 17\gamma_0^2 + \alpha(-384 - 576\gamma_0 + 360\gamma_0^2 - 48\gamma_0^3)$. Set $\frac{dF_4(\beta)}{d\beta} = 0$, we get $\alpha_{32} = \frac{16-8\gamma_0-17\gamma_0^2}{24(-4+\gamma_0)^2(1+2\gamma_0)}$. we should compare α_{32} with 0 and α_{31} . Set $16 - 8\gamma_0 - 17\gamma_0^2 = 0$, we get $\gamma_{01} = \frac{4}{17}(-1 - 3\sqrt{2})$ and $\gamma_{02} = \frac{4}{17}(-1 + 3\sqrt{2})$. Replace $\gamma = \gamma_{02}$ into $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma}$, we get $\frac{d\pi_{ML}(w_L, \gamma)}{d\gamma} = \frac{4913(-8+7\sqrt{2})+2304(-456+433\sqrt{2})\alpha}{4896(-6+\sqrt{2})^3} < 0$, then $\gamma_0 < \gamma_{02}$ and $\alpha_{32} > 0$. Compare α_{32} with α_{31} , we get $\alpha_{31} - \alpha_{32} = \frac{17}{24+48\gamma_0} > 0$, so $\alpha_{32} < \alpha_{31}$. If $\alpha > \alpha_{31}$, then $\frac{dF_4(\beta)}{d\beta} < 0$. If $\alpha_{32} < \alpha < \alpha_{31}$, then $\frac{dF_4(\beta)}{d\beta} < 0$. If $\alpha < \alpha_{32}$, then $\frac{dF_4(\beta)}{d\beta} > 0$. $F_4(\beta) = 9(1 - \gamma_0)(4 - 3\gamma_0 + \alpha(-32 - 16\gamma_0 + 14\gamma_0^2 - 2\gamma_0^3))$. Set $4 - 3\gamma_0 + \alpha(-32 - 16\gamma_0 + 14\gamma_0^2 - 2\gamma_0^3) = 0$, we get $\alpha_{33} = \frac{4-3\gamma_0}{2(-4+\gamma_0)^2(1+\gamma_0)}$. we should compare α_{33} with α_{31} and α_{32} . Compare α_{33} with α_{31} , we get $\alpha_{33} - \alpha_{31} = \frac{-20-7\gamma_0+6\gamma_0^2}{2(-4+\gamma_0)^2(1+\gamma_0)(1+2\gamma_0)} < 0$, so $\alpha_{33} < \alpha_{31}$. Compare α_{33} with α_{32} , we get $\alpha_{33} - \alpha_{32} = \frac{32+52\gamma_0-47\gamma_0^2+17\gamma_0^3}{24(-4+\gamma_0)^2(1+\gamma_0)(1+2\gamma_0)} > 0$, so $\alpha_{33} > \alpha_{32}$. Therefore, $\alpha_{32} < \alpha_{33} < \alpha_{31}$. If $\alpha > \alpha_{31}$, then $F_4(\beta) < 0$. If $\alpha_{33} <$

$\alpha < \alpha_{31}$, then $F_4(\beta) < 0$. If $\alpha_{32} < \alpha < \alpha_{33}$, then $F_4(\beta) > 0$. If $0 < \alpha < \alpha_{32}$, then $F_4(\beta) > 0$. Therefore, if $0 < \alpha < \alpha_{33}$ or $\alpha > \alpha_{33}$ and $\gamma_0 < \beta < \beta_{12}$, then $\pi^r > \pi^n$. Otherwise, $\pi^r < \pi^n$.

Therefore, if $0 < \alpha < \alpha_2$ or $\alpha > \alpha_2$ and $\gamma_0 < \beta < \beta_2$, then $\pi^r > \pi^n$. Otherwise, $\pi^r < \pi^n$. where $\alpha_2 = \frac{4-3\gamma_0}{2(4-\gamma_0)^2(1+\gamma_0)}$ and β_2 is upper second root of $F_4(\beta)$.

PS model

(1) For the pharmaceutical manufacturer 1, from formula (4), we get $\pi_{MH}^r(w_H) - \pi_{MH}^n(w_H) = \frac{1}{(-4+\beta)^2(-4+\gamma_1)^2} [\beta^2(-1+\gamma_1) + 8\gamma_1 + \gamma_1^2 + \beta(-8-\gamma_1^2)]$. Set $F_5(\beta) = \beta^2(-1+\gamma_1) + 8\gamma_1 + \gamma_1^2 + \beta(-8-\gamma_1^2)$,

we get $\Delta = (-8-2\gamma_1+\gamma_1^2)^2 > 0$. Set $F_5(\beta) = 0$, we get $\beta_{11} = \frac{8+\gamma_1}{-1+\gamma_1}$ and $\beta_{12} = \gamma_1$. Then $\pi_{MH}^r(w_H) < \pi_{MH}^n(w_H)$.

For the pharmaceutical manufacturer 2, from formula (5), we get $\pi_{ML}^r(w_L, \gamma) - \pi_{ML}^n(w_L, \gamma) = \frac{1}{4(-4+\beta)^2(-4+\gamma_1)^2} [\beta^4(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + \beta^3(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + \beta(16 - 7\gamma_1^2 - 256\alpha\gamma_1^2 +$

$128\alpha\gamma_1^3 - 16\alpha\gamma_1^4) + \beta^2(-16 - 512\alpha + 7\gamma_1 + 256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4) - 16\gamma_1 + 16\gamma_1^2 + 512\alpha\gamma_1^2 - 256\alpha\gamma_1^3 + 32\alpha\gamma_1^4]$. Set $F_6(\beta) = \beta^4(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + \beta^3(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + \beta(16 - 7\gamma_1^2 - 256\alpha\gamma_1^2 + 128\alpha\gamma_1^3 - 16\alpha\gamma_1^4) + \beta^2(-16 - 512\alpha + 7\gamma_1 + 256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4) - 16\gamma_1 + 16\gamma_1^2 +$

$512\alpha\gamma_1^2 - 256\alpha\gamma_1^3 + 32\alpha\gamma_1^4$, we get $\frac{dF_6(\beta)}{d\beta} = 4\beta^3(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + 3\beta^2(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + 2\beta(-16 - 512\alpha + 7\gamma_1 + 256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4) + 16 - 7\gamma_1^2 - 256\alpha\gamma_1^2 + 128\alpha\gamma_1^3 - 16\alpha\gamma_1^4$,

$\frac{d^2F_6(\beta)}{d\beta^2} = 12\beta^2(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + 6\beta(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + 2(-16 - 512\alpha + 7\gamma_1 +$

$256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4)$ and $\frac{d^3F_6(\beta)}{d\beta^3} = 24\beta(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + 6(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2)$. Set

$\beta = \gamma_1$, we get $\frac{d^3F_6(\beta)}{d\beta^3} = 48\alpha(-4 + \gamma_1)^2(2 - \gamma_1) > 0$, $\frac{d^2F_6(\beta)}{d\beta^2} = -2(16 + 512\alpha - (7 + 1024\alpha)\gamma_1 + 576\alpha\gamma_1^2 - 128\alpha\gamma_1^3 + 10\alpha\gamma_1^4) - 5e < 0$,

$\frac{dF_6(\beta)}{d\beta} = (4 - \gamma_1)(4 - (7 + 256\alpha)\gamma_1 + 192\alpha\gamma_1^2 - 48\alpha\gamma_1^3 + 4\alpha\gamma_1^4) = (4 - \gamma_1)(4 - (7 + 256\alpha)\gamma_1 + 192\alpha\gamma_1^2 - 48\alpha\gamma_1^3 + 4\alpha\gamma_1^4 + h) = 0$ and $F_6(\beta) = 0$. Therefore, γ_1 is the smallest root and multiple roots of $F_6(\beta)$. Set

$\beta = 1$, we get $\frac{d^3F_6(\beta)}{d\beta^3} = 48\alpha(-4 + \gamma_1)^2 > 0$, $\frac{d^2F_6(\beta)}{d\beta^2} = 2(-16 + 64\alpha + (7 - 32\alpha)\gamma_1 + 36\alpha\gamma_1^2 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4) = 2(-16 + 64\alpha + (7 - 32\alpha)\gamma_1 + 36\alpha\gamma_1^2 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4) + e = -36 + 21\gamma_1 + \alpha(128 + 192\gamma_1 -$

$120\gamma_1^2 + 16\gamma_1^3)$. If $\alpha > \frac{3(12-7\gamma_1)}{8(-4+\gamma_1)^2(1+2\gamma_1)}$, then $\frac{d^2F_6(\beta)}{d\beta^2} > 0$. If $\alpha < \frac{3(12-7\gamma_1)}{8(-4+\gamma_1)^2(1+2\gamma_1)}$, then $\frac{d^2F_6(\beta)}{d\beta^2} < 0$. $\frac{dF_6(\beta)}{d\beta} =$

$-16(1 + 24\alpha) + 2(7 + 96\alpha)\gamma_1 - (7 + 216\alpha)\gamma_1^2 + 96\alpha\gamma_1^3 - 12\alpha\gamma_1^4 = -16(1 + 24\alpha) + 2(7 + 96\alpha)\gamma_1 - (7 + 216\alpha)\gamma_1^2 + 96\alpha\gamma_1^3 - 12\alpha\gamma_1^4 - 3e = -4(1 + 96\alpha) - (7 + 576\alpha)\gamma_1 + (-7 + 360\alpha)\gamma_1^2 - 48\alpha\gamma_1^3 < 0$, $F_6(\beta) = 9(-1 + \gamma_1)(32\alpha + (1 + 16\alpha)\gamma_1 - 14\alpha\gamma_1^2 + 2\alpha\gamma_1^3) < 0$. Therefore, $F_6(\beta)$ decreases in β and $F_6(\beta) < 0$.

Then $\pi_{ML}^r(w_L, \gamma) < \pi_{ML}^n(w_L, \gamma)$.

(2) For the pharmacy, from formula (6), we get $\pi_R^r(q_H, q_L) - \pi_R^n(q_H, q_L) = \frac{3(\beta-\gamma_1)}{2(-4+\beta)(-4+\gamma_1)} > 0$, then

$\pi_R^r(q_H, q_L) > \pi_R^n(q_H, q_L)$.

