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Optimal subsidy strategies in a smart supply chain driven by dual innovation

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A B S T R A C T

Due to the deep integration of modern information technology, supply chain management has moved into a new stage of a smart supply chain. Considering the dual smart innovation of the manufacturer's production and retailer's service, the manufacturer-led Stackelberg game model is constructed in the smart supply chain. Under the single and coordinated government subsidy strategies, the optimal decisions of the smart supply chain are researched, and the impacts of manufacturers' risk aversion on the government subsidy strategies and supply chain decisions are analysed. In addition, the efficiencies of different government subsidy strategies are compared and analysed by numerical simulation. Finally, the results show that: (i) The moderate risk aversion by the manufacturer can improve social welfare and help provide consumers with more affordable products. (ii) The government expenditure and product prices are highest under the coordinated subsidy strategy. (iii) Subsidising manufacturers is more beneficial than subsidising retailers among the two single government subsidy strategies. (iv) In general, the coordinated government subsidy strategy is more effective than the single subsidy strategy for the innovative development of a smart supply chain. In conclusion, the research provides a significant practical reference for jointly building the smart supply chain.

1. Introduction

As society develops into the Industry 4.0 era, where information technology drives the industrial revolution, the development connotation of the supply chain continues to be extended. Due to the wide application of artificial intelligence, big data analysis and other information technology, the supply chain is deeply integrated with the Internet and the Internet of Things. Therefore, supply chain management begins to enter a new smart supply chain development stage. The smart supply chain refers to a comprehensive, integrated system built by the traditional supply chain, which absorbs information technologies such as the Internet, the Internet of Things and artificial intelligence. It combines modern management theory so that enterprises can realise digitalisation, informatisation, intelligence and networking of supply chain technology and management (Wu *et al.,* 2016). From the perspective of national economic development, the construction of a smart supply chain can promote the balance of social supply and demand and consumption upgrading. It is also essential for enterprises to enhance their market competitive advantage. In addition, from the perspective of the international competition situation, the Sino-US trade dispute is severe. Its essence is to compete for the control of the global supply chain. Thus, the modern management level of the supply chain, especially the development level of the smart supply chain, has become one of the key indicators to measure the country's comprehensive strength. At the same time, the international competition has also entered the stage of supply chain competition from enterprise competition. Therefore, the research on developing a smart supply chain has vital practical significance.

Under such economic development trends, the country advocates the strategic concept of data-driven and data enabling, which provides new development opportunities for intelligent manufacturing, so the big data smart supply chain is gradually rising. Many enterprises have invested a lot of human resources, material resources and funds to build the smart supply chain.

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Governments have also given high support to promote the optimisation and innovation of the supply chain. For example, since the 19th National Congress of the Communist Party of China in 2017 first proposed to develop a modern supply chain, many Chinese policies have continuously guided the construction of a smart supply chain system. In the same year, China's State Council issued guidance on promoting supply chain innovation and application, which proposed that China should innovate the new mode of supply chain development. It also requires China to build a smart supply chain covering critical industries by 2020. Later, to further implement the positioning of supply chain innovation and development, the national development and Reform Commission issued relevant documents on March 2, 2019, which also clearly mentioned that enterprises should improve the intellectual level of the supply chain, realise the pulling effect of logistics on agriculture, and encourage supply chain enterprises to develop extensive data and cloud computing products. With the construction of a smart supply chain, China held another meeting in March 2020, indicating that infrastructure construction such as the 5G network and data centre should be strengthened to speed up the upgrading and innovation of the supply chain. In less than three years, China has successively issued many heavy documents on constructing a modern supply chain, all of which show that the country has paid unprecedented attention to developing a smart supply chain.

China's series of relevant industrial policies shows that the government tries to combine supportive policies (such as subsidies, protectionism, etc.) with challenging policies (such as development planning, etc.) to push enterprises in an ideal direction. At the same time, because the innovation and upgrading of a smart supply chain require enterprises to pay a fixed cost, and successful R&D also requires continuous capital investment by supply chain members, the government needs to play a coordinating role to avoid the "poverty trap"(Mahmood & Rufin 2005). Among the government's many support strategies, the subsidy policy is often the most direct and effective for the industry's innovation. Moreover, government subsidies to encourage enterprises to innovate the supply chain are reflected in many countries. For example, "made in China 2025" clearly requires the government to increase the support of financial and tax policies to improve the innovation ability of the manufacturing industry and speed up the deep integration of information and industrialisation. In addition, many Chinese leading enterprises, associations and the government jointly established the China Smart Supply Chain Investment and Construction Alliance in 2017 to boost the development of the smart supply chain. Although the subsidy policies have promoted the investment and construction of enterprises in the smart supply chain, the effect of the strategies are different due to the different subsidy objects and quantities. Therefore, it is worth studying who, how much and how to subsidise the government to promote better the innovation and development of a smart supply chain.

Besides that, in terms of the whole smart supply chain, the operational risks are more prominent because of the increasing complexity of the consumer market, the continuous progress of science and technology, the acceleration of product upgrading, the rising price volatility, and the more unstable supply-demand relationship. However, a large number of innovative measures need to be implemented in the pre construction period of the smart supply chain, such as the application of new modes of production and sales, the use of new digital technologies, etc., which further increases the operational risk of the supply chain (Liu *et al.* 2021). Furthermore, in terms of the single firm, it has to face the overall market risk of the supply chain and bears its own intelligent innovation cost risk and enterprise management risk. Enterprises will invest a lot of money to build digital information exchange platforms, build smart logistics and warehousing systems, develop new production techniques and purchase new energy materials. So, the cost of products may increase, or consumers may not adapt to the application of new technologies, which will lead to a significant increase in the management risk and market risk of enterprises. Through the above analysis, we know that risk aversion is a factor that cannot be ignored in the innovation and development process of a smart supply chain. Therefore, the participants in the supply chain will not only pursue the maximum of their income but also take into account their risk tolerance. They often carry a risk-averse preference in the decision-making. This is why it is necessary to incorporate the risk-averse characteristics of enterprises' intelligent innovation into smart supply chain research.

Given the concerns mentioned above, considering the dual smart innovation of manufacturer's production and retailer's service, this study aims to investigate the optimal decision of the smart supply chain under the single or coordinated subsidy strategies. By constructing the manufacturer-led Stackelberg game model, this paper calculates the optimal product price, firm innovation level and profit, government subsidy rate and social welfare level. At last, the impacts of the manufacturer's risk aversion on the optimal decisions are analysed, and the conclusions are validated with numerical simulations. This study has important practical implications for optimising government subsidy efficiency and promoting smart supply chain development.

The remainder of this paper is organised as follows. The relevant literature is reviewed in Section 2. The theoretical models are depicted in Section 3. The models are solved and analysed based on various government subsidy strategies in Section 4. Numerical simulations in Section 5 validate the conclusions. Finally, the study's main conclusions and management insights are summarised in Section 6.

2. Literature Review

Four areas of research highly relevant to this study are the development of a smart supply chain, research on supply chain innovation, government subsidies on supply chain decisions, and the impact of risk aversion on supply chain decisions.

