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Comparative Study on Low-Carbon Strategy and Government Subsidy Model of Pharmaceutical Supply Chain

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Abstract: Despite the growing urgency to curb carbon emissions worldwide, the healthcare industry, particularly the pharmaceutical industry, has received little attention from the sustainability community in terms of its contribution to the global carbon footprint. This paper constructs a differential game model of the secondary pharmaceutical supply chain consisting of pharmaceutical enterprises and medical institutions in the context of centralized drug procurement policy, considering the effects of health insurance reimbursement and consumers' low-carbon preferences, and compares and analyzes the feedback equilibrium strategies of low-carbon inputs and marketing efforts, supply chain profits, and social welfare levels under four government subsidy models and further discusses them with arithmetic examples. The results illustrated that government subsidies have a significant impact on the low-carbon investment of pharmaceutical enterprises and the low-carbon marketing of medical institutions; subsidies for pharmaceutical enterprises can significantly increase the low-carbon investment and profit level of pharmaceutical enterprises; subsidies for medical institutions can effectively promote the implementation of the "zero-rate" policy and the realization of the emission reduction target under the centralization policy of medical institutions, increase the market demand for low-carbon drugs, and thus gain higher profits; the dual-subsidy model of the government brings higher social welfare than the single-subsidy model, and under a reasonable subsidy ratio, the profit and social welfare of the whole supply chain can be maximized.

Keywords: low-carbon economy; government subsidies; consumer preferences; differential game; pharmaceutical supply chain

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1. Introduction

The pharmaceutical industry is a high-risk, high-input, high-tech, and high-return industry [1], but also environmental governance, energy conservation, and greenhouse gas emission reduction are very heavy tasks of the industry [2]. According to a September 2019 report by ARUP and Health Care Without Harm (HCWH), the global healthcare sector accounts for 4.4 percent of all carbon emissions. In absolute terms, total global CO_2 emissions from the healthcare sector are about 2.4 billion tons, compared to a global total of 54.4 billion tons of carbon emissions [3]. These carbon emissions originate from various parts of the entire supply chain of the healthcare industry: for example, the production and supply of energy required for the manufacturing process of pharmaceuticals and emissions resulting from activities are related to healthcare facilities, including various raw materials, energy, chemicals, drugs, medical devices, etc. Therefore, both pharmaceutical enterprises and healthcare organizations need to work towards achieving carbon neutrality in their future development process.

Since the outbreak of the COVID-19, ibuprofen, the Lianhua Qingwen Capsule, and other therapeutic drugs were snapped up to be empty. For instance, ibuprofen belongs to the class of non-steroidal anti-inflammatory drugs (NSAIDs) and is included in the World Health Organization's list of essential drugs, with tens of billions of tablets in use each year. Nowadays, it is mainly produced in China, India, and the United States.

Ibuprofen is produced in a variety of ways [4]; the key is process mass intensity (PMI) [5]. Process mass intensity represents the weight of raw material required to produce 1 kg of ibuprofen. In general, the higher the PMI, the higher the carbon footprint. Currently, the PMI for ibuprofen is between 2 and 7, which precisely reflects the huge difference in carbon footprint.

As large international pharmaceutical enterprises carry out carbon neutral planning, many pharmaceutical enterprises have taken the lead in setting and disclosing their carbon neutrality targets, such as AstraZeneca, which will use 100% renewable electricity and heat by 2025, Novo Nordisk, which will achieve zero carbon emissions in operations and logistics by 2030, and Bayer Group, which will achieve carbon neutrality in operations by 2030 [6]. In addition, since the announcement of China's dual carbon targets of "achieving carbon peaking by 2030 and carbon neutrality by 2060" in 2021 [7], policies related to carbon reduction in the pharmaceutical industry have been introduced, such as "Guidance on Promoting Green Development of API Industry" [8], "Deepening Green and Low-carbon Leading Action in Public Institutions to Promote Carbon Peaking Implementation Plan" [9], "The 14th Five-Year Plan for the Development of Pharmaceutical Industry" [10], etc. Chinese pharmaceutical enterprises are facing more stringent pressure and challenges to reduce emissions. However, most Chinese pharmaceutical enterprises are still in the initial stage of "double carbon" action, and although there are emission reduction actions being carried out, there is still much room for improvement in terms of disclosure of targets and tracking of carbon management progress. In recent years, local governments have also introduced policies to encourage pharmaceutical enterprises to make low-carbon transformation, such as in Hebei Province, where pharmaceutical enterprises are compensated for 15% of their low-carbon cost investment [11]. Thus, government intervention and guidance for the development of low-carbon transformation of pharmaceutical enterprises have become increasingly important. However, considering the high cost of government subsidies, how to develop a reasonable and effective subsidy model is one of the focuses of this paper.