(3) For the pharmaceutical supply chain, we get $\pi^r - \pi^n = \frac{1}{4(-4+\beta)^2(-4+\gamma_1)^2}[-80\gamma_1 + 44\gamma_1^2 + 512\alpha\gamma_1^2 - 256\alpha\gamma_1^3 + 32\alpha\gamma_1^4 + \beta^4(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + \beta^3(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + \beta(80 - 17\gamma_1^2 - 256\alpha\gamma_1^2 + 128\alpha\gamma_1^3 - 16\alpha\gamma_1^4) + \beta^2(-44 - 512\alpha + 17\gamma_1 + 256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4)]$. Set $F_7(\beta) = -80\gamma_1 + 44\gamma_1^2 + 512\alpha\gamma_1^2 - 256\alpha\gamma_1^3 + 32\alpha\gamma_1^4 + \beta^4(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + \beta^3(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + \beta(80 - 17\gamma_1^2 - 256\alpha\gamma_1^2 + 128\alpha\gamma_1^3 - 16\alpha\gamma_1^4) + \beta^2(-44 - 512\alpha + 17\gamma_1 + 256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4)$, we get $\frac{dF_7(\beta)}{d\beta} = 80 - 17\gamma_1^2 - 256\alpha\gamma_1^2 + 128\alpha\gamma_1^3 - 16\alpha\gamma_1^4 + 4\beta^3(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + 3\beta^2(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + 2\beta(-44 - 512\alpha + 17\gamma_1 + 256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4)$, $\frac{d^2F_7(\beta)}{d\beta^2} = 12\beta^2(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + 6\beta(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2) + 2(-44 - 512\alpha + 17\gamma_1 + 256\alpha\gamma_1 - 16\alpha\gamma_1^3 + 2\alpha\gamma_1^4)$ and $\frac{d^3F_7(\beta)}{d\beta^3} = 24\beta(-32\alpha + 16\alpha\gamma_1 - 2\alpha\gamma_1^2) + 6(256\alpha - 128\alpha\gamma_1 + 16\alpha\gamma_1^2)$. And we get four roots of $F_7(\beta)$, β_{11} , β_{12} , β_{13} and β_{14} . Set $\beta = \gamma_1$, we get $\frac{d^3F_7(\beta)}{d\beta^3} = 48\alpha(-4 + \gamma_1)^2(2 - \gamma_1) > 0$, $\frac{d^2F_7(\beta)}{d\beta^2} = -2(44 + 512\alpha - (17 + 1024\alpha)\gamma_1 + 576\alpha\gamma_1^2 - 128\alpha\gamma_1^3 + 10\alpha\gamma_1^4) = -2(44 + 512\alpha - (17 + 1024\alpha)\gamma_1 + 576\alpha\gamma_1^2 - 128\alpha\gamma_1^3 + 10\alpha\gamma_1^4) - 5e = -4(17 + 256\alpha) + (-1 + 768\alpha)\gamma_1 - 192\alpha\gamma_1^2 + 16\alpha\gamma_1^3 < 0$, $\frac{dF_7(\beta)}{d\beta} = (4 - \gamma_1)(20 - (17 + 256\alpha)\gamma_1 + 192\alpha\gamma_1^2 - 48\alpha\gamma_1^3 + 4\alpha\gamma_1^4 + e) = (4 - \gamma_1)(16 - 10\gamma_1) > 0$ and $F_7(\beta) = 0$. Therefore, γ_1 is the smallest root of $F_7(\beta)$. Set $\beta = 1$, we get $\frac{d^3F_7(\beta)}{d\beta^3} = 48\alpha(-4 + \gamma_1)^2 > 0$, $\frac{d^2F_7(\beta)}{d\beta^2} = -88 + 128\alpha + (34 - 64\alpha)\gamma_1 + 72\alpha\gamma_1^2 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4 = -88 + 128\alpha + (34 - 64\alpha)\gamma_1 + 72\alpha\gamma_1^2 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4 + e = -92 + 41\gamma_1 + \alpha(128 + 192\gamma_1 - 120\gamma_1^2 + 16\gamma_1^3)$. Set $\frac{d^2F_7(\beta)}{d\beta^2} = 0$, we get $\alpha_{31} = \frac{92-41\gamma_1}{8(-4+\gamma_1)^2(1+2\gamma_1)}$. If $\alpha > \alpha_{31}$, then $\frac{d^2F_7(\beta)}{d\beta^2} > 0$. If $\alpha < \alpha_{31}$, then $\frac{d^2F_7(\beta)}{d\beta^2} < 0$. $\frac{dF_7(\beta)}{d\beta} = -8(1 + 48\alpha) + 2(17 + 96\alpha)\gamma_1 - (17 + 216\alpha)\gamma_1^2 + 96\alpha\gamma_1^3 - 12\alpha\gamma_1^4 = -8(1 + 48\alpha) + 2(17 + 96\alpha)\gamma_1 - (17 + 216\alpha)\gamma_1^2 + 96\alpha\gamma_1^3 - 12\alpha\gamma_1^4 - 3e = 4 + 13\gamma_1 - 17\gamma_1^2 + \alpha(-384 - 576\gamma_1 + 360\gamma_1^2 - 48\gamma_1^3)$. Set $\frac{dF_7(\beta)}{d\beta} = 0$, we get $\alpha_{32} = \frac{4+13\gamma_1-17\gamma_1^2}{24(-4+\gamma_1)^2(1+2\gamma_1)}$. Compare α_{32} with α_{31} , we get $\alpha_{31} - \alpha_{32} = \frac{17}{24+48\gamma_1} > 0$, so $\alpha_{32} < \alpha_{31}$. If $\alpha > \alpha_{31}$, then $\frac{dF_7(\beta)}{d\beta} < 0$. If $\alpha_{32} < \alpha < \alpha_{31}$, then $\frac{dF_7(\beta)}{d\beta} < 0$. If $\alpha < \alpha_{32}$, then $\frac{dF_7(\beta)}{d\beta} > 0$. $F_7(\beta) = 9(1 - \gamma_1)(4 - 3\gamma_1 + \alpha(-32 - 16\gamma_1 + 14\gamma_1^2 - 2\gamma_1^3))$. Set $F_7(\beta) = 0$, we get $\alpha_{33} = \frac{4-3\gamma_1}{2(-4+\gamma_1)^2(1+\gamma_1)}$. we should compare α_{33} with α_{31} and α_{32} . Compare α_{33} with α_{31} , we get $\alpha_{31} - \alpha_{33} = \frac{76+31\gamma_1-17\gamma_1^2}{8(-4+\gamma_1)^2(1+\gamma_1)(1+2\gamma_1)} > 0$, so $\alpha_{33} < \alpha_{31}$. Compare α_{33} with α_{32} , we get $\alpha_{32} - \alpha_{33} = -\frac{44+43\gamma_1-68\gamma_1^2+17\gamma_1^3}{24(-4+\gamma_1)^2(1+\gamma_1)(1+2\gamma_1)} < 0$, so $\alpha_{33} > \alpha_{32}$. Therefore, $\alpha_{32} < \alpha_{33} < \alpha_{31}$. If $\alpha > \alpha_{31}$, then $F_7(\beta) < 0$. If $\alpha_{33} < \alpha < \alpha_{31}$, then $F_7(\beta) < 0$. If $\alpha_{32} < \alpha < \alpha_{33}$, then $F_7(\beta) > 0$. If $0 < \alpha < \alpha_{32}$, then $F_7(\beta) > 0$. Therefore, if $0 < \alpha < \alpha_{33}$ or $\alpha > \alpha_{33}$ and $\gamma_1 < \beta < \beta_{12}$, then $\pi^r > \pi^n$. Otherwise, $\pi^r < \pi^n$. Therefore, if $0 < \alpha < \alpha_2$ or $\alpha > \alpha_2$ and $\gamma_1 < \beta < \beta_2$, then $\pi^r > \pi^n$. Otherwise, $\pi^r < \pi^n$. where $\alpha_2 = \frac{4-3\gamma_1}{2(-4+\gamma_1)^2(1+\gamma_1)}$ and β_2 is upper second root of $F_7(\beta)$.

VN model

(1) For the pharmaceutical manufacturer 1, from formula (4), we get $\pi_{MH}^r(w_H) - \pi_{MH}^n(w_H) = \frac{9[\beta^2(-1+\gamma_2)+63\gamma_2+\gamma_2^2+\beta(-63-\gamma_2^2)]}{(-9+\beta)^2(-9+\gamma_2)^2}$. Set $F_8(\beta) = \beta^2(-1+\gamma_2) + 63\gamma_2 + \gamma_2^2 + \beta(-63-\gamma_2^2)$, we get $\Delta = (-63 -$

$2\gamma_2 + \gamma_2^2)^2 > 0$. Set $F_8(\beta) = 0$, we get $\beta_{11} = \frac{63+\gamma_2}{-1+\gamma_2}$ and $\beta_{12} = \gamma_2$. Then $\pi_{MH}^r(w_H) < \pi_{MH}^n(w_H)$.

For the pharmaceutical manufacturer 2, from formula (5), we get $\pi_{ML}^r(w_L, \gamma) - \pi_{ML}^n(w_L, \gamma) = \frac{1}{2(-9+\beta)^2(-9+\gamma_2)^2} [\beta^4(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + \beta^3(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + \beta(162 - 34\gamma_2^2 - 1458\alpha\gamma_2^2 +$

$324\alpha\gamma_2^3 - 18\alpha\gamma_2^4) + \beta^2(-162 - 6561\alpha + 34\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) - 162\gamma_2 + 162\gamma_2^2 + 6561\alpha\gamma_2^2 - 1458\alpha\gamma_2^3 + 81\alpha\gamma_2^4]$. Set $F_9(\beta) = \beta^4(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + \beta^3(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + \beta(162 - 34\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 - 18\alpha\gamma_2^4) + \beta^2(-162 - 6561\alpha + 34\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) -$

$162\gamma_2 + 162\gamma_2^2 + 6561\alpha\gamma_2^2 - 1458\alpha\gamma_2^3 + 81\alpha\gamma_2^4$, we get $\frac{dF_9(\beta)}{d\beta} = 162 - 34\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 -$

$18\alpha\gamma_2^4 + 4\beta^3(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 3\beta^2(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + 2\beta(-162 - 6561\alpha + 34\gamma_2 +$

$1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4)$, $\frac{d^2F_9(\beta)}{d\beta^2} = 12\beta^2(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 6\beta(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) +$

$2(-162 - 6561\alpha + 34\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4)$ and $\frac{d^3F_9(\beta)}{d\beta^3} = 24\beta(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) +$

$6(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2)$. Set $\beta = \gamma_2$, we get $\frac{d^3F_9(\beta)}{d\beta^3} = 12\alpha(-9 + \gamma_2)^2(9 - 2\gamma_2) > 0$, $\frac{d^2F_9(\beta)}{d\beta^2} =$

$-2(81(2 + 81\alpha) - 2(17 + 2916\alpha)\gamma_2 + 1458\alpha\gamma_2^2 - 144\alpha\gamma_2^3 + 5\alpha\gamma_2^4) = -2(81(2 + 81\alpha) - 2(17 +$

$2916\alpha)\gamma_2 + 1458\alpha\gamma_2^2 - 144\alpha\gamma_2^3 + 5\alpha\gamma_2^4) - 10k = 6(-3(13 + 729\alpha) + (-17 + 729\alpha)\gamma_2 - 81\alpha\gamma_2^2 +$

$3\alpha\gamma_2^3) < 0$, $\frac{dF_9(\beta)}{d\beta} = 2(9 - \gamma_2)(9 - (17 + 729\alpha)\gamma_2 + 243\alpha\gamma_2^2 - 27\alpha\gamma_2^3 + \alpha\gamma_2^4) = 2(9 - \gamma_2)(9 - (17 +$

$729\alpha)\gamma_2 + 243\alpha\gamma_2^2 - 27\alpha\gamma_2^3 + \alpha\gamma_2^4 + k) = 0$ and $F_9(\beta) = 0$. Therefore, γ_2 is the smallest root and multiple

roots of $F_9(\beta)$. Set $\beta = 1$, we get $\frac{d^3F_9(\beta)}{d\beta^3} = 84\alpha(-9 + \gamma_2)^2 > 0$, $\frac{d^2F_9(\beta)}{d\beta^2} = 2(-81(2 + 33\alpha) + (34 +$

$594\alpha)\gamma_2 + 48\alpha\gamma_2^2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) = 2(-81(2 + 33\alpha) + (34 + 594\alpha)\gamma_2 + 48\alpha\gamma_2^2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) + 2k =$

$6(-57 - 891\alpha + (17 + 441\alpha)\gamma_2 - 65\alpha\gamma_2^2 + 3\alpha\gamma_2^3) < 0$, $\frac{dF_9(\beta)}{d\beta} = -2(81(1 + 56\alpha) - 2(17 + 504\alpha)\gamma_2 +$

$(17 + 704\alpha)\gamma_2^2 - 144\alpha\gamma_2^3 + 8\alpha\gamma_2^4) = -2(81(1 + 56\alpha) - 2(17 + 504\alpha)\gamma_2 + (17 + 704\alpha)\gamma_2^2 - 144\alpha\gamma_2^3 +$

$8\alpha\gamma_2^4) - 16k = -2(9 + 4536\alpha + 6(17 + 804\alpha)\gamma_2 + (17 - 1240\alpha)\gamma_2^2 + 72\alpha\gamma_2^3) < 0$ and $F_9(\beta) = 64(-1 + \gamma_2)(81\alpha + (2 + 63\alpha)\gamma_2 - 17\alpha\gamma_2^2 + \alpha\gamma_2^3) < 0$. Therefore, $F_9(\beta)$ decreases in β and $F_9(\beta) < 0$. Then $\pi_{ML}^r(w_L, \gamma) < \pi_{ML}^n(w_L, \gamma)$.