2.1 Development of smart supply chain

The concept of a smart supply chain was first proposed in a conference paper published by Ivanov et al. in 2004. They studied novel planning ideas and models of the rapid reform of intelligent supply chains in virtual enterprises(Ivanov *et al.*, 2004). Subsequently, this concept was more widely recognised by scholars when IBM proposed the grand strategy of a “smart planet” in 2008 (Palmisano 2008). Luo Gang of Fudan University was the first scholar in China to give a complete definition of a smart supply chain. He proposed in 2009 that a smart supply chain is an integrated system combining the theories, methods and technologies of Internet of things technology and modern supply chain management. The accepted connotation in academia is that the smart supply chain is a transformation of the deep integration of the traditional supply chain and modern information technology(Abdel-Basset *et al.,* 2018). Büyüközkan and Göçer (2018) point out that the nature of a smart supply chain is a digital supply chain. Based on the deep analysis of the concept and characteristics of a smart supply chain, many scholars have empirically found that constructing the smart supply chain has a positive effect on socio-economic development(Wu, Yue *et al.*, 2016; Ramanathan, 2017). So, it is indispensable to optimize the management model of the smart supply chain to promote cooperation among enterprises (Ma & Lu 2018). Jamil *et al*. (2019) described the smart drug supply chain integrated management platform based on Hyperledger-Fabric. They measured the performance of the design system through a large number of experiments to optimize the availability and efficiency of the management platform. Wan et al. studied three poverty alleviation models of the government in the smart supply chain, introduced the smart service platform into the agricultural product supply chain, and found that the benefits of the supply chain under the three models have improved (Wan & Qie, 2019). However, because the concept of a smart supply chain has been put forward for a short time, there is little literature on the optimisation model of smart supply chain management.

2.2 Research on supply chain innovation

Supply chain innovation helps to reduce costs, shorten delivery times, provide consistent product quality, and increase flexibility in dealing with a rapidly changing business environment(Abdelkafi & Pero 2018). Gao et al. found that supply chain innovation mainly occurs in manufacturer’s market-oriented, technology R & D-oriented and logistics-oriented innovation activities(Gao *et al.,* 2017). With the increasing pressure to efficiently develop new products and services, enterprises have been committed to promoting more excellent supply chain collaborative innovation to maintain and improve their long-term performance (Isaksson *et al.,* 2016; Todo *et al.,* 2016). Collaborative innovation means that two or more supply chain members, such as suppliers, manufacturers, distributors, retailers and even customers, work together to plan and implement R & D innovation in the supply chain network (Luomaranta & Martinsuo, 2019; Wang *et al.,* 2020). Liu *et al.* (2018) constructed a factor model that affected the technological innovation of logistics equipment manufacturers from market demand, environment, innovation strategy and enterprise characteristics, combined with the features of logistics equipment. Reimann *et al*. (2019) analyse the impact of a manufacturer’s technical innovation on pricing decisions in a closed-loop supply chain. Based on the challenges faced by the recycling and remanufacturing industry, Chai *et al.* (2021) used the game model to analyse the innovation strategy of product remanufacturing in the closed-loop supply chain composed of suppliers and manufacturers. The literature on supply chain innovation mainly studies the impact of manufacturer’s production process innovation activities on the development of the supply chain while ignoring the critical implications of retailer’s service innovation on product sales.

2.3 The impact of government subsidies on supply chain decisions

Since innovative development requires a fixed cost and sustained capital investment, the state needs to play a coordinating role to avoid the “poverty trap”(Mahmood & Rufin 2005). At present, the research on the optimisation of government subsidy strategy in the supply chain is mainly focused on the field of the sustainable supply chain, and the purpose is to promote low-carbon production. The main subsidy objects in the literature are manufacturers, retailers and consumers, most of which assume that there is only a single subsidy object. Most of the literature is about government subsidies to manufacturers and consumers. Yi and Li (2018a) solved the optimal decision of the supply chain when the government provided subsidies to manufacturers producing energy-saving and emission reduction products. They further analysed cost-sharing contracts' coordination effect on enterprises' production and marketing (Yi & Li, 2018b). Meng et al. constructed a closed-loop supply chain game model under government consumption subsidies, obtained the government's optimal consumption subsidy strategy, and discussed the impact of consumption subsidies on product prices, supply chain profits, consumer surplus and social welfare (Meng *et al.,* 2021). Under uncertain demand, Zhang *et al.* (2021) assumed that the government subsidised the cold chain preservation cost of fresh food suppliers, constructed decentralised and centralised subsidy game models, and designed contracts to improve the effectiveness of government subsidies. Besides, some scholars have compared the strategic effects of government subsidies to different supply chain entities. Yu et al. studied the situation of government subsidies to manufacturers and consumers. They analysed the production and sales of products when subsidies are given to manufacturers and consumers simultaneously (Yu *et al.,* 2018). Shang et al. considered the scenario in which the government subsidies the retailer’s green sales cost (Shang & Teng, 2020) but still did not examine the case in which the government concurrently coordinates subsidies between the manufacturer and the retailer. It can be seen that most of the literature only studied the single subsidy strategy of the government subsidies to manufacturers or consumers, ignored the government subsidies to retailers, and even less the research situation of the government coordinating subsidies to different entities of the supply chain at the same time.

2.4 The impact of risk aversion on supply chain decisions

The research results of the above literature are mainly based on the assumption that the participants in the supply chain are risk-neutral and do not specifically describe the risk aversion characteristics caused by their attempts to innovate in the supply chain. A few scholars have noticed that there are certain management risks and market risks in the innovation practice of the supply chain, which is more evident in the development of a smart supply chain. Many methods describe the risk behaviour in supply chain management, including the mean-variance method, value at risk (VaR) method, and conditional value at risk (CVaR) method. Chen et al. (2020) used the general definition of CVaR to establish the decision-making model and studied the choice of natural risk management strategy for agricultural and sideline products. In addition, because the calculation process of the mean-variance method is relatively simple, many scholars use it to measure the risk aversion of supply chain subjects and obtain more research results. Hie et al. discussed the trade-off between risks and benefits of enterprises in two different supply chain structures (Hie *et al.* 2015). Cohen *et al*. (2016) assumed that there is market uncertainty in demand for green products and studied the impact of the government's green subsidy policy on enterprises' production and sales decisions. Fu *et al.* (2019) also examined the effect of different risk aversion characteristics of manufacturers and retailers on supply chain pricing and profits under the background of government subsidies.

In contrast, Cao Yu *et al.* (2019) only analysed the impact of risk aversion characteristics of retailers on optimal decision-making. Kouvelis *et al.* (2021) also studied the effect of retailers' risk aversion on production decisions in the case of price delay. They found that the price delay trading method helps reduce the risk caused by market demand uncertainty for downstream retailers. Liu *et al.* (2021) identified risk factors in the smart supply chain and constructed a risk assessment index system for reducing potential losses in intelligent manufacturing (Liu, Ji *et al.*, 2021). These all illustrate that it is important to consider risk aversion in a smart supply chain and lay the theoretical foundation for this paper.