Therefore, this paper intends to explore the following three questions:

RQ1: Under what conditions would the government choose to provide subsidies to pharmaceutical supply chain members?

RQ2: What is the impact of the implementation of government subsidies on the low-carbon strategy and profits of the pharmaceutical supply chain?

RQ3: How to take advantage of the government subsidies to enhance the triple benefits of economy, environment, and society in the pharmaceutical supply chain?

In order to solve the above three problems, this paper constructs a differential game model of the secondary pharmaceutical supply chain consisting of pharmaceutical enterprises and medical institutions in the context of centralized drug procurement policy, considering the effects of health insurance reimbursement and consumers' low-carbon preferences and four different government subsidy models: (1) no government subsidy model (NS), (2) pharmaceutical enterprise subsidy model (MS), (3) medical institution subsidy model (HS), and (4) government dual subsidy model (DS), which analyzes the effects of different government subsidy models on the low-carbon strategies, profit levels, and social welfare of pharmaceutical supply chain members and further discusses them with arithmetic examples.

Our paper contributes to both theoretical research and practical significance. In terms of theoretical research, it fills the gap in the research on government-led low-carbon transformation of pharmaceutical industry and expands the research field related to government subsidies in pharmaceutical supply chain. Its practical significance is that when the government subsidizes low-carbon pharmaceutical supply chain, pharmaceutical enterprises and medical institutions can profit from it, and economic, environmental, and social-related benefits can be improved. This paper can provide some references for pharmaceutical supply chain members to improve their economic benefits and fulfill their social responsibilities with the help of government subsidies.

The remainder of this paper is organized as follows. In Section 2, we summarize the relevant literature. Sections 3 and 4 introduce the relevant models and analyze the optimal equilibrium strategy under each subsidy model. Section 5 compares the optimal decisions under the four subsidy models and analyzes the social welfare under different subsidy models. Section 6 presents numerical analysis of key parameters in order to draw further conclusions. In Section 7, the conclusions drawn in this paper are summarized, and the important implications are discussed.

2. Literature Review

The main studies related to this paper can be divided into three categories: pharmaceutical supply chain member decision making, supply chain carbon emission reduction research, and the effect of government low-carbon subsidies on supply chain carbon reduction.

2.1. Pharmaceutical Supply Chain Member Decision Making

The existing studies analyze the factors influencing pharmaceutical supply chain members' decisions, including health insurance reimbursement, market size, centralized procurement, and price control. Zhang et al. [12] used a natural experiment implemented by China's New Cooperative Medical Scheme (NCMS) to study the impact of pharmaceutical firms' innovation on drugs for diseases covered by the NCMS and showed that health insurance policies effectively stimulate pharmaceutical firms' technology development. Lan et al. [13] examine the impact of health insurance and patient preferences on manufacturer encroachment in the pharmaceutical supply chain and further analyze the impact of perceived drug quality on social welfare. Jiang et al. [14] constructed a dual-channel game model based on the vertical differentiation of drugs to study the equilibrium pricing and profits of drugs reimbursed by medical insurance, and the results showed that the pricing and profits of medical insurance drug retailers decreased as the out-of-pocket ratio of patients increased. Pierre et al. [15] quantitatively analyzed the relationship between market size and R&D of pharmaceutical enterprises and found that pharmaceutical innovation is closely related to expected market size, which is influenced by factors such as population, industry competition, and subsidy policies. Wu et al. [16] studied the impact of different price limit policies on the procurement strategies of pharmaceutical supply chains and analyzed the optimal procurement strategies of medical institutions under different market sizes and volume discounts. Zhang et al. [17,18] comparatively analyzed the impact of dual oligopoly pharmaceutical enterprises on innovation investment under centralized and non-centralized procurement from different perspectives. It was found that the degree of incentive of centralized procurement on innovation depended on the fee system adopted by the procurement platform, and the two-part fee system was more conducive to corporate innovation. Shin et al. [19] compared the effects of various policies, such as price controls and innovation incentives, on technological upgrading. The study found that appropriate price controls can promote technology investment and, when matched with incentive policies, can promote a win–win situation. Wang et al. [20] and Zhou et al. [21] similarly argue that the government should further deregulate the price of medical services and allow prices to regulate supply and demand in the medical services market.