(2) For the pharmacy, from formula (6), we get $\pi_R^r(q_H, q_L) - \pi_R^n(q_H, q_L) = \frac{\beta^2(-9-7\gamma_2)-729\gamma_2+9\gamma_2^2+\beta(729+7\gamma_2^2)}{(-9+\beta)^2(-9+\gamma_2)^2}$. Set

$F_{10}(\beta) = \beta^2(-9-7\gamma_2) - 729\gamma_2 + 9\gamma_2^2 + \beta(729 + 7\gamma_2^2)$, we get $\Delta = (-729 + 18\gamma_2 + 7\gamma_2^2)^2 > 0$. Set

$F_{10}(\beta) = 0$, we get $\beta_{11} = \frac{9(81-\gamma_2)}{9+7\gamma_2}$ and $\beta_{12} = \gamma_2$. Since $\gamma_2 < \beta \leq 1$, we should compare β_{11} with these

thresholds. Compare β_{11} with 1, we get $\beta_{11} - 1 = \frac{16(45-\gamma_2)}{9+7\gamma_2} > 0$. Therefore, $\pi_R^r(q_H, q_L) > \pi_R^n(q_H, q_L)$.

(3) For the pharmaceutical supply chain, we get $\pi^r - \pi^n = \frac{1}{2(-9+\beta)^2(-9+\gamma_2)^2} [\beta^4(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) +$

$\beta^3(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + \beta(486 - 38\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 - 18\alpha\gamma_2^4) + \beta^2(-198 - 6561\alpha + 38\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) - 486\gamma_2 + 198\gamma_2^2 + 6561\alpha\gamma_2^2 - 1458\alpha\gamma_2^3 + 81\alpha\gamma_2^4]$. Set $F_{11}(\beta) = \beta^4(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + \beta^3(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + \beta(486 - 38\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 - 18\alpha\gamma_2^4) + \beta^2(-198 - 6561\alpha + 38\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) - 486\gamma_2 + 198\gamma_2^2 + 6561\alpha\gamma_2^2 - 1458\alpha\gamma_2^3 + 81\alpha\gamma_2^4$, we get $\frac{dF_{11}(\beta)}{d\beta} = 486 - 38\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 - 18\alpha\gamma_2^4 + 4\beta^3(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 3\beta^2(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + 2\beta(-198 - 6561\alpha + 38\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4)$, $\frac{d^2F_{11}(\beta)}{d\beta^2} = 12\beta^2(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 6\beta(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + 2(-198 - 6561\alpha + 38\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4)$ and $\frac{d^3F_{11}(\beta)}{d\beta^3} = 24\beta(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 6(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2)$. And we get four roots of $F_{11}(\beta)$, β_{11} , β_{12} , β_{13} and β_{14} . Set $\beta = \gamma_2$, we get $\frac{d^3F_{11}(\beta)}{d\beta^3} = 12\alpha(-9 + \gamma_2)^2(9 - 2\gamma_2) > 0$, $\frac{d^2F_{11}(\beta)}{d\beta^2} = -2(9(22 + 729\alpha) - 2(19 + 2916\alpha)\gamma_2 + 1458\alpha\gamma_2^2 - 144\alpha\gamma_2^3 + 5\alpha\gamma_2^4) = -2(9(22 + 729\alpha) - 2(19 + 2916\alpha)\gamma_2 + 1458\alpha\gamma_2^2 - 144\alpha\gamma_2^3 + 5\alpha\gamma_2^4) - 10k = 2(-9(17 + 729\alpha) + (-47 + 2187\alpha)\gamma_2 - 243\alpha\gamma_2^2 + 9\alpha\gamma_2^3) < 0$, $\frac{dF_{11}(\beta)}{d\beta} = 2(9 - \gamma_2)(27 - (19 + 729\alpha)\gamma_2 + 243\alpha\gamma_2^2 - 27\alpha\gamma_2^3 + \alpha\gamma_2^4) = 2(9 - \gamma_2)(27 - (19 + 729\alpha)\gamma_2 + 243\alpha\gamma_2^2 - 27\alpha\gamma_2^3 + \alpha\gamma_2^4 + k) = 4(9 - \gamma_2)^2 > 0$ and $F_{11}(\beta) = 0$. Therefore, γ_2 is the smallest root of $F_{11}(\beta)$. Set $\beta = 1$, we get $\frac{d^3F_{11}(\beta)}{d\beta^3} = 84\alpha(-9 + \gamma_2)^2 > 0$, $\frac{d^2F_{11}(\beta)}{d\beta^2} = 2(-99(2 + 27\alpha) + (38 + 594\alpha)\gamma_2 + 48\alpha\gamma_2^2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) = 2(-99(2 + 27\alpha) + (38 + 594\alpha)\gamma_2 + 48\alpha\gamma_2^2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) + 2k = 2(-9(23 + 297\alpha) + (55 + 1323\alpha)\gamma_2 - 195\alpha\gamma_2^2 + 9\alpha\gamma_2^3) < 0$, $\frac{dF_{11}(\beta)}{d\beta} = 90 - 9072\alpha + 4(19 + 504\alpha)\gamma_2 - 2(19 + 704\alpha)\gamma_2^2 + 288\alpha\gamma_2^3 - 16\alpha\gamma_2^4 - 16k = -2(-117 + 98\gamma_2 + 19\gamma_2^2) - 2\alpha(4536 + 4824\gamma_2 - 1240\gamma_2^2 + 72\gamma_2^3)$. Set $\frac{dF_{11}(\beta)}{d\beta} = 0$, we get $\alpha_{31} = \frac{117 - 98\gamma_2 - 19\gamma_2^2}{8(-9 + \gamma_2)^2(7 + 9\gamma_2)}$. If $\alpha > \alpha_{31}$, then $\frac{dF_{11}(\beta)}{d\beta} < 0$. If $\alpha < \alpha_{31}$, then $\frac{dF_{11}(\beta)}{d\beta} > 0$. $F_{11}(\beta) = 32(1 - \gamma_2)(9 - 5\gamma_2 + \alpha(-162 - 126\gamma_2 + 34\gamma_2^2 - 2\gamma_2^3))$. Set $F_{11}(\beta) = 0$, we get $\alpha_{32} = \frac{9 - 5\gamma_2}{2(-9 + \gamma_2)^2(1 + \gamma_2)}$. Compare α_{32} with α_{31} , $\alpha_{31} - \alpha_{32} = -\frac{135 + 165\gamma_2 - 63\gamma_2^2 + 19\gamma_2^3}{8(-9 + \gamma_2)^2(1 + \gamma_2)(7 + 9\gamma_2)} < 0$, so $\alpha_{31} < \alpha_{32}$. If $\alpha > \alpha_{32}$, then $F_{11}(\beta) < 0$. If $\alpha_{31} < \alpha < \alpha_{32}$, then $F_{11}(\beta) > 0$. If $0 < \alpha < \alpha_{31}$, then $F_{11}(\beta) > 0$. Therefore, if $0 < \alpha < \alpha_{32}$ or $\alpha > \alpha_{32}$ and $\gamma_2 < \beta < \beta_{12}$, then $\pi^r > \pi^n$. Otherwise, $\pi^r < \pi^n$. Therefore, if $0 < \alpha < \alpha_2$ or $\alpha > \alpha_2$ and $\gamma_2 < \beta < \beta_2$, then $\pi^r > \pi^n$. Otherwise, $\pi^r < \pi^n$. where $\alpha_2 = \frac{9 - 5\gamma_2}{2(-9 + \gamma_2)^2(1 + \gamma_2)}$ and β_2 is upper second root of $F_{11}(\beta)$.

Proof of Proposition 2

(1) For the MS model, we get $W_s^r - W_s^n = \frac{1}{8(-4 + \beta)^2(-4 + \gamma_0)^2} [\beta^4(-64\alpha + 32\alpha\gamma_0 - 4\alpha\gamma_0^2) + \beta^3(512\alpha - 256\alpha\gamma_0 + 32\alpha\gamma_0^2) + \beta(208 - 33\gamma_0^2 - 512\alpha\gamma_0^2 + 256\alpha\gamma_0^3 - 32\alpha\gamma_0^4) + \beta^2(-92 - 1024\alpha + 33\gamma_0 + 512\alpha\gamma_0 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4) - 208\gamma_0 + 92\gamma_0^2 + 1024\alpha\gamma_0^2 - 512\alpha\gamma_0^3 + 64\alpha\gamma_0^4]$. Set $E_1(\beta) = \beta^4(-64\alpha + 32\alpha\gamma_0 - 4\alpha\gamma_0^2) + \beta^3(512\alpha - 256\alpha\gamma_0 + 32\alpha\gamma_0^2) + \beta(208 - 33\gamma_0^2 - 512\alpha\gamma_0^2 + 256\alpha\gamma_0^3 - 32\alpha\gamma_0^4) + \beta^2(-92 - 1024\alpha + 33\gamma_0 + 512\alpha\gamma_0 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4) - 208\gamma_0 + 92\gamma_0^2 + 1024\alpha\gamma_0^2 - 512\alpha\gamma_0^3 + 64\alpha\gamma_0^4$, we get