2.5 Literature review

To sum up, as social development enters the industrial 4.0 era in which information technology promotes the industrial revolution, the supply chain is deeply integrated with the Internet and the Internet of things, and supply chain management begins to enter a new stage of smart supply chain development. To promote the innovative development of a smart supply chain, the state has issued several policies. Various scholars have also cut in from multiple angles to improve the development theory and optimise management efficiency. The existing literature includes the development of smart supply chain, supply chain innovation, government subsidy policies and enterprise risk aversion, but there are still many research fields to be explored:

(1) Because the concept of a smart supply chain has been put forward for a short time, most of the literature focuses on the connotation and development path of a smart supply chain. There is more macro theoretical and empirical analysis of the smart supply chain but less research on optimising the smart supply chain management model at the micro-level.

(2) As for the research on supply chain innovation, the literature primarily focuses on the manufacturer's production technology innovation. It ignores the retailer's marketing service innovation, but its service quality is paramount to improving consumers' demand for innovative products.

(3) The research on government subsidy strategy mainly focuses on promoting the low-carbon development of a green supply chain, and the majority of them only consider the subsidy to a single subject, ignoring the research on coordinated subsidy strategy; Few scholars believe the role of government subsidy strategy in promoting innovation and development in the smart supply chain, and there is a lack of Optimization Research on it.

(4) The previous research literature on the supply chain mainly assumes that supply chain participants are risk-neutral. Not many researchers consider the impact of risk aversion characteristics of enterprises on the construction of a smart supply chain.

Finally, based on the research of the above literature and the existing shortcomings, this paper considers the risk aversion of both manufacturers and retailers in the smart supply chain driven by dual innovation, studies the optimal decision-making of the supply chain under the background of government subsidies by constructing Stackelberg game models led by manufacturer, and compares the effects of three government subsidy strategies. This study aims to provide a reference for the government to optimize subsidy strategies, promote the innovation and upgrading of the smart supply chain, and make up for the lack of relevant research on the smart supply chain.

Table 1
Major notation and explanation

Notation	Explanation
For the supply chain	
F	The level of social welfare
SP	Total profit of supply chain
CS	Consumer surplus
G	Government subsidies
s	Government subsidy ratio
ε	Uncertainty of market demand
For the manufacturer	
β	Manufacturer's risk aversion
g	Manufacturer's production process innovation level
g^2	Manufacturer's production process innovation cost
c	The production cost of the product
w	Manufacturer's wholesale price
π^m	Manufacturer's profit
U^m	Manufacturer's utility
For the retailer	
p	Retailer's retail price
h	Retailer's service innovation level
h^2	Retailer's service innovation cost
π^r	Retailer's profit
U^r	Retailer's utility

3. Problem definition and assumptions

A three-stage game model is constructed between the government and a smart supply chain consisting of manufacturers and retailers. In this model, the manufacturer dominates the supply chain and uses information technology to intelligently produce products that meet consumers' needs. As a follower, the retailer uses internet technology to innovate smart services to improve the competitiveness of their products, including precision marketing and smart warehousing. So, to stimulate smart innovation in the supply chain and promote the production and sale of products, the government chooses to subsidize the manufacturer and retailer to cover their innovation cost.

Based on the research needs of this paper, the notations are explained in Table 1, and the main hypotheses are as follows:

(1) According to Hong et al.'s assumption of market demand.(Hong and Guo 2019), the general linear demand function is adopted, and the market demand function is set to $D = 1 - p + g + h + \varepsilon\,(0 < p < 1)$. Considering the market risk aversion of enterprises, it is used ε to represent the uncertainty of product demand and $\varepsilon \sim (0,\ \sigma^2)$ (Fu, Zhang et al., 2019). To simplify the calculation, the total market demand is converted into 1, and the relevant cost coefficients are assumed to be 1. This is because, in many studies, it is found that the coefficient only expresses its sensitivity to the impact of the demand function(Wen *et al.* 2018). Moreover, the focus of this study is not to discuss the impact of the change of the sensitivity coefficient of relevant costs, so taking the cost coefficient as 1 will not affect the overall research conclusion of this paper(Cao, Li et al. 2019; Zhang *et al.* 2019).

(2) Suppose the manufacturer produces a smart product, and the product price is $0 < c < w < p < 1$. Referring to Ghosh et al.(Ghosh and Shah 2015), the investment cost of innovation is a quadratic function of the level of innovation. It is positively correlated, so assume that the manufacturer's production process innovation cost is g^2 and the retailer's service innovation cost is h^2. As with hypothesis (1), the effect of the cost coefficient is not considered. Besides, the smart innovation cost of both is a one-time investment borne by each.

(3) Assume that the government subsidises manufacturers and retailers according to their level of intellectual innovation. The government subsidy ratio is set at s, and $s \in [0,1]$. The subsidy ratio is ultimately determined by maximising the level of social welfare(Shang and Teng 2020).

(4) It is assumed that the manufacturer has risk aversion to dealing with market demand uncertainty. At the same time, the

retailer, as the follower of supply chain decision-making, is risk-neutral.

(5) The level of social welfare (F) is determined linearly by the total profit of the supply chain (SP), consumer surplus(CS) and government subsidies (G) (Sun & Yu, 2018; Shang & Teng, 2020), i.e. $F = SP + CS - G$.

(6) To simplify the description, subscripts 1, 2 and 3 denote the three research scenarios of manufacturer subsidy strategy, retailer subsidy strategy, and government coordinated subsidy strategy, superscripts m and r represent manufacturers and retailers, respectively.

According to the above assumptions, the expected utility function of the risk-averse manufacturer is derived as:

$$U^m = E(\pi^m) - \eta Var(\pi^m) = (w-c)(1-p+g+h) - g^2 - \eta(w-c)^2\sigma^2 \tag{1}$$

Comprehensively considering the expected value and variance of profit, the mean-variance theory proposed by Markowitz is used to measure the risk aversion of the manufacturer(Zhang, Li et al. 2019). Since η represents the manufacturer's sensitivity coefficient to risk aversion and σ^2 is the variance of market demand uncertainty, this paper uses $\beta = \eta\sigma^2\ (\beta > 0)$ to represent the manufacturer's overall degree of risk aversion for computational convenience.