In summary, the production and sale of innovative drugs have always been the focus of pharmaceutical supply chain research. However, the process of R&D, production, and transportation of innovative drugs is inevitably accompanied by huge amounts of carbon emissions [22]. Given the increasingly strict carbon emission control and a deepening of the concept of sustainable development, the pharmaceutical industry is under increasing pressure to reduce emissions, but the existing research on carbon emission reduction strategies for drug development, production, and sales is very scarce. In addition, most of the existing studies on pharmaceutical supply chain members' decision-making adopt empirical analysis and static game methods, ignoring the influence of time factors on decision making. Carbon emission reduction is a long-term task, and supply chain members

need to consider their future profits and development. Therefore, considering the strategic decision of low carbon and sustainable development from the perspective of dynamic game is more in line with the actual needs of current pharmaceutical supply chain members.

2.2. Supply Chain Carbon Emission Reduction Study

With the prominence of external environmental issues, more and more enterprises are taking up environmental social responsibility. As a major participant in economic activities, enterprises should not only consider profit as the primary goal but also deal with the relationship between environmental protection and economic growth and take practical actions to reduce emissions and consumption, and starting from the operation level of the supply chain is one of the most effective measures to implement carbon emission reduction [23]. Therefore, many scholars have tackled the issue of carbon emission reduction from the supply chain perspective, aiming to improve the overall carbon emission reduction level of low-carbon supply chains, mainly involving two aspects.

Concerning the government's low-carbon policy, government policies on carbon emissions have an important impact on enterprises' emission reduction. Nowadays, carbon emission-related policies can be broadly divided into two categories: punitive policies based on carbon emissions trading and carbon taxes and incentive policies based on industrial subsidies and consumer subsidies [24]. Benjaafar et al. [25] first introduced carbon emission policies into the study of supply chain operation management and initially analyzed the impact of different carbon emission policies on corporate decision-making as well as emission reduction. Li et al. [26] investigated the level of emission reduction efforts in supply chains under a cap-and-trade mechanism when the government-imposed carbon limits on firms' total production emissions or unit production emissions, respectively, and found that unit production emission limits were more effective in stimulating firms to make higher carbon reduction efforts compared with total production emission limits. Cao et al. [27] explored the effects of carbon taxes and bank interest rates on manufacturers' carbon emission reductions and retailers' order quantity in the presence of financial constraints for manufacturers and retailers.

Consumer low-carbon preferences and the influence of consumers in the process of corporate emission reduction practices should not be overlooked either. Hong et al. [28] studied the pricing of green products considering consumer preferences. Gong [29] et al. studied the influence of consumer low-carbon preferences on the price of new energy vehicles and sellers' profits and established pricing models for centralized and decentralized scenarios. Zhang et al. [30] studied a dual-channel supply chain product pricing and low-carbon decision problem based on consumers' low-carbon preferences. Meng et al. [31] proposed a product pricing model for a dual-channel green supply chain considering consumers' low-carbon preferences and channel preferences.

In the medical field, the emission reduction strategy of drug recycling has attracted more scholars' attention. Xie et al. [32] used community pharmacies as a study to design a green closed-loop supply network using a cross-border approach, which effectively boosted the demand for pharmaceutical waste recycling. Weraikat et al. [33] designed an incentive mechanism in which 28% of drugs were effectively recycled through communication and cooperation between pharmaceutical enterprises. Ghosh et al. [34] used fuzzy technology to design a sustainable carbon mechanism to address the multi-objective transport of medical waste. Tirkolaee et al. [35] developed a new mixed integer linear programming model to facilitate decision-making around strategies for low-carbon management of municipal solid waste management, minimizing the total cost of solid waste treatment, minimizing carbon emissions, and maximizing citizen satisfaction.

Most of the supply chain carbon reduction studies are in the new energy and green product industries, while the number of studies on carbon reduction in the pharmaceutical industry is relatively small and dominated by medical waste recycling. Due to the implementation of centralized drug procurement policy, the price of drugs is determined by direct negotiation between pharmaceutical enterprises and medical institutions represented

by the government, eliminating the double markup effect caused by intermediate channels, and patients can purchase drugs at wholesale prices. Therefore, the unique structure of pharmaceutical supply chains makes the research results of other types of supply chains not applicable to pharmaceutical supply chains. In addition, influenced by the low-carbon concept, many patients prefer to purchase medical products with easy decomposition and non-polluting green products, so this paper introduces consumers' low-carbon preferences into the pharmaceutical supply chain and further explores its impact on supply chain members.