$\frac{dE_1(\beta)}{d\beta} = 4\beta^3(-64\alpha + 32\alpha\gamma_0 - 4\alpha\gamma_0^2) + 3\beta^2(512\alpha - 256\alpha\gamma_0 + 32\alpha\gamma_0^2) + 2\beta(-92 - 1024\alpha + 33\gamma_0 + 512\alpha\gamma_0 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4) + 208 - 33\gamma_0^2 - 512\alpha\gamma_0^2 + 256\alpha\gamma_0^3 - 32\alpha\gamma_0^4$, $\frac{d^2E_1(\beta)}{d\beta^2} = 12\beta^2(-64\alpha + 32\alpha\gamma_0 - 4\alpha\gamma_0^2) + 6\beta(512\alpha - 256\alpha\gamma_0 + 32\alpha\gamma_0^2) + 2(-92 - 1024\alpha + 33\gamma_0 + 512\alpha\gamma_0 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4)$, $\frac{d^3E_1(\beta)}{d\beta^3} = 24\beta(-64\alpha + 32\alpha\gamma_0 - 4\alpha\gamma_0^2) + 6(512\alpha - 256\alpha\gamma_0 + 32\alpha\gamma_0^2)$. And we get four roots of $E_1(\beta)$, β_{11} , β_{12} , β_{13} and β_{14} . Set $\beta = \gamma_0$, we get $\frac{d^3E_1(\beta)}{d\beta^3} = 96\alpha(-4 + \gamma_0)^2(2 - \gamma_0) > 0$, $\frac{d^2E_1(\beta)}{d\beta^2} = -8(23 + 256\alpha) + (66 + 4096\alpha)\gamma_0 - 2304\alpha\gamma_0^2 + 512\alpha\gamma_0^3 - 40\alpha\gamma_0^4 = -8(23 + 256\alpha) + (66 + 4096\alpha)\gamma_0 - 2304\alpha\gamma_0^2 + 512\alpha\gamma_0^3 - 40\alpha\gamma_0^4 - 20h = -8(13 + 256\alpha) + 2(-37 + 768\alpha)\gamma_0 - 384\alpha\gamma_0^2 + 32\alpha\gamma_0^3 < 0$, $\frac{dE_1(\beta)}{d\beta} = (4 - \gamma_0)(52 - (33 + 512\alpha)\gamma_0 + 384\alpha\gamma_0^2 - 96\alpha\gamma_0^3 + 8\alpha\gamma_0^4) = (4 - \gamma_0)(52 - (33 + 512\alpha)\gamma_0 + 384\alpha\gamma_0^2 - 96\alpha\gamma_0^3 + 8\alpha\gamma_0^4 + 4h) = (4 - \gamma_0)(36 - 5\gamma_0) > 0$ and $E_1(\beta) = 0$. Therefore, γ_0 is the smallest root of $E_1(\beta)$. Set $\beta = 1$, we get $\frac{d^3E_1(\beta)}{d\beta^3} = 96\alpha(-4 + \gamma_0)^2 > 0$, $\frac{d^2E_1(\beta)}{d\beta^2} = 2(-92 + 128\alpha + (33 - 64\alpha)\gamma_0 + 72\alpha\gamma_0^2 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4) = 2(-92 + 128\alpha + (33 - 64\alpha)\gamma_0 + 72\alpha\gamma_0^2 - 32\alpha\gamma_0^3 + 4\alpha\gamma_0^4) + 4h = -200 + 94\gamma_0 + \alpha(256 + 384\gamma_0 - 240\gamma_0^2 + 32\gamma_0^3)$. Set $\frac{d^2E_1(\beta)}{d\beta^2} = 0$, we get $\alpha_{11} = \frac{100 - 47\gamma_0}{8(-4 + \gamma_0)^2(1 + 2\gamma_0)}$. If $\alpha > \alpha_{11}$, then $\frac{d^2E_1(\beta)}{d\beta^2} > 0$. If $\alpha < \alpha_{11}$, then $\frac{d^2E_1(\beta)}{d\beta^2} < 0$. $\frac{dE_1(\beta)}{d\beta} = -3(-8 + 256\alpha - 2(11 + 64\alpha)\gamma_0 + (11 + 144\alpha)\gamma_0^2 - 64\alpha\gamma_0^3 + 8\alpha\gamma_0^4) = -3(-8 + 256\alpha - 2(11 + 64\alpha)\gamma_0 + (11 + 144\alpha)\gamma_0^2 - 64\alpha\gamma_0^3 + 8\alpha\gamma_0^4) - 12h = -3(-24 + 6\gamma_0 + 11\gamma_0^2) - 3\alpha(256 + 384\gamma_0 - 240\gamma_0^2 + 32\gamma_0^3)$. Set $\frac{dE_1(\beta)}{d\beta} = 0$, we get $\alpha_{12} = \frac{24 - 6\gamma_0 - 11\gamma_0^2}{16(-4 + \gamma_0)^2(1 + 2\gamma_0)}$. Compare α_{12} with α_{11} , we get $\alpha_{11} - \alpha_{12} = \frac{11}{16 + 32\gamma_0} > 0$, so $\alpha_{12} < \alpha_{11}$. If $\alpha < \alpha_{12}$, then $\frac{dE_1(\beta)}{d\beta} > 0$. If $\alpha_{12} < \alpha < \alpha_{11}$, then $\frac{dE_1(\beta)}{d\beta} < 0$. If $\alpha > \alpha_{11}$, then $\frac{dE_1(\beta)}{d\beta} < 0$. $E_1(\beta) = (-1 + \gamma_0)(-116 + 59\gamma_0) + \alpha(-1 + \gamma_0)(576 + 288\gamma_0 - 252\gamma_0^2 + 36\gamma_0^3)$. Set $E_1(\beta) = 0$, we get $\alpha_{13} = \frac{116 - 59\gamma_0}{36(-4 + \gamma_0)^2(1 + \gamma_0)}$. we should compare α_{13} with α_{11} and α_{12} . Compare α_{13} with α_{11} , we get $\alpha_{11} - \alpha_{13} = \frac{668 + 131\gamma_0 - 187\gamma_0^2}{72(-4 + \gamma_0)^2(1 + \gamma_0)(1 + 2\gamma_0)} > 0$, so $\alpha_{13} < \alpha_{11}$. Compare α_{13} with α_{12} , we get $\alpha_{12} - \alpha_{13} = -\frac{248 + 530\gamma_0 - 319\gamma_0^2 + 99\gamma_0^3}{144(-4 + \gamma_0)^2(1 + \gamma_0)(1 + 2\gamma_0)} < 0$, so $\alpha_{13} > \alpha_{12}$. Therefore, $\alpha_{12} < \alpha_{13} < \alpha_{11}$. If $0 < \alpha < \alpha_{12}$, then $E_1(\beta) > 0$. If $\alpha_{12} < \alpha < \alpha_{13}$, then $E_1(\beta) > 0$. If $\alpha_{13} < \alpha < \alpha_{11}$, then $E_1(\beta) < 0$. If $\alpha > \alpha_{11}$, then $E_1(\beta) < 0$. Therefore, if $0 < \alpha < \alpha_{13}$ or $\alpha > \alpha_{13}$ and $\gamma_0 < \beta < \beta_{12}$, then $W_s^r > W_s^n$. Otherwise, $W_s^r < W_s^n$. Therefore, if $0 < \alpha < \alpha_3$ or $\alpha > \alpha_3$ and $\gamma_0 < \beta < \beta_3$, then $W_s^r > W_s^n$. Otherwise, $W_s^r < W_s^n$. where $\alpha_3 = \frac{116 - 59\gamma_0}{36(-4 + \gamma_0)^2(1 + \gamma_0)}$ and β_3 is upper second root of $E_1(\beta)$.

(2) For the PS model, we get $W_s^r - W_s^n = \frac{1}{8(-4 + \beta)^2(-4 + \gamma_1)^2} [\beta^4(-64\alpha + 32\alpha\gamma_1 - 4\alpha\gamma_1^2) + \beta^3(512\alpha - 256\alpha\gamma_1 + 32\alpha\gamma_1^2) + \beta(208 - 33\gamma_1^2 - 512\alpha\gamma_1^2 + 256\alpha\gamma_1^3 - 32\alpha\gamma_1^4) + \beta^2(-92 - 1024\alpha + 33\gamma_1 + 512\alpha\gamma_1 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4) - 208\gamma_1 + 92\gamma_1^2 + 1024\alpha\gamma_1^2 - 512\alpha\gamma_1^3 + 64\alpha\gamma_1^4]$. Set $E_2(\beta) = \beta^4(-64\alpha + 32\alpha\gamma_1 -$

$4\alpha\gamma_1^2) + \beta^3(512\alpha - 256\alpha\gamma_1 + 32\alpha\gamma_1^2) + \beta(208 - 33\gamma_1^2 - 512\alpha\gamma_1^2 + 256\alpha\gamma_1^3 - 32\alpha\gamma_1^4) + \beta^2(-92 - 1024\alpha + 33\gamma_1 + 512\alpha\gamma_1 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4) - 208\gamma_1 + 92\gamma_1^2 + 1024\alpha\gamma_1^2 - 512\alpha\gamma_1^3 + 64\alpha\gamma_1^4$, we get $\frac{dE_2(\beta)}{d\beta} = 208 - 33\gamma_1^2 - 512\alpha\gamma_1^2 + 256\alpha\gamma_1^3 - 32\alpha\gamma_1^4 + 4\beta^3(-64\alpha + 32\alpha\gamma_1 - 4\alpha\gamma_1^2) + 3\beta^2(512\alpha - 256\alpha\gamma_1 + 32\alpha\gamma_1^2) + 2\beta(-92 - 1024\alpha + 33\gamma_1 + 512\alpha\gamma_1 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4)$, $\frac{d^2E_2(\beta)}{d\beta^2} = 12\beta^2(-64\alpha + 32\alpha\gamma_1 - 4\alpha\gamma_1^2) + 6\beta(512\alpha - 256\alpha\gamma_1 + 32\alpha\gamma_1^2) + 2(-92 - 1024\alpha + 33\gamma_1 + 512\alpha\gamma_1 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4)$ and $\frac{d^3E_2(\beta)}{d\beta^3} = 24\beta(-64\alpha + 32\alpha\gamma_1 - 4\alpha\gamma_1^2) + 6(512\alpha - 256\alpha\gamma_1 + 32\alpha\gamma_1^2)$. And we get four roots of $E_2(\beta)$, β_{11} , β_{12} , β_{13} and β_{14} . Set $\beta = \gamma_1$, we get $\frac{d^3E_2(\beta)}{d\beta^3} = 96\alpha(-4 + \gamma_1)^2(2 - \gamma_1) > 0$, $\frac{d^2E_2(\beta)}{d\beta^2} = -8(23 + 256\alpha) + (66 + 4096\alpha)\gamma_1 - 2304\alpha\gamma_1^2 + 512\alpha\gamma_1^3 - 40\alpha\gamma_1^4 = -8(23 + 256\alpha) + (66 + 4096\alpha)\gamma_1 - 2304\alpha\gamma_1^2 + 512\alpha\gamma_1^3 - 40\alpha\gamma_1^4 - 10e = 4(-4(9 + 128\alpha) + (-1 + 384\alpha)\gamma_1 - 96\alpha\gamma_1^2 + 8\alpha\gamma_1^3) < 0$, $\frac{dE_2(\beta)}{d\beta} = (4 - \gamma_1)(52 - (33 + 512\alpha)\gamma_1 + 384\alpha\gamma_1^2 - 96\alpha\gamma_1^3 + 8\alpha\gamma_1^4 + 2e) = (4 - \gamma_1)(44 - 19\gamma_1) > 0$ and $E_2(\beta) = 0$. Therefore, γ_1 is the smallest root of $E_2(\beta)$. Set $\beta = 1$, we get $\frac{d^3E_2(\beta)}{d\beta^3} = 96\alpha(-4 + \gamma_1)^2 > 0$, $\frac{d^2E_2(\beta)}{d\beta^2} = 2(-92 + 128\alpha + (33 - 64\alpha)\gamma_1 + 72\alpha\gamma_1^2 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4) = 2(-92 + 128\alpha + (33 - 64\alpha)\gamma_1 + 72\alpha\gamma_1^2 - 32\alpha\gamma_1^3 + 4\alpha\gamma_1^4) + 2e = 16(-12 + 5\gamma_1 + \alpha(16 + 24\gamma_1 - 15\gamma_1^2 + 2\gamma_1^3))$. Set $\frac{d^2E_2(\beta)}{d\beta^2} = 0$, we get $\alpha_{21} = \frac{12-5\gamma_1}{(-4+\gamma_1)^2(1+2\gamma_1)}$. If $\alpha > \alpha_{21}$, then $\frac{d^2E_2(\beta)}{d\beta^2} > 0$. If $\alpha < \alpha_{21}$, then $\frac{d^2E_2(\beta)}{d\beta^2} < 0$. $\frac{dE_2(\beta)}{d\beta} = -3(-8 + 256\alpha - 2(11 + 64\alpha)\gamma_1 + (11 + 144\alpha)\gamma_1^2 - 64\alpha\gamma_1^3 + 8\alpha\gamma_1^4) = -3(-8 + 256\alpha - 2(11 + 64\alpha)\gamma_1 + (11 + 144\alpha)\gamma_1^2 - 64\alpha\gamma_1^3 + 8\alpha\gamma_1^4) - 6e = 3(16 + 8\gamma_1 - 11\gamma_1^2 + \alpha(-256 - 384\gamma_1 + 240\gamma_1^2 - 32\gamma_1^3))$. Set $\frac{dE_2(\beta)}{d\beta} = 0$, we get $\alpha_{22} = \frac{16+8\gamma_1-11\gamma_1^2}{16(-4+\gamma_1)^2(1+2\gamma_1)}$. Compare α_{22} with α_{21} , we get $\alpha_{21} - \alpha_{22} = \frac{11}{16+32\gamma_1} > 0$, so $\alpha_{22} < \alpha_{21}$. If $\alpha < \alpha_{22}$, then $\frac{dE_2(\beta)}{d\beta} > 0$. If $\alpha_{22} < \alpha < \alpha_{21}$, then $\frac{dE_2(\beta)}{d\beta} < 0$. If $\alpha > \alpha_{21}$, then $\frac{dE_2(\beta)}{d\beta} < 0$. $E_2(\beta) = (1 - \gamma_1)(116 - 59\gamma_1 + \alpha(-576 - 288\gamma_1 + 252\gamma_1^2 - 36\gamma_1^3))$. Set $E_2(\beta) = 0$, we get $\alpha_{23} = \frac{116-59\gamma_1}{36(-4+\gamma_1)^2(1+\gamma_1)}$. we should compare α_{23} with α_{21} and α_{22} . Compare α_{23} with α_{21} , we get $\alpha_{21} - \alpha_{23} = \frac{316+79\gamma_1-62\gamma_1^2}{36(-4+\gamma_1)^2(1+\gamma_1)(1+2\gamma_1)} > 0$, so $\alpha_{23} < \alpha_{21}$. Compare α_{23} with α_{22} , we get $\alpha_{22} - \alpha_{23} = -\frac{320+476\gamma_1-445\gamma_1^2+99\gamma_1^3}{144(-4+\gamma_1)^2(1+\gamma_1)(1+2\gamma_1)} < 0$, so $\alpha_{23} > \alpha_{22}$. Therefore, $\alpha_{22} < \alpha_{23} < \alpha_{21}$. If $0 < \alpha < \alpha_{22}$, then $E_2(\beta) > 0$. If $\alpha_{22} < \alpha < \alpha_{23}$, then $E_2(\beta) > 0$. If $\alpha_{23} < \alpha < \alpha_{21}$, then $E_2(\beta) < 0$. If $\alpha > \alpha_{21}$, then $E_2(\beta) < 0$. Therefore, if $0 < \alpha < \alpha_{23}$ or $\alpha > \alpha_{23}$ and $\gamma_1 < \beta < \beta_{12}$, then $W_s^r > W_s^n$. Otherwise, $W_s^r < W_s^n$. Therefore, if $0 < \alpha < \alpha_3$ or $\alpha > \alpha_3$ and $\gamma_1 < \beta < \beta_3$, then $W_s^r > W_s^n$. Otherwise, $W_s^r < W_s^n$. where $\alpha_3 = \frac{316+79\gamma_1-62\gamma_1^2}{36(-4+\gamma_1)^2(1+\gamma_1)(1+2\gamma_1)}$ and β_3 is upper second root of $E_2(\beta)$.