The retailer's expected utility function is:

$$U^r = E(\pi^r) = (p-w)(1-p+g+h) - h^2 \tag{2}$$

The expected social welfare function is:

$$F = E(SP + CS - G) = (p-c)(1-p+g+h) - \frac{1}{2}(1-p+g+h)^2 - G \tag{3}$$

4. Model and the Solution

4.1 Subsidy strategy for the manufacturer

To build a smart supply chain production system, the manufacturer needs to invest in higher costs of smart production process innovation, including the construction of information exchange platforms and intelligent production systems, which can reduce the incentive for the manufacturer to engage in smart production. Therefore, to encourage manufacturers to improve their innovation level, the government subsidies the manufacturer. Its subsidy ratio relates to the manufacturer's production process innovation level and the subsidy $s_1 g_1$ amount. In this case, the government only subsidises the manufacturer. The utility functions of the manufacturer and retailer are:

$$U_1^m = (w_1 - c)(1 - p_1 + g_1 + h_1) - g_1^{\ 2} - \beta(w_1 - c)^2 + s_1 g_1 \tag{4}$$

$$U_1^r = (p_1 - w_1)(1 - p_1 + g_1 + h_1) - h_1^2 \tag{5}$$

At this point, the social welfare function is:

$$F_1 = (p_1 - c)(1 - p_1 + g_1 + h_1) - \frac{1}{2}(1 - p_1 + g_1 + h_1)^2 - s_1 g_1 \tag{6}$$

Solution 1. According to the inverse solution method, the second derivatives of p_1 and h_1 is obtained through the retailer's utility function (5), and both results are $-2 < 0$. Therefore, U_1^r is the strictly concave function about p_1 and h_1 respectively and the optimal $p_1^*(w_1, g_1)$ and $h_1^*(w_1, g_1)$ can be obtained. Then the Hessian matrix g_1 and w_1 is obtained through the manufacturer's utility function (4), and it is found that the matrix is negative definite when $0 < \beta < 0.25$. The optimal $w_1^*(s_1)$ and $g_1^*(s_1)$ can be solved by substituting the $p_1^*(w_1, g_1)$ and $h_1^*(w_1, g_1)$ into the function (4). Then we substitute $w_1^*(s_1)$ and $g_1^*(s_1)$ into $p_1^*(w_1, g_1)$ and $h_1^*(w_1, g_1)$ to obtain the optimal $p_1^*(s_1)$ and $h_1^*(s_1)$, to obtain the optimal utility functions $U_1^{m*}(s_1)$ and $U_1^{r*}(s_1)$, and the optimal social welfare function $F_1^*(s_1)$. Finally, taking $F_1^*(s_1)$

maximisation as the goal, the optimal government subsidy ratio s_1^* is solved, and then it is replaced with each optimal solution to obtain the following proposition.

Proposition 1. Under the subsidy strategy for a manufacturer, the optimal decisions in the smart supply chain are as follows.

The government optimal subsidy ratio: $s_1^* = \frac{(1-c)(7+45\beta+54\beta^2)}{6(2+3\beta)^2}$

The optimal wholesale price: $w_1^* = \frac{11+18\beta+c(5+30\beta+36\beta^2)}{4(2+3\beta)^2}$

The optimal manufacturer's production process innovation level: $g_1^* = \frac{3(1-c)(1+2\beta)}{8+12\beta}$

The optimal retail price: $p_1^* = \frac{55+156\beta+108\beta^2-c(7+12\beta)}{12(2+3\beta)^2}$

The optimal retailer's service innovation level: $h_1^* = \frac{(1-c)(1+3\beta)(11+18\beta)}{12(2+3\beta)^2}$

Substituting the optimal solutions into Eqs. (4) - (6) can obtain the optimal profit of the supply chain.

The manufacturer's optimal utility: $U_1^{m*} = \frac{(1-c)^2(109+453\beta+648\beta^2+324\beta^3)}{48(2+3\beta)^3}$

The retailer's optimal utility: $U_1^{r*} = \frac{(1-c)^2(11+51\beta+54\beta^2)^2}{48(2+3\beta)^4}$

The optimal level of social welfare: $F_1^* = \frac{(1-c)^2(25+108\beta+108\beta^2)}{12(2+3\beta)^2}$.

After the above solution analysis, we know that the optimal decisions of government subsidy and smart supply chain are mainly influenced by the manufacturer's risk aversion β under the manufacturer's subsidy strategy. Therefore, this paper further studies the impacts of a manufacturer's risk aversion on various decisions. Combined with the conditions of $0<c<p<1$ and $0<\beta<0.25$, the following proposition can be obtained.

Proposition 1. Under the subsidy strategy for a manufacturer, the impacts of the manufacturer's risk aversion (β) on optimal government subsidy and smart supply chain decisions are as follows:

(1.1) $\frac{\delta s_1^*}{\delta\beta} = \frac{(1-c)(16+27\beta)}{2(2+3\beta)^3} > 0$, $\frac{\delta g_1^*}{\delta\beta} = \frac{3(1-c)}{4(2+3\beta)^2} > 0$,

$\frac{\delta h_1^*}{\delta\beta} = \frac{3(1-c)(4+7\beta)}{4(2+3\beta)^3} > 0$, $\frac{\delta w_1^*}{\delta\beta} = \frac{3(c-1)(5+9\beta)}{2(2+3\beta)^3} < 0$,

$\frac{\delta p_1^*}{\delta\beta} = \frac{3(c-1)(1+2\beta)}{2(2+3\beta)^3} < 0$;

(1.2) $\frac{\delta U_1^{m*}}{\delta\beta} = -\frac{(-1+c)^2(25+42\beta)}{16(2+3\beta)^4} < 0$,

$\frac{\delta U_1^{r*}}{\delta\beta} = \frac{3(-1+c)^2(4+7\beta)(11+51\beta+54\beta^2)}{8(2+3\beta)^5} > 0$,

$$\frac{\delta F_1^*}{\delta\beta} = \frac{(-1+c)^2(11+18\beta)}{2(2+3\beta)^3} > 0 .$$

Proposition 1 shows that:

(1) According to (1.1) of Proposition 1, With the increase of the manufacturer's market risk aversion increases, the ratio of government subsidies to manufacturer gradually increases, which urges the manufacturer to continuously improve the innovation level of intelligent production, and the retailer also enhances the innovation efforts for intelligent services. As the supply chain becomes more intelligent, the overall production and distribution efficiency of the smart supply chain increases so that the wholesale and retail prices of products gradually decrease.

(2) According to (1.2) of Proposition 1, the manufacturer's degree of market risk aversion gradually increases, which reduces its own expected utility but helps to increase the retailer's optimal utility. In general, the level of social welfare will increase with the increase in risk aversion.

4.2 Subsidy strategy for a retailer

In the development wave of new retail, overcoming the drawbacks of traditional retail is inseparable from the service innovation carried out by retailers to construct the smart supply chain. Therefore, to incentivise retailers to increase their service innovation, the government will subsidise retailers. The subsidy amount is related to the level of smart service innovation of retailers, set as s_2h_2. At this point, the government only subsidises the retailer, and the utility functions of the manufacturer and retailer are:

$$U_2^m = (w_2 - c)(1 - p_2 + g_2 + h_2) - {g_2}^2 - \beta(w_2 - c)^2 \tag{7}$$

$$U_2^r = (p_2 - w_2)(1 - p_2 + g_2 + h_2) - h_2^2 + s_2h_2 \tag{7}$$

The total social welfare function is:

$$F_2 = (p_2 - c)(1 - p_2 + g_2 + h_2) - (1 - p_2 + g_2 + h_2)^2/2 - s_2h_2 \tag{8}$$

Solution 2. This process is the same as solution 1. Similarly, by first finding the relevant second derivative of the utility function and the Hessian matrix, it is obtained that there are optimal solutions for the smart supply chain decision-making under the conditions of $0 < c < p < 1$ and $0 < \beta < 0.25$. From the inverse solution method, the optimal decisions of the government and the smart supply chain can be found. So, the following proposition is obtained.