2.3. The Effect of Government Low-Carbon Subsidies on Supply Chain Carbon Reduction

The literature on government subsidies to promote green development in supply chains demonstrates that government subsidies have a positive impact on firms' innovation and that market participants receiving government subsidies will generate more profits and greater social welfare [36–38], and the game between the government, firms, and their competitors determines the extent to which subsidy policy affects firms' innovation [39–41]. Cao et al. [42] found that low-carbon subsidy policies outperformed carbon tax policies in curbing carbon emissions in a dual-channel supply chain analysis of recycled and new products. Xu et al. [43] considered the impact of horizontal supply chain integration on subsidy policy implementation, where horizontal integration of supply chains would change the highest level of subsidies. Zhang et al. [44] developed a secondary low-carbon supply chain government subsidy model and found that by appropriately adjusting wholesale and retail prices, the subsidy policy would have the same effect regardless of who the subsidy was targeted at. Peng et al. [45] construct a multi-objective dynamic programming model that considers the effect of government subsidies on green marketing strategies to explore the balance between product price, customer environmental voluntariness, and corporate environmental responsibility. In the medical field, Choi et al. [46] analyzed the relationship between public R&D subsidies and private R&D investments based on data from the Korean pharmaceutical industry and showed that government R&D subsidies stimulated private R&D activities in small biotechnology companies. Lanahan et al. [47] and Kleine et al. [48] find that in addition to government subsidies, firm heterogeneity can lead firms with different production capabilities to pursue various innovation strategies. At the same time, government subsidy programs often have a significant impact on technologically innovative firms [49]. Zhao et al. [50] identified government revenue subsidies as an important means to alleviate the plight of public medical institutions to reform. Chen et al. [51] found that government subsidies reduced the burden of medical costs on patients and improved the cost efficiency of healthcare institutions. Chen et al. [52] constructed a two-stage dynamic game model and found that drug revenues were positively related to the amount of R&D subsidies per product under different subsidy strategies. Huang et al. [53] compared the effects of government subsidy strategies on pharmaceutical firms' new drug R&D decisions, profits, and social welfare under horizontal and vertical spillover effects in the pharmaceutical industry.

The existing literature on green government subsidies mostly focuses on sales channels and product pricing, but the pharmaceutical supply chain is influenced by centralized procurement policies, and pharmaceutical distributors play more of a logistics and distribution role in the pharmaceutical industry, and the sales channels and product pricing methods are vastly different from those of other industries. Early studies on government subsidies in pharmaceutical supply chains did not consider the impact of centralized procurement policies on the supply chain structure and mostly focused on empirical studies. There is a clear absence of comprehensive research on the impact of multi-level supply chains, consumers' low-carbon preferences, government subsidies for low-carbon activities, and the implementation of policies such as centralized procurement and health insurance reimbursement on the supply chain. In this study, we address all these issues. First, we introduce a secondary pharmaceutical supply chain with centralized procurement and medical insurance reimbursement policies, which is rarely studied in the literature. Second,

we compare the profit levels of supply chain members under different models for different government subsidies to pharmaceutical enterprise and medical institution. In addition, the impact of government subsidies on the supply chain decision-making process is the main issue of this study.

3. Model Description and Assumptions

A two-level pharmaceutical supply chain system consists of a pharmaceutical enterprise M and a medical institution H. The pharmaceutical enterprise produces a low-carbon drug through abatement investments; the medical institution promotes patient market demand through certain marketing efforts. In the sales process of drugs, pharmaceutical enterprise determined the marginal profit of drugs w, which is also the centralized procurement price. A medical institution purchases drugs from a pharmaceutical enterprise and administers them to patients according to the centralized procurement policy, which determines the marginal profit of their services p. In addition, to incentivize the development of low-carbon transformation in the pharmaceutical supply chain, the government provides subsidies to pharmaceutical enterprise for low-carbon cost investment and medical institution for low-carbon drug use.

Based on the above analysis, we considered four different subsidy models: no government subsidy model NS, pharmaceutical enterprise subsidy model MS, healthcare provider subsidy model HS, and government dual subsidy model DS. In the Stackelberg differential game process, the pharmaceutical enterprise is the channel leader, and the medical institution is the channel follower. To better advance the subsequent study, the relevant assumptions of this paper are as follows.

For the sake of clarity of the model formulation, the notations used in this paper and their meanings are listed in Table 1.

Table 1. Notation and definitions.