(3) For the VN model, we get $W_s^r - W_s^n = \frac{1}{2(-9+\beta)^2(-9+\gamma_2)^2}[\beta^4(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + \beta^3(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + \beta(729 - 37\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 - 18\alpha\gamma_2^4) + \beta^2(-207 - 6561\alpha + 37\gamma_2 +$

$1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) - 729\gamma_2 + 207\gamma_2^2 + 6561\alpha\gamma_2^2 - 1458\alpha\gamma_2^3 + 81\alpha\gamma_2^4]$. Set $E_3(\beta) = \beta^4(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + \beta^3(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + \beta(729 - 37\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 - 18\alpha\gamma_2^4) + \beta^2(-207 - 6561\alpha + 37\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) - 729\gamma_2 + 207\gamma_2^2 + 6561\alpha\gamma_2^2 - 1458\alpha\gamma_2^3 + 81\alpha\gamma_2^4$,

we get $\frac{dE_3(\beta)}{d\beta} = 729 - 37\gamma_2^2 - 1458\alpha\gamma_2^2 + 324\alpha\gamma_2^3 - 18\alpha\gamma_2^4 + 4\beta^3(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 3\beta^2(1458\alpha -$

$324\alpha\gamma_2 + 18\alpha\gamma_2^2) + 2\beta(-207 - 6561\alpha + 37\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4)$, $\frac{d^2E_3(\beta)}{d\beta^2} = 12\beta^2(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 6\beta(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2) + 2(-207 - 6561\alpha + 37\gamma_2 + 1458\alpha\gamma_2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4)$

and $\frac{d^3E_3(\beta)}{d\beta^3} = 24\beta(-81\alpha + 18\alpha\gamma_2 - \alpha\gamma_2^2) + 6(1458\alpha - 324\alpha\gamma_2 + 18\alpha\gamma_2^2)$. And we get four roots of $E_3(\beta)$,

$\beta_{11}, \beta_{12}, \beta_{13}$ and β_{14} . Set $\beta = \gamma_2$, we get $\frac{d^3E_3(\beta)}{d\beta^3} = 12\alpha(-9 + \gamma_2)^2(9 - 2\gamma_2) > 0$, $\frac{d^2E_3(\beta)}{d\beta^2} = -2(9(23 + 729\alpha) - (37 + 5832\alpha)\gamma_2 + 1458\alpha\gamma_2^2 - 144\alpha\gamma_2^3 + 5\alpha\gamma_2^4) = -2(9(23 + 729\alpha) - (37 + 5832\alpha)\gamma_2 + 1458\alpha\gamma_2^2 - 144\alpha\gamma_2^3 + 5\alpha\gamma_2^4) - 10k = 6(-27(2 + 81\alpha) + (-16 + 729\alpha)\gamma_2 - 81\alpha\gamma_2^2 + 3\alpha\gamma_2^3) < 0$, $\frac{dE_3(\beta)}{d\beta} = (9 - \gamma_2)(81 - (37 + 1458\alpha)\gamma_2 + 486\alpha\gamma_2^2 - 54\alpha\gamma_2^3 + 2\alpha\gamma_2^4) = (9 - \gamma_2)(81 - (37 + 1458\alpha)\gamma_2 + 486\alpha\gamma_2^2 - 54\alpha\gamma_2^3 + 2\alpha\gamma_2^4 + 2k) = (9 - \gamma_2)(63 - 3\gamma_2) > 0$ and $E_3(\beta) = 0$. Therefore, γ_2 is the smallest root of $E_3(\beta)$.

Set $\beta = 1$, we get $\frac{d^3E_3(\beta)}{d\beta^3} = 84\alpha(-9 + \gamma_2)^2 > 0$, $\frac{d^2E_3(\beta)}{d\beta^2} = 2(-9(23 + 297\alpha) + (37 + 594\alpha)\gamma_2 + 48\alpha\gamma_2^2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) = 2(-9(23 + 297\alpha) + (37 + 594\alpha)\gamma_2 + 48\alpha\gamma_2^2 - 18\alpha\gamma_2^3 + \alpha\gamma_2^4) + 2k = 6(-9(8 + 99\alpha) + 9(2 + 49\alpha)\gamma_2 - 65\alpha\gamma_2^2 + 3\alpha\gamma_2^3) < 0$, $\frac{dE_3(\beta)}{d\beta} = 315 - 9072\alpha + (74 + 2016\alpha)\gamma_2 - (37 + 1408\alpha)\gamma_2^2 + 288\alpha\gamma_2^3 - 16\alpha\gamma_2^4 = 315 - 9072\alpha + (74 + 2016\alpha)\gamma_2 - (37 + 1408\alpha)\gamma_2^2 + 288\alpha\gamma_2^3 - 16\alpha\gamma_2^4 - 16k = 459 - 198\gamma_2 - 37\gamma_2^2 + \alpha(-9072 - 9648\gamma_2 + 2480\gamma_2^2 - 144\gamma_2^3)$. Set $\frac{dE_3(\beta)}{d\beta} = 0$, we get $\alpha_{31} =$

$\frac{459-198\gamma_2-37\gamma_2^2}{16(-9+\gamma_2)^2(7+9\gamma_2)}$. If $\alpha > \alpha_{31}$, then $\frac{dE_3(\beta)}{d\beta} < 0$. If $\alpha < \alpha_{31}$, then $\frac{dE_3(\beta)}{d\beta} > 0$. $E_3(\beta) = 2(1 - \gamma_2)(261 - 85\gamma_2 +$

$\alpha(-2592 - 2016\gamma_2 + 544\gamma_2^2 - 32\gamma_2^3))$. Set $E_3(\beta) = 0$, we get $\alpha_{32} = \frac{261-85\gamma_2}{32(-9+\gamma_2)^2(1+\gamma_2)}$. Compare α_{32} with α_{31} ,

$\alpha_{31} - \alpha_{32} = -\frac{909+1232\gamma_2-295\gamma_2^2+74\gamma_2^3}{32(-9+\gamma_2)^2(1+\gamma_2)(7+9\gamma_2)} < 0$, so $\alpha_{31} < \alpha_{32}$. If $\alpha > \alpha_{32}$, then $E_3(\beta) < 0$. If $\alpha_{31} < \alpha < \alpha_{32}$, then

$E_3(\beta) > 0$. If $0 < \alpha < \alpha_{31}$, then $E_3(\beta) > 0$. Therefore, if $0 < \alpha < \alpha_{32}$ or $\alpha > \alpha_{32}$ and $\gamma_2 < \beta < \beta_{12}$, then $W_s^r > W_s^n$. Otherwise, $W_s^r < W_s^n$.

Therefore, if $0 < \alpha < \alpha_3$ or $\alpha > \alpha_3$ and $\gamma_2 < \beta < \beta_3$, then $W_s^r > W_s^n$. Otherwise, $W_s^r < W_s^n$. where $\alpha_3 =$

$\frac{261-85\gamma_2}{32(-9+\gamma_2)^2(1+\gamma_2)}$ and β_3 is upper second root of $E_3(\beta)$.

Proof of Proposition 3

From proposition 1 and 2, we get $\alpha_2^m - \alpha_3^m = \frac{-44+5\gamma_0}{36(-4+\gamma_0)^2(1+\gamma_0)} < 0$, so $\alpha_2^m < \alpha_3^m$. Similarly, we get $\alpha_2^p < \alpha_3^p$ and

$\alpha_2^v < \alpha_3^v$. Combined to the figure 2, we know that $\beta_2^j < \beta_3^j$. Therefore, If $0 < \alpha < \alpha_2^j$ or $\alpha > \alpha_2^j$ and $\gamma^{nj} < \beta < \beta_2^j$, then $\pi^{rj} > \pi^{nj}$ and $W_s^{rj} > W_s^{nj}$.