Proposition 2. Under the subsidy strategy for retailers, the optimal decisions in the smart supply chain are as follows.

The government optimal subsidy ratio: $s_2^* = \dfrac{(1-c)(1+3\beta)(7+9\beta)}{24+87\beta+81\beta^2}$

The optimal wholesale price: $w_2^* = \dfrac{11+21\beta+c(5+37\beta+54\beta^2)}{16+58\beta+54\beta^2}$

The optimal manufacturer's production process innovation level: $g_2^* = \dfrac{(1-c)(11+21\beta)}{6(8+29\beta+27\beta^2)}$

The optimal retail price: $p_2^* = \dfrac{55+171\beta+126\beta^2+c(-7+3\beta+36\beta^2)}{6(8+29\beta+27\beta^2)}$

The optimal retailer's service innovation level: $h_2^* = \dfrac{(1-c)(3+14\beta+15\beta^2)}{8+29\beta+27\beta^2}$

Substituting the optimal solutions into Eqs (7-9) can obtain the optimal profit of the supply chain.

The manufacturer's optimal utility: $U_2^{m*} = \dfrac{(1-c)^2(5+9\beta)(11+21\beta)^2}{36(8+29\beta+27\beta^2)^2}$

The retailer's optimal utility: $U_2^{r*} = \dfrac{(1-c)^2(1+3\beta)^2(103+378\beta+351\beta^2)}{9(8+29\beta+27\beta^2)^2}$

The optimal level of social welfare: $F_2^* = \dfrac{(1-c)^2(1+3\beta)(25+39\beta)}{6(8+\beta(29+27\beta))}$.

Then, under the retailer's subsidy strategy, the impacts of the manufacturer's risk aversion (β) on the government's and the smart supply chain's optimal decisions are analysed. The following proposition can be derived by combining the conditions $0 < c < p < 1$ and $0 < \beta < 0.25$.

Proposition 2. Under the subsidy strategy for retailers, the impacts of the manufacturer's risk aversion (β) on government subsidies and optimal decisions in the smart supply chain are as follows.

(1.3) $\dfrac{\delta s_2^*}{\delta\beta} = \dfrac{(c-1)(-37-54\beta+27\beta^2)}{3(8+29\beta+27\beta^2)^2} > 0$, $\dfrac{\delta h_2^*}{\delta\beta} = \dfrac{(1-c)(25+78\beta+57\beta^2)}{(8+29\beta+27\beta^2)^2} > 0$,

$\dfrac{\delta g_2^*}{\delta\beta} = \dfrac{(c-1)(151+594\beta+567\beta^2)}{6(8+29\beta+27\beta^2)^2} < 0$, $\dfrac{\delta w_2^*}{\delta\beta} = \dfrac{(1-c)(151+594\beta+567\beta^2)}{2(8+29\beta+27\beta^2)^2} < 0$,

$\dfrac{\delta p_2^*}{\delta\beta} = \dfrac{(1-c)(227+954\beta+963\beta^2)}{6(8+29\beta+27\beta^2)^2} < 0$.

(1.4) $\dfrac{\delta U_2^{m*}}{\delta\beta} = -\dfrac{(-1+c)^2(11+21\beta)X_1}{36(8+29\beta+27\beta^2)^3} < 0$ (where $X_1 = 718+4275\beta+8208\beta^2+5103\beta^3$),

$\dfrac{\delta U_2^{r*}}{\delta\beta} = \dfrac{2(-1+c)^2(1+3\beta)X_2}{9(8+29\beta+27\beta^2)^3} > 0$ (where $X_2 = 997+5373\beta+9639\beta^2+5751\beta^3$),

$\dfrac{\delta F_2^*}{\delta\beta} = \dfrac{(-1+c)^2(187+522\beta+315\beta^2)}{6(8+29\beta+27\beta^2)^2} > 0$.

Proposition 2 shows that:

(1) Under the retailer subsidy strategy, with the manufacturer's risk aversion gradually enhanced, the government should increase the subsidy ratio to improve the retailer's intelligent service innovation level. The retailer's utility level will continue to improve. So, it is beneficial to the retailer.

(2) However, the government's single subsidy to the retailer is not conducive to the manufacturer to improve production process innovation, and the utility level of the manufacturer continues to decline with the increase of risk aversion.

(3) In general, as the manufacturer improves risk aversion, the optional wholesale price and retail price of products will gradually decrease, conducive to improving consumer satisfaction. Therefore, the level of social welfare will continue to rise in the overall smart supply chain operation.

4.3 Coordinated subsidy strategy

In reality, if the government only subsidises the innovative production cost of manufacturers, retailers may reduce their efforts of smart service innovation to reduce marketing investment. Similarly, if the government only subsidises the innovation investment of retailers, the motivation for manufacturers' smart innovation will decline. Therefore, to prevent the phenomenon that non-subsidised objects reduce their investment in smart innovation under the government's single subsidy policy, this paper puts forward the coordinated subsidy strategy of the government subsidising manufacturers and retailers at the same time. Under the government's coordinated subsidy strategy, since both manufacturers and retailers have made innovation efforts to construct a smart supply chain, to encourage them to increase investment in smart innovation, the government provides subsidies to both the manufacturer and retailer. In this case, the utility functions of the manufacturer and the retailer are:

$$U_3^m = (w_3 - c)(1 - p_3 + g_3 + h_3) - g_3{}^2 - \beta(w_3 - c)^2 + s_3 g_3 \tag{9}$$

$$U_3^r = (p_3 - w_3)(1 - p_3 + g_3 + h_3) - h_3^2 + s_3 h_3 \tag{10}$$

The total social welfare function is:

$$F_3 = (p_3 - c)(1 - p_3 + g_3 + h_3) - (1 - p_3 + g_3 + h_3)^2 / 2 - s_3 g_3 - s_s h_3 \tag{11}$$

Solution 3. This process is also the same as solution 1. Similarly, by finding the relevant second-order derivatives of the utility function and the Hessian matrix, the optimal solutions for the smart supply chain decisions exist under the conditions of $0 < c < p < 1$ and $0 < \beta < 0.25$. From the inverse solution method, the optimal decisions of the government and the manufacturer and retailer in the smart supply chain can be found, yielding the following proposition.

Proposition 3. Under the coordinated subsidy strategy, the optimal decisions of the government and the smart supply chain are as follows.