Notation	Definitions
State variable	
$G(t)$	Low-carbon goodwill
Decision variable	
$r(t)$	Low-carbon input level of pharmaceutical enterprise
$s(t)$	Level of marketing effort for medical institution
Parameters	
w	Marginal profit of pharmaceutical enterprise's drugs, centralized drug procurement prices
p	Marginal profit of medical institution services
μ	Coefficient of impact of low-carbon inputs on low-carbon goodwill
k	Natural decay rate of low-carbon goodwill
a	Initial drug requirements
δ	Coefficient of impact of low-carbon inputs on demand
β	Coefficient of influence of marketing efforts on demand
λ	Consumers low-carbon preferences
θ	Pharmaceutical enterprise low-carbon input cost subsidy ratio
η	Medical institutions centralized procurement product subsidy ratio
ρ	Discount rate
b	Percentage of patient's own price

Assumption 1. *The low-carbon goodwill of the supply chain is determined by the low-carbon inputs of pharmaceutical enterprise and decays over time, and the Nerlove–Arrow [54] model is used to describe the change process of low-carbon goodwill in the supply chain:*

$$\dot{G}(t) = \mu r(t) - kG(t),\ G(0) = G_0 \tag{1}$$

where $r(t)$ represents the low-carbon input level of pharmaceutical enterprise, $\mu > 0$ represents the influence coefficient of low-carbon input on low-carbon goodwill, $k > 0$ is the natural attenuation coefficient, and G_0 represents initial low-carbon goodwill.

Assumption 2. *Refer to the assumptions of MA et al. [55]; the demand function for low-carbon products is a deterministic linear function. Products with higher levels of low-carbon inputs, marketing, and low-carbon goodwill are more popular in the market. In particular, the health insurance reimbursement rate of centrally procured drugs also affects the market demand. Therefore, the demand function for low-carbon products can be obtained as shown below.*

$$Q(t) = a - bw + \delta r(t) + \beta s(t) + \lambda G(t) \tag{2}$$

$a > 0$ represents initial drug demand; $b > 0$ represents the proportion of the patient's self-financing price; $s(t)$ represents the level of marketing effort for medical institution; $\delta r(t)$ and $\beta s(t)$ represent the expansion of potential market scale caused by the investment of pharmaceutical enterprise in low-carbon technologies and the promotion of low-carbon products by medical institution; $\delta > 0$ and $\beta > 0$ reflect the sensitivity coefficient to market demand; $\lambda > 0$ represents consumers' low-carbon preference. According to the theory of consumers' low-carbon preference, product demand is proportional to the low-carbon level of the product.

Assumption 3. *Refer to the assumptions of Li et al. [56] and Zhang et al. [57] on the cost function; the low-carbon input cost of pharmaceutical enterprise $C_{\mathrm{M}}(t)$ and the marketing cost of medical institution $C_{\mathrm{H}}(t)$ are*

$$\begin{cases} C_{\mathrm{M}}(R(t)) = \frac{1}{2}\kappa_{\mathrm{M}} r^2(t) \\ C_{\mathrm{H}}(S(t)) = \frac{1}{2}\kappa_{\mathrm{H}} s^2(t) \end{cases} \tag{3}$$

$\kappa_{\mathrm{M}}, \kappa_{\mathrm{H}} > 0$ represents the low-carbon input cost coefficient and marketing cost coefficient, which are standardized as 1 in this paper for the convenience of calculation.

Assumption 4. *In order to achieve the carbon neutrality target and increase the incentive of low-carbon development in the pharmaceutical supply chain, the government provides subsidies to the main body that produces and sells low-carbon medical products. The government gives a subsidy of $\theta > 0$ proportional to the low-carbon input cost of the pharmaceutical enterprise. Meanwhile, in order to encourage the medical institution to speed up the structural transformation, the government gives a subsidy of ηw unit price to medical institutions using low-carbon products, where $\eta > 0$ is the subsidy ratio and $w > 0$ is the centralized procurement price of drugs. The government mainly makes subsidy decisions based on maximizing social welfare, which includes profits of pharmaceutical enterprise π_{M}, profits of medical institution π_{H}, and consumer surplus CS. The social welfare function is expressed as follows:*

$$SW = \pi_{\mathrm{M}} + \pi_{\mathrm{H}} + CS \tag{4}$$

Refer to the calculation of consumer surplus by Panda et al. [58]:

$$\mathrm{CS} = \int_{P_{\min}}^{P_{\max}} D(p)\mathrm{d}p = \int_{(a-D)/b}^{a/b} (a - bp)\mathrm{d}p = \frac{D^2}{2b}$$

D denotes the demand function of the market (i.e., Q in this paper), normalizing b to 1 for ease of calculation.