Proof of Proposition 4

MS model

From proof of proposition 1, we know $\pi_{MH}^n(w_H) - \pi_{MH}^r(w_H) = \frac{2(8\beta + \beta^2 - 8\gamma_0 - \beta^2\gamma_0 - \gamma_0^2 + \beta\gamma_0^2)}{(-4 + \beta)^2(-4 + \gamma_0)^2}$. For quality regulation

model, $\theta_H^m p_H q_H = \frac{3(2 - \beta)\theta_H^m}{2(4 - \beta)^2}$. Set $\frac{2(8\beta + \beta^2 - 8\gamma_0 - \beta^2\gamma_0 - \gamma_0^2 + \beta\gamma_0^2)}{(-4 + \beta)^2(-4 + \gamma_0)^2} = \frac{3(2 - \beta)\theta_H^m}{2(4 - \beta)^2}$, we get $\theta_H^m = \frac{4(\beta - \gamma_0)[8 + \beta + (1 - \beta)\gamma_0]}{3(2 - \beta)(4 - \gamma_0)^2}$.

$\pi_{ML}^n(w_L, \gamma) - \pi_{ML}^r(w_L, \gamma) = \frac{-F_2(\beta)}{2(4 - \beta)^2(4 - \gamma_0)^2}$. For quality regulation model, $\theta_L^m p_L q_L = \frac{\beta(5 - 2\beta)\theta_L^m}{4(-4 + \beta)^2}$. Set

$\frac{-F_2(\beta)}{2(4 - \beta)^2(4 - \gamma_0)^2} = \frac{\beta(5 - 2\beta)\theta_L^m}{4(-4 + \beta)^2}$, we get $\theta_L^m = \frac{-2F_2(\beta)}{\beta(5 - 2\beta)(4 - \gamma_0)^2}$.

PS model

From proof of proposition 1, we know $\pi_{MH}^n(w_H) - \pi_{MH}^r(w_H) = \frac{\beta(8 + \beta) - (8 + \beta^2)\gamma_1 + (-1 + \beta)\gamma_1^2}{(-4 + \beta)^2(-4 + \gamma_1)^2}$. For quality regulation

model, $\theta_H^p p_H q_H = \frac{3(2 - \beta)\theta_H^p}{2(4 - \beta)^2}$. Set $\frac{\beta(8 + \beta) - (8 + \beta^2)\gamma_1 + (-1 + \beta)\gamma_1^2}{(-4 + \beta)^2(-4 + \gamma_1)^2} = \frac{3(2 - \beta)\theta_H^p}{2(4 - \beta)^2}$, we get $\theta_H^p = \frac{2(\beta - \gamma_1)[8 + \beta + (1 - \beta)\gamma_1]}{3(2 - \beta)(4 - \gamma_1)^2}$.

$\pi_{ML}^n(w_L, \gamma) - \pi_{ML}^r(w_L, \gamma) = \frac{-F_6(\beta)}{4(-4 + \beta)^2(-4 + \gamma_1)^2}$. For quality regulation model, $\theta_L^p p_L q_L = \frac{\beta(5 - 2\beta)\theta_L^p}{4(-4 + \beta)^2}$. Set

$\frac{-F_6(\beta)}{4(-4 + \beta)^2(-4 + \gamma_1)^2} = \frac{\beta(5 - 2\beta)\theta_L^p}{4(-4 + \beta)^2}$, we get $\theta_L^p = \frac{-F_6(\beta)}{\beta(5 - 2\beta)(4 - \gamma_1)^2}$.

VN model

From proof of proposition 1, we know $\pi_{MH}^n(w_H) - \pi_{MH}^r(w_H) = \frac{9[\beta^2(1 - \gamma_2) - 63\gamma_2 - \gamma_2^2 + \beta(63 + \gamma_2^2)]}{(-9 + \beta)^2(-9 + \gamma_2)^2}$. For quality

regulation model, $\theta_H^v p_H q_H = \frac{6(3 - \beta)\theta_H^v}{(9 - \beta)^2}$. Set $\frac{9[\beta^2(1 - \gamma_2) - 63\gamma_2 - \gamma_2^2 + \beta(63 + \gamma_2^2)]}{(-9 + \beta)^2(-9 + \gamma_2)^2} = \frac{6(3 - \beta)\theta_H^v}{(9 - \beta)^2}$, we get $\theta_H^v =$

$\frac{3(\beta - \gamma_2)[63 + \beta + (1 - \beta)\gamma_2]}{2(3 - \beta)(9 - \gamma_2)^2}$. $\pi_{ML}^n(w_L, \gamma) - \pi_{ML}^r(w_L, \gamma) = \frac{-F_9(\beta)}{2(9 - \beta)^2(9 - \gamma_2)^2}$. For quality regulation model, $\theta_L^v p_L q_L =$

$\frac{(5 - \beta)\beta\theta_L^v}{(9 - \beta)^2}$. Set $\frac{-F_9(\beta)}{2(9 - \beta)^2(9 - \gamma_2)^2} = \frac{(5 - \beta)\beta\theta_L^v}{(9 - \beta)^2}$, we get $\theta_L^v = \frac{-F_9(\beta)}{2\beta(5 - \beta)(9 - \gamma_2)^2}$.

Proof of Lemma 2

No quality regulation model

From the proof of table 2, we know $h = -4 + (7 + 128\alpha)\gamma_0 - 96\alpha\gamma_0^2 + 24\alpha\gamma_0^3 - 2\alpha\gamma_0^4 = 0$, then we get $\alpha =$

$\frac{-4 + 7\gamma_0}{2(-4 + \gamma_0)^3\gamma_0}$ and $\gamma_0 < \frac{4}{7}$. $e = -4 + (7 + 256\alpha)\gamma_1 - 192\alpha\gamma_1^2 + 48\alpha\gamma_1^3 - 4\alpha\gamma_1^4 = 0$, then we get $\alpha =$

$\frac{-4 + 7\gamma_1}{4(-4 + \gamma_1)^3\gamma_1}$ and $\gamma_1 < \frac{4}{7}$. $k = -9 + (17 + 729\alpha)\gamma - 243\alpha\gamma^2 + 27\alpha\gamma^3 - \alpha\gamma^4 = 0$, then we get $\alpha = \frac{-9 + 17\gamma_2}{(-9 + \gamma_2)^3\gamma_2}$

and $\gamma_2 < \frac{9}{17}$.

(1) Compare γ_0 with γ_1 , replace γ_1 into h , we get $-4 + (7 + 128\alpha)\gamma_1 - 96\alpha\gamma_1^2 + 24\alpha\gamma_1^3 - 2\alpha\gamma_1^4 - \frac{1}{2}e =$

$-2 + \frac{7\gamma_1}{2} < 0$. If $\gamma = \gamma_1$, then $\frac{-4 + (7 + 128\alpha)\gamma - 96\alpha\gamma^2 + 24\alpha\gamma^3 - 2\alpha\gamma^4}{2(-4 + \gamma)^3} > 0$, then $\gamma_1 < \gamma_0$. Compare γ_1 with γ_2 , replace

γ_2 into e , we get $-4 + (7 + 256\alpha)\gamma_2 - 192\alpha\gamma_2^2 + 48\alpha\gamma_2^3 - 4\alpha\gamma_2^4 - 4k = 32 - (61 + 2660\alpha)\gamma_2 +$

$780\alpha\gamma_2^2 - 60\alpha\gamma_2^3 = \frac{612 + 5\gamma_2 - 1887\gamma_2^2 + 659\gamma_2^3 - 61\gamma_2^4}{(-9 + \gamma_2)^3}$. Set $F(\gamma_2) = 612 + 5\gamma_2 - 1887\gamma_2^2 + 659\gamma_2^3 - 61\gamma_2^4$, we get

$\frac{dF(\gamma_2)}{d\gamma_2} = 5 - 3774\gamma_2 + 1977\gamma_2^2 - 244\gamma_2^3$, $\frac{d^2F(\gamma_2)}{d(\gamma_2)^2} = -3774 + 3954\gamma_2 - 732\gamma_2^2$ and $\frac{d^3F(\gamma_2)}{d(\gamma_2)^3} = 3954 - 1464\gamma_2$.

Set $\gamma_2 = 0$, we get $\frac{d^3F(\gamma_2)}{d(\gamma_2)^3} = 3954 > 0$, $\frac{d^2F(\gamma_2)}{d(\gamma_2)^2} = -3774 < 0$, $\frac{dF(\gamma_2)}{d\gamma_2} = 5 > 0$ and $F(\gamma_2) = 612 > 0$. Set

$\gamma_2 = \frac{9}{17}$, we get $\frac{d^3F(\gamma_2)}{d(\gamma_2)^3} = \frac{54042}{17} > 0$, $\frac{d^2F(\gamma_2)}{d(\gamma_2)^2} = -\frac{545016}{289} < 0$, $\frac{dF(\gamma_2)}{d\gamma_2} = -\frac{7247156}{4913} < 0$ and $F(\gamma_2) = \frac{14929920}{83521} > 0$,

so $F(\gamma_2) > 0$ and $\frac{612+5\gamma_2-1887\gamma_2^2+659\gamma_2^3-61\gamma_2^4}{(-9+\gamma_2)^3} < 0$. If $\gamma = \gamma_2$, then $\frac{-4+(7+256\alpha)\gamma-192\alpha\gamma^2+48\alpha\gamma^3-4\alpha\gamma^4}{4(-4+\gamma)^3} > 0$, then

$\gamma_2 < \gamma_1$. Therefore, $\gamma_2 < \gamma_1 < \gamma_0$.

(2) For unit wholesale price of product H, we get $w_H^{nm} - w_H^{nv} = \frac{6+10\gamma_2-\gamma_0(15+\gamma_2)}{(-4+\gamma_0)(-9+\gamma_2)} > 0$, so $w_H^{nm} > w_H^{nv}$. $w_H^{nv} -$

$w_H^{np} = \frac{3-11\gamma_2+2\gamma_1(3+\gamma_2)}{(-4+\gamma_1)(-9+\gamma_2)}$, $3-11\gamma_2+2\gamma_1(3+\gamma_2) > 3-5 \times \frac{4}{7} + 6\gamma_1 - 6\gamma_2 + 2\gamma_1\gamma_2 = \frac{1}{7} + 6\gamma_1 - 6\gamma_2 +$

$2\gamma_1\gamma_2 > 0$, so $w_H^{nv} > w_H^{np}$. Therefore, $w_H^{nm} > w_H^{nv} > w_H^{np}$.

For unit wholesale price of product L, we get $w_L^{nm} - w_L^{np} = \frac{8\gamma_0-8\gamma_0^2-4\gamma_1-\gamma_0\gamma_1+2\gamma_0^2\gamma_1+4\gamma_1^2-\gamma_0\gamma_1^2}{2(-4+\gamma_0)(-4+\gamma_1)} > 0$, so $w_L^{nm} >$

w_L^{np} . $w_L^{np} - w_L^{nv} = \frac{9\gamma_1-9\gamma_1^2-8\gamma_2+\gamma_1\gamma_2+\gamma_1^2\gamma_2+8\gamma_2^2-2\gamma_1\gamma_2^2}{2(-4+\gamma_1)(-9+\gamma_2)} > 0$, so $w_L^{np} > w_L^{nv}$. Therefore, $w_L^{nm} > w_L^{np} > w_L^{nv}$.

(3) For the optimal order quantity of product H, we get $q_H^{nm} - q_H^{np} = \frac{\gamma_0-\gamma_1}{(-4+\gamma_0)(-4+\gamma_1)} > 0$, so $q_H^{nm} > q_H^{np}$. $q_H^{np} -$

$q_H^{nm} = \frac{3-3\gamma_0+\gamma_2}{(-4+\gamma_0)(-9+\gamma_2)} > 0$, so $q_H^{nv} > q_H^{nm}$. Therefore, $q_H^{nv} > q_H^{nm} > q_H^{np}$.