The government optimal subsidy ratio: $s_3^* = \dfrac{(1-c)(2+3\beta)(7+27\beta)}{2(23+69\beta+54\beta^2)}$

The optimal wholesale price: $w_3^* = \dfrac{36+10c+63\beta+75c\beta+108c\beta^2}{2(23+69\beta+54\beta^2)}$

The optimal manufacturer's production process innovation level: $g_3^* = \dfrac{(1-c)(38+9\beta(13+9\beta))}{4(23+69\beta+54\beta^2)}$

The optimal retail price: $p_3^* = \dfrac{3(5+6\beta)(4+7\beta)-c(14+3\beta(13+6\beta))}{2(23+69\beta+54\beta^2)}$

The optimal retailer's service innovation level: $h_3^* = \dfrac{(1-c)(38+9\beta(21+23\beta))}{4(23+69\beta+54\beta^2)}$

Substituting the optimal solutions in Proposition 3 into Eq. (10)-(12) yields that

The manufacturer's optimal utility: $U_3^{m*} = \dfrac{(1-c)^2 X_3}{16(23+69\beta+54\beta^2)^2}$

where $X_3 = 3076 + 17364\beta + 34857\beta^2 + 28026\beta^3 + 6561\beta^4$.

The retailer's optimal utility: $U_3^{r*} = \dfrac{(1-c)^2 X_4}{16(23+69\beta+54\beta^2)^2}$

where $X_4 = 1924 + 18516\beta + 65025\beta^2 + 98334\beta^3 + 54189\beta^4$.

The optimal level of social welfare: $F_3^* = \dfrac{(1-c)^2(2+3\beta)(26+75\beta)}{4(23+69\beta+54\beta^2)}$.

Then, under the coordinated subsidy strategy, the effects of the manufacturer's risk aversion (β) on the optimal decisions of the government and the smart supply chain are studied in depth.

Proposition 3. Under the coordinated subsidy strategy, the role of the manufacturer's risk aversion (β) on the optional decisions of government and smart supply chains are as follows.

(1.5) $\dfrac{\delta s_3^*}{\delta\beta} = \dfrac{3(1-c)(253+738\beta+513\beta^2)}{2(23+69\beta+54\beta^2)^2} > 0$,

$$\frac{\delta h_3^*}{\delta\beta}=\frac{(1-c)(38+9\beta(21+23\beta))}{4(23+69\beta+54\beta^2)}>0,$$

$$\frac{\delta g_3^*}{\delta\beta}=\frac{3(c-1)(-23+126\beta+243\beta^2)}{4(23+69\beta+54\beta^2)^2}$$

where, when $0<\beta<0.143$, $\frac{\delta g_3^*}{\delta\beta}>0$; when $0.143<\beta<0.25$, $\frac{\delta g_3^*}{\delta\beta}<0$,

$$\frac{\delta w_3^*}{\delta\beta}=\frac{9(c-1)(115+432\beta+378\beta^2)}{2(23+69\beta+54\beta^2)^2}<0,$$

$$\frac{\delta p_3^*}{\delta\beta}=\frac{3(c-1)(23+228\beta+288\beta^2)}{2(23+69\beta+54\beta^2)^2}<0.$$

(1.6) $$\frac{\delta U_3^{m*}}{\delta\beta}=-\frac{3(-1+c)^2X_5}{8(23+69\beta+54\beta^2)^3}<0$$

(where $X_5=4186+43185\beta+146529\beta^2+204525\beta^3+101331\beta^4$),

$$\frac{\delta U_3^{r*}}{\delta\beta}=\frac{3(-1+c)^2X_6}{8(23+69\beta+54\beta^2)^3}>0$$

(where $X_6=26726+216327\beta+630909\beta^2+791289\beta^3+361341\beta^4$),

$$\frac{\delta F_3^*}{\delta\beta}=\frac{9(-1+c)^2(184+526\beta+357\beta^2)}{4(23+69\beta+54\beta^2)^2}>0.$$

Proposition 3 shows that:

(1) Under the coordinated subsidy strategy, as the manufacturer’s risk aversion increases, the government’s optimal subsidy ratio increases, which raises the retailer’s service innovation level and is conducive to improving the retailer’s utility. So, it is beneficial to the retailer.

(2) For the manufacturer, the utility level negatively correlates with the degree of risk aversion. Only when the manufacturer’s relatively low-risk aversion will the manufacturer’s production process innovation level gradually improve. The production process innovation level will gradually decrease when the risk aversion is relatively high.

(3) On the whole, the wholesale and retail prices of products are declining, beneficial to consumers. Under the coordinated subsidy strategy, the level of social welfare continues to improve with the rise of manufacturers' risk aversion.

4.4 Comparative analysis of different subsidy strategies

Proposition 4. Taking the maximisation of the optimal social welfare level as the government's goal to make subsidy policy, this study compares the efficiency of three different subsidy strategies combined with conditions of $0<c<p<1$ and $0<\beta<0.25$, and it is easy to get $F_3^*>F_1^*>F_2^*$.

Proposition 4 shows that the level of social welfare under the coordinated subsidy strategy is always higher than that under the single subsidy strategy. In comparison, the manufacturer subsidy strategy has a higher level of social welfare than the retailer subsidy strategy. It indicates that the government’s incentive to subsidise the manufacturer and retailer simultaneously is better than the incentive to one entity alone. In the coordinated subsidy strategy, the government integrates the manufacturer’s level of production process innovation with the retailer’s level of service innovation to determine the subsidy ratio, which simultaneously motivates them to carry out smart innovation. Therefore, to a certain extent, this helps manufacturers and retailers collaborate to jointly promote the overall benefit growth of the smart supply chain system.

In addition, the effectiveness of the three government subsidy strategies in terms of the optimal utility and innovation levels of the manufacturer and the retailer, the amount of government expenditure, the price of the products, etc., will be analysed more concisely in the form of graphs in the following numerical simulation.

5. Numerical Simulation

The following will further analyse and verify the correctness of the above findings by assigning values to the parameters. From the above analysis, it can be seen that the manufacturer's risk aversion is the primary variable affecting the optimal decisions of smart supply chains under dual innovation. Therefore, this study refers to the setting of parameters by Cao et al.(Cao, Li *et al.*, 2019), takes $c = 0.1$, and focuses on the influence of the manufacturer's risk aversion in the range of $0 < \beta < 0.25$, while comparing the effectiveness of three government subsidy strategies.

5.1 The impact of manufacturer's risk aversion (β) on the level of social welfare (F) and government expenditure (G)

According to Fig. 1, under the three subsidy strategies, F^* increases with β. Moreover, the social welfare level of the government coordinated subsidy strategy is the highest, followed by the manufacturer subsidy strategy, and the retailer subsidy strategy is the lowest. It can be seen that the coordinated subsidy policy of the government is more conducive to improving the level of social welfare than the single subsidy policy. This is because the government simultaneously encourages the intelligent innovation motivation of manufacturers and retailers, coordinates their production and marketing cooperation from the outside of the supply chain, and promotes the overall revenue growth of the smart supply chain system.