Assumption 5. *The pharmaceutical enterprise and medical institution have the same time discount rate ρ. In the $[0, +\infty)$ time period, both sides seek to maximize their profits. The present value of profits of pharmaceutical enterprise and medical institution for each of the four models are*

$$\begin{aligned} \max_r \pi_{\mathrm{M}}^{\mathrm{NS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \tfrac{1}{2}r^2(t)\right\}\mathrm{d}t \\ \max_s \pi_{\mathrm{H}}^{\mathrm{NS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{pQ(t) - \tfrac{1}{2}s^2(t)\right\}\mathrm{d}t \end{aligned} \tag{5}$$

$$\begin{aligned} \max_r \pi_{\mathrm{M}}^{\mathrm{MS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \tfrac{1}{2}(1-\theta)r^2(t)\right\}\mathrm{d}t \\ \max_s \pi_{\mathrm{H}}^{\mathrm{MS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{pQ(t) - \tfrac{1}{2}s^2(t)\right\}\mathrm{d}t \end{aligned} \tag{6}$$

$$\begin{aligned} \max_r \pi_{\mathrm{M}}^{\mathrm{HS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \tfrac{1}{2}r^2(t)\right\}\mathrm{d}t \\ \max_s \pi_{\mathrm{H}}^{\mathrm{HS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{(p+\eta w)Q(t) - \tfrac{1}{2}s^2(t)\right\}\mathrm{d}t \end{aligned} \tag{7}$$

$$\begin{aligned} \max_r \pi_{\mathrm{M}}^{\mathrm{DS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \tfrac{1}{2}(1-\theta)r^2(t)\right\}\mathrm{d}t \\ \max_s \pi_{\mathrm{H}}^{\mathrm{DS}}(r;s) &= \int_0^{+\infty} e^{-\rho t}\left\{(p+\eta w)Q(t) - \tfrac{1}{2}s^2(t)\right\}\mathrm{d}t \end{aligned} \tag{8}$$

4. Model Analysis

Based on the problem description and decision assumptions in the previous section, we first discuss NS in the benchmark model in this section. Secondly, we explored MS, HS, and DS and obtained the optimal steady-state strategies and profits for manufacturers and healthcare institutions under four different subsidy models. In addition, we also analyze the social welfare under each model.

4.1. No Government Subsidy Model (NS)

In the benchmark model without government subsidies, the pharmaceutical enterprise and medical institution play a Stackelberg differential game with the business goal of maximizing their own profits. The pharmaceutical enterprise first determines the editorial profit of the drug w. In order to expand the market demand, the pharmaceutical enterprise needs to determine his low-carbon input $r(t)$. The medical institution will centrally purchase the drug for sale and determine the marginal profit p. In order to expand the patient market demand, the medical institution needs to conduct marketing activities and determine its marketing effort $s(t)$. The goal of the pharmaceutical enterprise and the medical institution is to maximize their respective profits by providing the product, and when there is no government subsidy, the optimization problem is as follows:

$$\begin{aligned} &\max_r \pi_{\mathrm{M}}^{\mathrm{NS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \tfrac{1}{2}r^2(t)\right\}\mathrm{d}t \\ &\max_s \pi_{\mathrm{H}}^{\mathrm{NS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{pQ(t) - \tfrac{1}{2}s^2(t)\right\}\mathrm{d}t \\ &\text{st. } \dot{G}^{\mathrm{NS}}(t) = \mu r(t) - kG(t), G(0) = G_0 \end{aligned} \tag{9}$$

Proposition 1. *In the benchmark model, the optimal time trajectory of low-carbon goodwill under the no government subsidy model is* $G^{\mathrm{NS}}(t) = G_0^{\mathrm{NS}}e^{-kt} + \left(1-e^{-kt}\right)\frac{\mu w}{k}\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$*, and the corresponding optimal steady-state strategy and optimal steady-state profit are*

$$\begin{aligned} r^{\mathrm{NS}} &= w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) \\ s^{\mathrm{NS}} &= p\beta \end{aligned} \tag{10}$$

$$\begin{aligned} V_{\mathrm{M}}^{\mathrm{NS}}(t) &= \tfrac{\lambda w}{\rho+k}G(t) + \tfrac{w}{\rho}\left[a - bw + \beta^2 p + \tfrac{w}{2}\left(\tfrac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \\ V_{\mathrm{H}}^{\mathrm{NS}}(t) &= \tfrac{\lambda p}{\rho+k}G(t) + \tfrac{p}{\rho}\left[a - bw + \tfrac{\beta^2 p}{2} + w\left(\tfrac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \end{aligned} \tag{11}$$

Proof. See Appendix A. □

Proposition 1 states that all optimal strategies are constant over time. We can more intuitively see that these decision variables are relatively static. From a management perspective, it is easier to execute fixed input decisions and marketing decisions. The

stronger the consumer's low-carbon preference (i.e., the larger λ), the greater the input of pharmaceutical enterprises to develop and produce more low-carbon drugs to expand their market share. Medical institutions cannot profit from the sale of low-carbon drugs due to the zero-rate policy, and consumer low-carbon preferences do not change their marketing strategies. In addition, the decay rate and discount factor have a negative impact on pharmaceutical enterprises input decisions.