For the optimal order quantity of product L, we get $q_L^{nm} - q_L^{np} = \frac{\gamma_0-\gamma_1}{2(-4+\gamma_0)(-4+\gamma_1)} > 0$, so $q_L^{nm} > q_L^{np}$. $q_L^{np} -$

$q_L^{nv} = \frac{1+2\gamma_1-\gamma_2}{2(-4+\gamma_1)(-9+\gamma_2)} > 0$, so $q_L^{np} > q_L^{nv}$. Therefore, $q_L^{nm} > q_L^{np} > q_L^{nv}$.

(4) For unit retail price of product H, we get $p_H^{nm} - p_H^{np} = -\frac{3(\gamma_0-\gamma_1)}{(-4+\gamma_0)(-4+\gamma_1)} < 0$, so $p_H^{np} > p_H^{nm}$. $p_H^{nm} - p_H^{nv} =$

$\frac{6-15\gamma_0+10\gamma_2-\gamma_0\gamma_2}{2(-4+\gamma_0)(-9+\gamma_2)} > 0$, so $p_H^{nm} > p_H^{nv}$. Therefore, $p_H^{np} > p_H^{nm} > p_H^{nv}$.

For unit retail price of product L, we get $p_L^{nm} - p_L^{np} = \frac{10\gamma_0-4\gamma_0^2-10\gamma_1+\gamma_0^2\gamma_1+4\gamma_1^2-\gamma_0\gamma_1^2}{(-4+\gamma_0)(-4+\gamma_1)} > 0$, so $p_L^{nm} > p_L^{np}$. $p_L^{np} -$

$p_L^{nv} = \frac{45\gamma_1-18\gamma_1^2-40\gamma_2+5\gamma_1\gamma_2+2\gamma_1^2\gamma_2+8\gamma_2^2-2\gamma_1\gamma_2^2}{2(-4+\gamma_1)(-9+\gamma_2)} > 0$, so $p_L^{np} > p_L^{nv}$. Therefore, $p_L^{nm} > p_L^{np} > p_L^{nv}$.

Quality regulation model

(1) From the table 2, we get $\gamma^{rm} = \gamma^{rp} = \gamma^{rv} = \beta$.

(2) For unit wholesale price of product H, we get $w_H^{rm} - w_H^{rv} = \frac{(1-\beta)(6+\beta)}{(9-\beta)(4-\beta)} > 0$, so $w_H^{rm} > w_H^{rv}$. $w_H^{rv} - w_H^{rp} =$

$\frac{(1-\beta)(3-2\beta)}{(9-\beta)(4-\beta)} > 0$, so $w_H^{rv} > w_H^{rp}$. Therefore, $w_H^{rm} > w_H^{rv} > w_H^{rp}$.

For unit wholesale price of product L, we get $w_L^{rm} - w_L^{rp} = \frac{(1-\beta)\beta}{2(4-\beta)} > 0$, so $w_L^{rm} > w_L^{rp}$. $w_L^{rp} - w_L^{rv} =$

$\frac{\beta-\beta^3}{72-26\beta+2\beta^2} > 0$, so $w_L^{rp} > w_L^{rv}$. Therefore, $w_L^{rm} > w_L^{rp} > w_L^{rv}$.

(3) For the optimal order quantity of product H, we get $q_H^{rm} - q_H^{rp} = 0$, so $q_H^{rm} = q_H^{rp}$. $q_H^{rm} - q_H^{rv} =$

$\frac{-3+2\beta}{(9-\beta)(4-\beta)} < 0$, so $q_H^{rm} < q_H^{rv}$. Therefore, $q_H^{rv} > q_H^{rm} = q_H^{rp}$.

For the optimal order quantity of product L, we get $q_L^{rm} - q_L^{rp} = 0$, so $q_L^{rm} = q_L^{rp}$. $q_L^{rm} - q_L^{rv} = \frac{1+\beta}{72-26\beta+2\beta^2} > 0$, so $q_L^{rm} > q_L^{rv}$. Therefore, $q_L^{rm} = q_L^{rp} > q_L^{rv}$.

(4) For unit retail price of product H, we get $p_H^{rm} - p_H^{rp} = 0$, so $p_H^{rm} = p_H^{rp}$. $p_H^{rm} - p_H^{rv} = \frac{6-5\beta-\beta^2}{2(9-\beta)(4-\beta)} > 0$, so $p_H^{rm} > p_H^{rv}$. Therefore, $p_H^{rm} = p_H^{rp} > p_H^{rv}$.

For unit retail price of product L, we get $p_L^{rm} - p_L^{rp} = 0$, so $p_L^{rm} = p_L^{rp}$. $p_L^{rm} - p_L^{rv} = \frac{5(1-\beta)\beta}{2(9-\beta)(4-\beta)} > 0$, so $p_L^{rm} > p_L^{rv}$. Therefore, $p_L^{rm} = p_L^{rp} > p_L^{rv}$.

Proof of Proposition 5

No quality regulation model

(1) For the pharmaceutical manufacturer 1, we get $\pi_{MH}^{nm}(w_H) - \pi_{MH}^{nv}(w_H) = \frac{18-90\gamma_0-9\gamma_0^2+108\gamma_2-36\gamma_0\gamma_2+9\gamma_0^2\gamma_2+2\gamma_2^2-2\gamma_0\gamma_2^2}{(-4+\gamma_0)^2(-9+\gamma_2)^2} > 0$, so $\pi_{MH}^{nm}(w_H) > \pi_{MH}^{nv}(w_H)$. $\pi_{MH}^{nv}(w_H) - \pi_{MH}^{np}(w_H) = \frac{63+9\gamma_1+9\gamma_1^2-126\gamma_2+54\gamma_1\gamma_2-9\gamma_1^2\gamma_2-\gamma_2^2+\gamma_1\gamma_2^2}{(-4+\gamma_1)^2(-9+\gamma_2)^2} > 0$, so $\pi_{MH}^{nv}(w_H) > \pi_{MH}^{np}(w_H)$. Therefore, $\pi_{MH}^{nm}(w_H) > \pi_{MH}^{nv}(w_H) > \pi_{MH}^{np}(w_H)$.

For the pharmaceutical manufacturer 2, we get $\pi_{ML}^{nm}(w_L, \gamma) - \pi_{ML}^{np}(w_L, \gamma) = \frac{1}{4(-4+\gamma_0)^2(-4+\gamma_1)^2} [-2(-4 + \gamma_0)^2(-4 + \gamma_1)^2(\gamma_0^2 - \gamma_1^2)\alpha + 32\gamma_0 - 32\gamma_0^2 - 16\gamma_1 - 8\gamma_0\gamma_1 + 15\gamma_0^2\gamma_1 + 16\gamma_1^2 - 6\gamma_0\gamma_1^2 - \gamma_0^2\gamma_1^2]$. Set $F_{12}(\alpha) = -2(-4 + \gamma_0)^2(-4 + \gamma_1)^2(\gamma_0^2 - \gamma_1^2)\alpha + 32\gamma_0 - 32\gamma_0^2 - 16\gamma_1 - 8\gamma_0\gamma_1 + 15\gamma_0^2\gamma_1 + 16\gamma_1^2 - 6\gamma_0\gamma_1^2 - \gamma_0^2\gamma_1^2$, $F_{12}(\alpha)$ decreases in α . Set $F_{12}(\alpha) = 0$, we get $\alpha_1 = \frac{32\gamma_0-32\gamma_0^2-16\gamma_1-8\gamma_0\gamma_1+15\gamma_0^2\gamma_1+16\gamma_1^2-6\gamma_0\gamma_1^2-\gamma_0^2\gamma_1^2}{2(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2-\gamma_1^2)}$. Compare α_1

with α , $\alpha_1 - \alpha = \frac{32\gamma_0-32\gamma_0^2-16\gamma_1-8\gamma_0\gamma_1+15\gamma_0^2\gamma_1+16\gamma_1^2-6\gamma_0\gamma_1^2-\gamma_0^2\gamma_1^2}{2(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2-\gamma_1^2)} - \frac{-4+7\gamma_0}{2(-4+\gamma_0)^3\gamma_0} =$

$\frac{1}{2(-4+\gamma_0)^3\gamma_0(-4+\gamma_1)^2(\gamma_0^2-\gamma_1^2)} (-64\gamma_0^2 + 48\gamma_0^3 - 32\gamma_0^4 + 64\gamma_0\gamma_1 - 16\gamma_0^2\gamma_1 - 12\gamma_0^3\gamma_1 + 15\gamma_0^4\gamma_1 - 64\gamma_1^2 + 48\gamma_0\gamma_1^2 + 44\gamma_0^2\gamma_1^2 - 9\gamma_0^3\gamma_1^2 - \gamma_0^4\gamma_1^2 + 32\gamma_1^3 - 56\gamma_0\gamma_1^3 - 4\gamma_1^4 + 7\gamma_0\gamma_1^4) > 0$, so $\alpha < \alpha_1$ and $F_{12}(\alpha) > 0$ and

$\pi_{ML}^{nm}(w_L, \gamma) > \pi_{ML}^{np}(w_L, \gamma)$. $\pi_{ML}^{np}(w_L, \gamma) - \pi_{ML}^{nv}(w_L, \gamma) = \frac{1}{4(-4+\gamma_1)^2(-9+\gamma_2)^2} [-2(-4 + \gamma_1)^2(-9 + \gamma_2)^2(\gamma_1^2 - \gamma_2^2)\alpha + 81\gamma_1 - 81\gamma_1^2 - 64\gamma_2 + 14\gamma_1\gamma_2 + 14\gamma_1^2\gamma_2 + 64\gamma_2^2 - 31\gamma_1\gamma_2^2 + 3\gamma_1^2\gamma_2^2]$. Set $F_{13}(\alpha) = -2(-4 + \gamma_1)^2(-9 + \gamma_2)^2(\gamma_1^2 - \gamma_2^2)\alpha + 81\gamma_1 - 81\gamma_1^2 - 64\gamma_2 + 14\gamma_1\gamma_2 + 14\gamma_1^2\gamma_2 + 64\gamma_2^2 - 31\gamma_1\gamma_2^2 + 3\gamma_1^2\gamma_2^2$, $F_{13}(\alpha)$ decreases in α . Set $F_{13}(\alpha) = 0$, we get $\alpha_2 = \frac{81\gamma_1-81\gamma_1^2-64\gamma_2+14\gamma_1\gamma_2+14\gamma_1^2\gamma_2+64\gamma_2^2-31\gamma_1\gamma_2^2+3\gamma_1^2\gamma_2^2}{2(-4+\gamma_1)^2(-9+\gamma_2)^2(\gamma_1^2-\gamma_2^2)}$. Compare α_2 with

α , $\alpha_2 - \alpha = \frac{81\gamma_1-81\gamma_1^2-64\gamma_2+14\gamma_1\gamma_2+14\gamma_1^2\gamma_2+64\gamma_2^2-31\gamma_1\gamma_2^2+3\gamma_1^2\gamma_2^2}{2(-4+\gamma_1)^2(-9+\gamma_2)^2(\gamma_1^2-\gamma_2^2)} - \frac{-4+7\gamma_1}{4(-4+\gamma_1)^3\gamma_1} =$

$\frac{1}{4(-4+\gamma_1)^3\gamma_1(-9+\gamma_2)^2(\gamma_1^2-\gamma_2^2)} (-324\gamma_1^2 + 243\gamma_1^3 - 162\gamma_1^4 + 512\gamma_1\gamma_2 - 312\gamma_1^2\gamma_2 + 42\gamma_1^3\gamma_2 + 28\gamma_1^4\gamma_2 - 324\gamma_2^2 + 55\gamma_1\gamma_2^2 + 380\gamma_1^2\gamma_2^2 - 93\gamma_1^3\gamma_2^2 + 6\gamma_1^4\gamma_2^2 + 72\gamma_2^3 - 126\gamma_1\gamma_2^3 - 4\gamma_2^4 + 7\gamma_1\gamma_2^4) > 0$, so $\alpha < \alpha_2$ and $F_{13}(\alpha) > 0$ and $\pi_{ML}^{np}(w_L, \gamma) > \pi_{ML}^{nv}(w_L, \gamma)$. Therefore, $\pi_{ML}^{nm}(w_L, \gamma) > \pi_{ML}^{np}(w_L, \gamma) > \pi_{ML}^{nv}(w_L, \gamma)$.