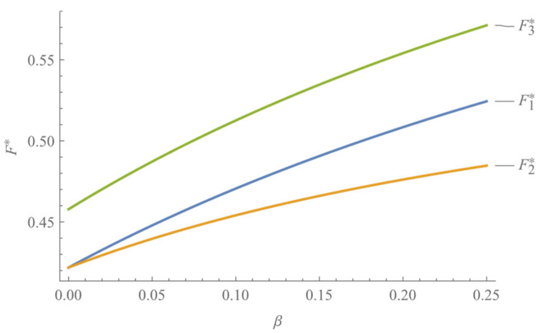

Fig. 1. The impact of manufacturer's risk aversion on the level of social welfare

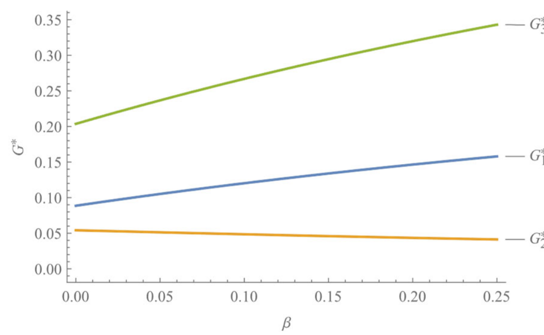

Fig. 2. The impact of manufacturer's risk aversion on the government expenditure

Among the three subsidy strategies, the government expenditure (G) refers to the total spending of manufacturers and retailers subsidised by the government, i.e. when the government only subsidises manufacturers, there is $G_1^* = s_1^* g_1^*$; when the government only subsidises retailers, there is $G_2^* = s_2^* g_2^*$; when the government subsidises them at the same time, there is $G_2^* = s_3^* g_3^* + s_3^* h_3^*$. As shown in Fig. 2, with the increase β, the government expenditure on manufacturer subsidy and coordinated subsidy strategy gradually increases, but the government expenditure on retailer subsidy strategy slowly decreases. In addition, the two figures jointly show that the higher the level of social welfare, the more government expenditure required by the subsidy strategy. Although the social welfare level of the coordinated subsidy strategy is the highest and the effect is the best, its spending is higher than the total expenditure of manufacturers and retailers with the single subsidy. Therefore, the relative cost of the coordinated government subsidy is more, and the government should implement the subsidy strategy according to the actual purpose.

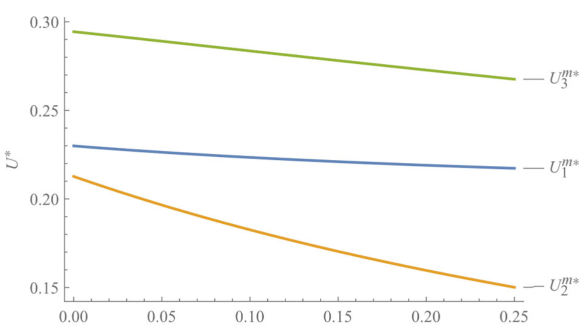

Fig. 3. The impact of the manufacturer's risk aversion on the manufacturer's utility

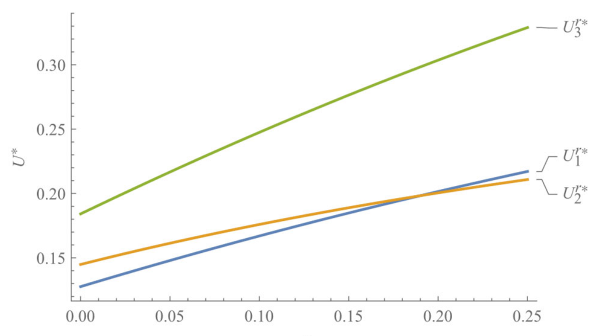

Fig. 4. The impact of the manufacturer's risk aversion on the retailer's utility

5.2 The impact of risk aversion (β) on the utility of the manufacturer and retailer

As can be seen from Fig. 3 and Fig. 4 below, among the three government subsidy strategies, the utility level of the manufacturer decreases gradually with the increase of risk aversion. Still, the utility level of the retailer increases slowly. Among them, the utility level of the manufacturer and retailer is the highest under the government coordinated subsidy strategy. In addition, for the manufacturer, it is evident that the profits under the government manufacturer subsidy strategy are more than those under the retailer subsidy strategy. Similarly, for the retailer, the utility level of government single subsidy retailers is higher than that of subsidy manufacturers in general. Only when the manufacturer's risk aversion is relatively high the retailer's utility level of the manufacturer subsidy strategy is higher than that of the retailer subsidy strategy. To avoid market risks, manufacturers will significantly reduce their investment in intelligent innovation. In contrast, as followers of supply chain decision-making, downstream retailers will also reduce the intensity of intelligent service innovation and can only make marketing efforts for fewer smart products, which has relatively little significance in increasing revenue. Therefore, at this time, the government directly subsidises manufacturers to encourage them to improve their innovation investment, which is more effective than subsidising retailers. This shows that the government's policy of single subsidy to the retailer is not always beneficial to retailers, which depends on the actual situation.

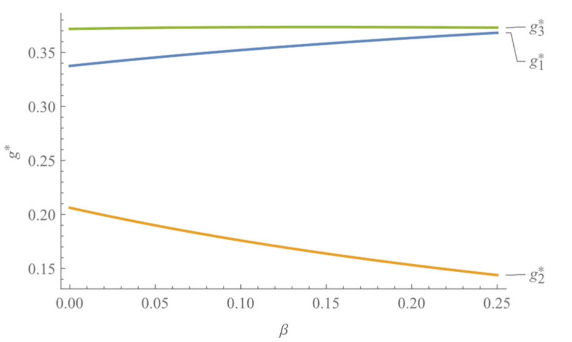

Fig. 5. The impact of the manufacturer's risk aversion on the manufacturer's production process innovation

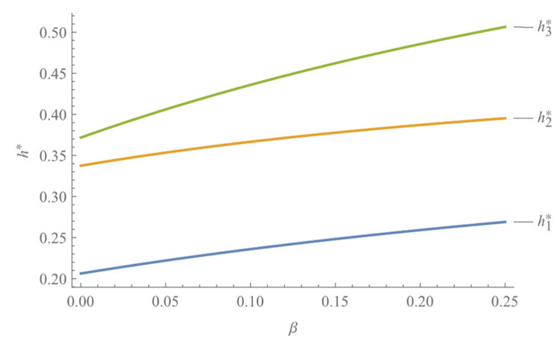

Fig. 6. The impact of manufacturer's risk aversion on the retailers' service innovation

5.3 The impact of risk aversion (β) on manufacturers' production process innovation and retailers' service innovation

From Fig. 5, if the manufacturer's risk aversion increases gradually, the manufacturer's production process innovation level will first increase and then decrease under the government coordinated subsidy strategy. The level of production process innovation under the manufacturer subsidy strategy will continue to improve. The level of production process innovation will gradually decline under the retailer subsidy strategy. With the improvement of manufacturers' risk aversion, manufacturers tend to improve the cost performance of products to reduce the risk of market demand. They want to improve production efficiency, and government subsidies to manufacturers are more conducive to manufacturers' intelligent production process innovation. So, g_1^* it continues to rise with β. However, when the government only subsidises retailers, manufacturers' motivation for product innovation will be reduced. The reduction is more significant than the manufacturer wants to improve production efficiency, g_2^* decreases with β. Finally, when the government subsidises manufacturers and retailers simultaneously, the rising and falling motivation of manufacturers' production process innovation offset each other, so the fluctuation of manufacturers' intelligent innovation level is not apparent under the government coordinated subsidy strategy.