The calculation method of social welfare SW^{NS} in the no government subsidy model is shown in Appendix A.

$$SW^{\mathrm{NS}} = \left\langle \begin{array}{l} \frac{\lambda(w+p)}{\rho+k}G(t) + \frac{1}{2}\left[a - bw + \delta w\left(\delta + \frac{\mu\lambda}{\rho+k}\right) + \beta^2 p + \lambda G(t)\right]^2 \\ +\frac{1}{\rho}\left[(a-bw)(w+p) + \beta^2 p\left(w + \frac{p}{2}\right) + w\left(\frac{w}{2}+p\right)\left(\frac{\mu\lambda}{\rho+k}+\delta\right)^2\right] \end{array} \right\rangle \tag{12}$$

4.2. Pharmaceutical Enterprise Subsidy Model (MS)

In the pharmaceutical enterprise subsidy model, the government provides proportion of low-carbon input subsidies for pharmaceutical enterprise; the government provides low-carbon subsidies in order to solve the problem of insufficient input in emission reduction activities of pharmaceutical enterprise in the pharmaceutical supply chain and to better achieve the goal of energy saving and emission reduction by incentivizing pharmaceutical enterprise to produce low-carbon drugs and also to improve the sustainability of pharmaceutical enterprise; the optimization problem is as follows:

$$\begin{array}{l} \max\limits_{r} \pi_{\mathrm{M}}^{\mathrm{MS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \frac{1}{2}(1-\theta)r^2(t)\right\}\mathrm{d}t \\ \max\limits_{s} \pi_{\mathrm{H}}^{\mathrm{MS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{pQ(t) - \frac{1}{2}s^2(t)\right\}\mathrm{d}t \\ \text{st. } \dot{G}^{\mathrm{MS}}(t) = \mu r(t) - kG(t), G(0) = G_0 \end{array} \tag{13}$$

Proposition 2. *The optimal time evolution trajectory of low-carbon goodwill under the pharmaceutical enterprise subsidy model is* $G^{\mathrm{MS}}(t) = G_0^{\mathrm{MS}}e^{-kt} + \left(1 - e^{-kt}\right)\frac{\mu w}{k(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$*, and the corresponding optimal steady-state strategy and optimal steady-state profit are*

$$\begin{array}{c} r^{\mathrm{MS}} = \frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) \\ s^{\mathrm{SS}} = \beta p \end{array} \tag{14}$$

$$\begin{array}{l} V_{\mathrm{M}}^{\mathrm{MS}} = \frac{\lambda w}{\rho+k}G(t) + \frac{w}{\rho}\left[a - bw + \beta^2 p + \frac{w}{2(1-\theta)}\left(\frac{\lambda\mu}{\rho+k}+\delta\right)^2\right] \\ V_{\mathrm{H}}^{\mathrm{MS}} = \frac{\lambda p}{\rho+k}G(t) + \frac{p}{\rho}\left[a - bw + \frac{\beta^2 p}{2} + \frac{w}{(1-\theta)}\left(\frac{\lambda\mu}{\rho+k}+\delta\right)^2\right] \end{array} \tag{15}$$

Proof. See Appendix A. □

Proposition 2 shows that a government subsidy increases the level of low-carbon inputs of pharmaceutical enterprises and further influences the low-carbon goodwill of drugs. Influenced by consumers low-carbon preferences, the market demand for drugs expands, and the service demand for corresponding drugs of medical institutions also increases, so medical institutions can achieve more service profits. Affected by cost factors, the marketing decisions of medical institutions do not change accordingly.

The calculation method of social welfare SW^{MS} in the pharmaceutical enterprise subsidy model is shown in Appendix A.

$$SW^{\mathrm{MS}} = \left\langle \begin{array}{l} \frac{\lambda(w+p)}{\rho+k}G(t) + \frac{1}{2}\left[a - bw + \frac{\delta w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) + \beta^2 p + \lambda G(t)\right]^2 \\ +\frac{1}{\rho}\left[(a-bw)(w+p) + \beta^2 p\left(w + \frac{p}{2}\right) + \frac{w}{(1-\theta)}\left(\frac{w}{2} + s - \frac{\theta\rho w}{2(1-\theta)}\right)\left(\delta + \frac{\lambda\mu}{(\rho+k)}\right)^2\right] \end{array} \right\rangle \tag{16}$$