(2) For the pharmacy, we get $\pi_R^{nm}(q_H, q_L) - \pi_R^{nv}(q_H, q_L) = \frac{-252+693\gamma_0-36\gamma_0^2-520\gamma_2+134\gamma_0\gamma_2-28\gamma_0^2\gamma_2+4\gamma_2^2+5\gamma_0\gamma_2^2}{4(-4+\gamma_0)^2(-9+\gamma_2)^2} < 0$,

so $\pi_R^{nm}(q_H, q_L) < \pi_R^{nv}(q_H, q_L)$. $\pi_R^{nv}(q_H, q_L) - \pi_R^{np}(q_H, q_L) = \frac{18+117\gamma_1-148\gamma_2+10\gamma_1\gamma_2+2\gamma_2^2+\gamma_1\gamma_2^2}{4(-4+\gamma_1)(-9+\gamma_2)^2} < 0$, so

$\pi_R^{nv}(q_H, q_L) < \pi_R^{np}(q_H, q_L)$. Therefore, $\pi_R^{np}(q_H, q_L) > \pi_R^{nv}(q_H, q_L) > \pi_R^{nm}(q_H, q_L)$.

(3) For the pharmaceutical supply chain, we get $\pi^{nm} - \pi^{np} = \frac{1}{4(-4+\gamma_0)^2(-4+\gamma_1)^2} [-2(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2 - \gamma_1^2)\alpha + 80\gamma_0 - 44\gamma_0^2 - 80\gamma_1 + 17\gamma_0^2\gamma_1 + 44\gamma_1^2 - 17\gamma_0\gamma_1^2]$. Set $F_{14}(\alpha) = -2(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2 - \gamma_1^2)\alpha + 80\gamma_0 - 44\gamma_0^2 - 80\gamma_1 + 17\gamma_0^2\gamma_1 + 44\gamma_1^2 - 17\gamma_0\gamma_1^2$, $F_{14}(\alpha)$ decreases in α . Set $F_{14}(\alpha) = 0$, we get $\alpha_1 = \frac{80\gamma_0-44\gamma_0^2-80\gamma_1+17\gamma_0^2\gamma_1+44\gamma_1^2-17\gamma_0\gamma_1^2}{2(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2-\gamma_1^2)}$. Compare α_1 with α , $\alpha_1 - \alpha = \frac{80\gamma_0-44\gamma_0^2-80\gamma_1+17\gamma_0^2\gamma_1+44\gamma_1^2-17\gamma_0\gamma_1^2}{2(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2-\gamma_1^2)} - \frac{-4+7\gamma_0}{2(-4+\gamma_0)^3\gamma_0} = \frac{1}{2(-4+\gamma_0)^3\gamma_0(-4+\gamma_1)^2(\gamma_0+\gamma_1)} (-256\gamma_0 + 144\gamma_0^2 - 44\gamma_0^3 + 64\gamma_1 + 32\gamma_0\gamma_1 - 56\gamma_0^2\gamma_1 + 17\gamma_0^3\gamma_1 - 32\gamma_1^2 + 60\gamma_0\gamma_1^2 - 7\gamma_0^2\gamma_1^2 + 4\gamma_1^3 - 7\gamma_0\gamma_1^3) > 0$, so $\alpha < \alpha_1$ and $F_{14}(\alpha) > 0$ and $\pi^{nm} > \pi^{np}$. $\pi^{nv} - \pi^{nm} = \frac{1}{4(-4+\gamma_0)^2(-9+\gamma_2)^2} [2(-4+\gamma_0)^2(-9+\gamma_2)^2(\gamma_0^2 - \gamma_2^2)\alpha + 180 - 495\gamma_0 + 234\gamma_0^2 + 152\gamma_2 + 14\gamma_0\gamma_2 - 40\gamma_0^2\gamma_2 - 76\gamma_2^2 + 33\gamma_0\gamma_2^2 - 2\gamma_0^2\gamma_2^2] > 0$, so $\pi^{nv} > \pi^{nm}$. Therefore, $\pi^{nv} > \pi^{nm} > \pi^{np}$.

Quality regulation model

(1) For the pharmaceutical manufacturer 1, we get $\pi_{MH}^{rm}(w_H) - \pi_{MH}^{rv}(w_H) = \frac{(1-\beta)(18+36\beta-7\beta^2)}{(9-\beta)^2(4-\beta)^2} > 0$, so

$\pi_{MH}^{rm}(w_H) > \pi_{MH}^{rv}(w_H)$. $\pi_{MH}^{rv}(w_H) - \pi_{MH}^{rp}(w_H) = \frac{(1-\beta)(63-54\beta+8\beta^2)}{(9-\beta)^2(4-\beta)^2} > 0$, so $\pi_{MH}^{rv}(w_H) > \pi_{MH}^{rp}(w_H)$. Therefore,

$\pi_{MH}^{rm}(w_H) > \pi_{MH}^{rv}(w_H) > \pi_{MH}^{rp}(w_H)$.

For the pharmaceutical manufacturer 2, we get $\pi_{ML}^{rm}(w_L, \gamma) - \pi_{ML}^{rp}(w_L, \gamma) = \frac{(1-\beta)\beta}{4(4-\beta)^2} > 0$, so $\pi_{ML}^{rm}(w_L, \gamma) >$

$\pi_{ML}^{rp}(w_L, \gamma)$. $\pi_{ML}^{rp}(w_L, \gamma) - \pi_{ML}^{rv}(w_L, \gamma) = \frac{\beta(17-3\beta-17\beta^2+3\beta^3)}{4(9-\beta)^2(4-\beta)^2} > 0$, so $\pi_{ML}^{rp}(w_L, \gamma) > \pi_{ML}^{rv}(w_L, \gamma)$. Therefore,

$\pi_{ML}^{rm}(w_L, \gamma) > \pi_{ML}^{rp}(w_L, \gamma) > \pi_{ML}^{rv}(w_L, \gamma)$.

(2) For the pharmacy, we get $\pi_R^{rm}(q_H, q_L) - \pi_R^{rv}(q_H, q_L) = \frac{-252+173\beta+102\beta^2-23\beta^3}{4(-9+\beta)^2(-4+\beta)^2} < 0$, so $\pi_R^{rm}(q_H, q_L) <$

$\pi_R^{rv}(q_H, q_L)$. $\pi_R^{rv}(q_H, q_L) - \pi_R^{rp}(q_H, q_L) = \frac{18-31\beta+12\beta^2+\beta^3}{4(-9+\beta)^2(-4+\beta)^2} < 0$, so $\pi_R^{rv}(q_H, q_L) < \pi_R^{rp}(q_H, q_L)$. Therefore,

$\pi_R^{rp}(q_H, q_L) > \pi_R^{rv}(q_H, q_L) > \pi_R^{rm}(q_H, q_L)$.

(3) For the pharmaceutical supply chain, we get $\pi^{rm} - \pi^{rp} = 0$, so $\pi^{rm} = \pi^{rp}$. $\pi^{rm} - \pi^{rv} =$

$\frac{-180+343\beta-172\beta^2+7\beta^3+2\beta^4}{4(-9+\beta)^2(-4+\beta)^2} < 0$, so $\pi^{rv} > \pi^{rm}$. Therefore, $\pi^{rv} > \pi^{rm} = \pi^{rp}$.

Proof of Proposition 6

(1) For no quality regulation model, we get $W_s^{nm} - W_s^{np} = \frac{1}{8(-4+\gamma_0)^2(-4+\gamma_1)^2} [-4(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2 -$

$\gamma_1^2)\alpha + 208\gamma_0 - 92\gamma_0^2 - 208\gamma_1 + 33\gamma_0^2\gamma_1 + 92\gamma_1^2 - 33\gamma_0\gamma_1^2]$. Set $F_{15}(\alpha) = -4(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2 - \gamma_1^2)\alpha + 208\gamma_0 - 92\gamma_0^2 - 208\gamma_1 + 33\gamma_0^2\gamma_1 + 92\gamma_1^2 - 33\gamma_0\gamma_1^2$, $F_{15}(\alpha)$ decreases in α . Set $F_{15}(\alpha) = 0$, we get

$\alpha_1 = \frac{208\gamma_0-92\gamma_0^2-208\gamma_1+33\gamma_0^2\gamma_1+92\gamma_1^2-33\gamma_0\gamma_1^2}{4(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2-\gamma_1^2)}$. Compare α_1 with α , $\alpha_1 - \alpha =$

$\frac{208\gamma_0-92\gamma_0^2-208\gamma_1+33\gamma_0^2\gamma_1+92\gamma_1^2-33\gamma_0\gamma_1^2}{4(-4+\gamma_0)^2(-4+\gamma_1)^2(\gamma_0^2-\gamma_1^2)} - \frac{-4+7\gamma_0}{2(-4+\gamma_0)^3\gamma_0} = \frac{1}{4(-4+\gamma_0)^3\gamma_0(-4+\gamma_1)^2(\gamma_0+\gamma_1)} (-704\gamma_0 + 352\gamma_0^2 - 92\gamma_0^3 +$

$128\gamma_1 + 80\gamma_0\gamma_1 - 112\gamma_0^2\gamma_1 + 33\gamma_0^3\gamma_1 - 64\gamma_1^2 + 120\gamma_0\gamma_1^2 - 14\gamma_0^2\gamma_1^2 + 8\gamma_1^3 - 14\gamma_0\gamma_1^3) > 0$, so $\alpha < \alpha_1$ and $F_{15}(\alpha) > 0$ and $W_s^{nm} > W_s^{np}$. $W_s^{nv} - W_s^{nm} = \frac{1}{8(-4+\gamma_0)^2(-9+\gamma_2)^2} [4(-4+\gamma_0)^2(-9+\gamma_2)^2(\gamma_0^2 - \gamma_2^2)\alpha + 612 - 1359\gamma_0 + 504\gamma_0^2 + 440\gamma_2 + 14\gamma_0\gamma_2 - 76\gamma_0^2\gamma_2 - 156\gamma_2^2 + 65\gamma_0\gamma_2^2 - 4\gamma_0^2\gamma_2^2] > 0$, so $W_s^{nv} > W_s^{nm}$. Therefore, $W_s^{nv} > W_s^{nm} > W_s^{np}$.

(2) For quality regulation model, we get $W_s^{rm} - W_s^{rp} = 0$, so $W_s^{rm} = W_s^{rp}$. $W_s^{rm} - W_s^{rv} = \frac{-612+919\beta-362\beta^2+11\beta^3+4\beta^4}{8(-9+\beta)^2(-4+\beta)^2} < 0$, so $W_s^{rv} > W_s^{rm}$. Therefore, $W_s^{rv} > W_s^{rm} = W_s^{rp}$.