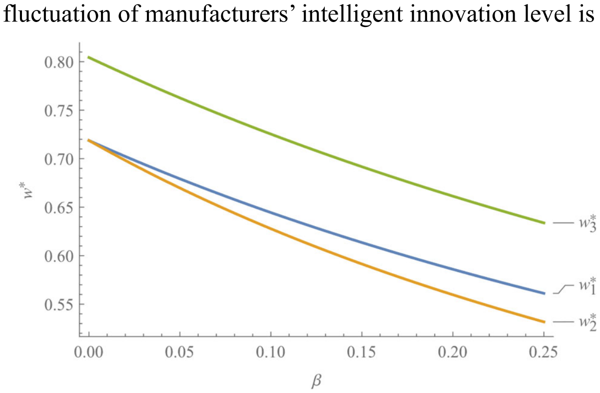

Fig. 7. The impact of the manufacturer's risk aversion on the wholesale price

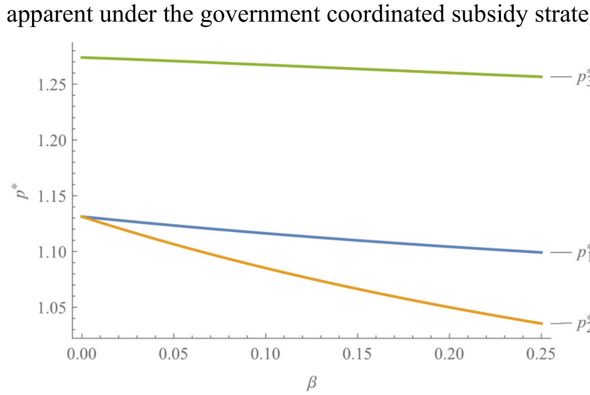

Fig. 8. The impact of the manufacturer's risk aversion on the retail price

From Fig. 6, to realise the precision marketing of consumers under the new retail situation, the level of smart service innovation of retailers will continue to strengthen with the improvement of the manufacturer’s risk aversion in the three government subsidy strategies. In addition, the intelligent innovation level of manufacturers and retailers under the coordination strategy is the highest, indicating that the government coordinated subsidy strategy is more conducive to the innovation and development of a smart supply chain than the single subsidy strategy. Moreover, in the single subsidy strategies, the government directly subsidised manufacturers can better motivate manufacturers to improve their production process innovation efforts, or now subsidised retailers can better encourage retailers to increase their service innovation investment.

5.4 The impact of risk aversion (β) on the wholesale price and retail price of the product

Fig. 7 and Fig. 8 show that the wholesale price and retail price of smart products continue to decline with the increase in manufacturers' risk aversion. Therefore, moderate risk aversion drives the smart supply chain system to provide consumers with better quality products at lower prices, which is beneficial to consumers. Comparing the three government subsidy strategies shows that the coordinated subsidy strategy has the highest prices, followed by the manufacturer subsidy strategy and the retailer subsidy strategy, so if the government wants to maximize the benefits to consumers, the single subsidy to retailers works best. However, suppose the overall level of social welfare is taken into account. In that case, the government should provide coordinated subsidies to manufacturers and retailers to increase the comprehensive benefits of the smart supply chain. In this case, part of the preferential price of smart products will be transferred to the innovation cost of the smart supply chain, which is conducive to enterprises to better realise social responsibility and promote the sustainable innovation development of the industry.

6 Conclusions and Insights

6.1 Conclusions

By constructing a Stackelberg game model in the smart supply chain driven by both manufacturer’s production process innovation and retailer’s service innovation and considering manufacturer’s risk aversion scenarios, the optimal smart supply chain decisions with two single government subsidy strategies and one coordinated subsidy strategy are investigated. The impacts of the manufacturer’s risk aversion are further analysed. The results of the study show that:

(1) The moderate risk aversion of manufacturers will lead to lower prices for smart products, stimulating manufacturers to increase production process innovation and retailers to improve their service innovation, which will help provide consumers with better quality products at lower prices. It makes the utility level of manufacturers decline, and the utility level of retailers rise, but the overall social welfare level increases.

(2) From the perspective of overall social welfare, the government coordinated subsidy strategy is more effective than the single subsidy strategy. Under the coordinated subsidy strategy, the utility level and the smart innovation of both manufacturers and retailers are the highest. Therefore, the government coordinated subsidy strategy is more conducive to encouraging enterprises to realise their social responsibility and promote the innovative development of a smart supply chain.

(3) However, the coordinated subsidy strategy has the highest level of government expenditure and the highest wholesale and retail prices, so the government should weigh the advantages and disadvantages against the actual needs when formulating subsidy strategies.

(4) In the single subsidy strategy, the government’s direct subsidy to manufacturers can stimulate them to increase production process innovation investment and improve the level of intelligent production, to increase their utility level. Similarly, direct government subsidies to retailers can also stimulate them to strengthen service innovation and increase retailers' revenue. In terms of social welfare level, the manufacturer subsidy strategy is more efficient, but the wholesale and retail prices of products are higher than the retailer subsidy strategy.

6.2 Management Insights

In the current Industry 4.0, this paper has some management implications for enterprises to promote the innovative development of smart supply chains with modern information technology and for governments to optimize their subsidy policies.

(1) At this stage, as an external intervener in the supply chain system, it is indispensable for the government to support the intelligent innovation of the supply chain through financial subsidies. The efficiency of the coordinated subsidy strategy is higher than that of the single subsidy strategy, so the government should determine a reasonable subsidy ratio by integrating the risk-averse characteristics of the supply chain players. However, as the coordinated subsidy strategy requires relatively high government expenditure and higher product prices, the government should also weigh the pros and cons in determining the subsidy strategy in combination with the actual needs.

(2) Risk aversion can adversely affect the manufacturer's level of utility, so it is more critical for manufacturers to actively use digital information technology to innovate intelligent production in the supply chain and integrate the traditional supply chain's commercial, logistics, and information flows, thereby improving the stability of the supply chain's operation and reducing the market risk of their products.

(3) The coordinated subsidy strategy works better than the single subsidy strategy because the government's coordinated subsidy promotes cooperation between manufacturers and retailers. So, the supply chain members should collaborate to promote the sustainable development of the smart supply chain regardless of the subsidy strategy.

6.3 The Future Extension

The subsequent research can be further expanded. To comprehensively analyse the government's various subsidy policies, we can consider the subsidy strategies for manufacturers, retailers and consumers. Secondly, we can consider introducing the internal cost contract of the supply chain to study the coordination subsidy strategy. Finally, the supply chain network structure is generally complex, so smart supply chain management involving multiple manufacturers and retailers also deserves further research.

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