4.3. Medical Institution Subsidy Model (HS)

In the subsidy model for medical institution, the government provides η proportion of the centralized procurement price subsidy to a medical institution using low-carbon drugs in order to promote the low-carbon transformation and upgrading of the medical institution and to better achieve the goal of energy saving and emission reduction by stimulating the reform of drug distribution in medical institution; the optimization problem is as follows:

$$\begin{aligned} &\max_r \pi_{\mathrm{M}}^{\mathrm{HS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \tfrac{1}{2}r^2(t)\right\}\mathrm{d}t \\ &\max_s \pi_{\mathrm{H}}^{\mathrm{HS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{(p+\eta w)Q(t) - \tfrac{1}{2}s^2(t)\right\}\mathrm{d}t \\ &\text{st. } \dot{G}^{\mathrm{HS}}(t) = \mu r(t) - kG(t), G(0) = G_0 \end{aligned} \tag{17}$$

Proposition 3. *The optimal time evolution trajectory of low-carbon goodwill under the medical institution subsidy model is* $G^{\mathrm{HS}}(t) = G_0^{\mathrm{HS}}e^{-kt} + (1-e^{-kt})\frac{\mu w}{k}\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$*, and the corresponding optimal steady-state strategy and optimal steady-state profit are*

$$\begin{aligned} r^{\mathrm{HS}} &= w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) \\ s^{\mathrm{HS}} &= \beta(p+\eta w) \end{aligned} \tag{18}$$

$$\begin{aligned} V_{\mathrm{M}}^{\mathrm{HS}}(t) &= \tfrac{w\lambda}{\rho+k}G(t) + \tfrac{w}{\rho}\left[a - bw + \beta^2\eta w + \beta^2(p+\eta w) + \tfrac{w}{2}\left(\tfrac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \\ V_{\mathrm{H}}^{\mathrm{HS}} &= \tfrac{\lambda(p+\eta w)}{\rho+k}G(t) + \tfrac{(p+\eta w)}{\rho}\left[a - bw + \tfrac{1}{2}\beta^2(p+\eta w) + w\left(\delta + \tfrac{\lambda\mu}{(\rho+k)}\right)^2\right] \end{aligned} \tag{19}$$

Proof. See Appendix A. □

In Proposition 3, the government provides a revenue incentive mechanism to medical institutions for promoting the use of low-carbon drugs. In order to obtain more state subsidies, medical institutions will adopt certain marketing strategies to attract patients buying low-carbon drugs, to ensure sufficient income subsidies in drug sales. In addition, the marketing behavior of medical institutions leads to the increase of market demand for low-carbon drugs, and pharmaceutical enterprises can also achieve more sales profits. However, without government subsidy support, pharmaceutical enterprises will not blindly change their low-carbon input decisions considering the costs and risks, and the low-carbon goodwill of the drugs themselves will not change; pharmaceutical enterprises are willing to accept this situation. The calculation method of social welfare SW^{HS} in the medical institution subsidy model is shown in Appendix A.

$$SW^{\mathrm{HS}} = \left\langle \begin{array}{l} \left[\frac{(w+p+\eta w)\lambda}{\rho+k} - \eta w\lambda\right]G(t) + \frac{1}{2}\left[a - bw + \delta w\left(\delta + \frac{\mu\lambda}{\rho+k}\right) + \beta^2(p+\eta w) + \lambda G(t)\right]^2 \\ +\frac{1}{\rho}\left\{\begin{array}{l} (a-bw)[w+p+(1-\rho)\eta w] + \beta^2(p+\eta w)\left[(1-\rho\eta)w + \frac{p+\eta w}{2}\right] \\ +w\left(\delta + \frac{\mu\lambda}{\rho+k}\right)\left[\left(\frac{w}{2} + p + \eta w\right)\left(\delta + \frac{\lambda\mu}{(\rho+k)}\right) - \rho\eta w\delta\right] \end{array}\right\} \end{array} \right\rangle \tag{20}$$

4.4. Government Dual Subsidy Model (DS)

In the government dual subsidy model, the government provides subsidies to both pharmaceutical enterprises and medical institutions to accelerate the transformation of the low-carbon structure of the pharmaceutical supply chain and help achieve the carbon peak and carbon neutrality goals. The optimization problem is as follows:

$$\begin{aligned} &\max_r \pi_{\mathrm{M}}^{\mathrm{DS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{wQ(t) - \tfrac{1}{2}(1-\theta)r^2(t)\right\}\mathrm{d}t \\ &\max_s \pi_{\mathrm{H}}^{\mathrm{DS}}(r;s) = \int_0^{+\infty} e^{-\rho t}\left\{(p+\eta w)Q(t) - \tfrac{1}{2}s^2(t)\right\}\mathrm{d}t \\ &\text{st. } \dot{G}^{\mathrm{DS}}(t) = \mu r(t) - kG(t), G(0) = G_0 \end{aligned} \tag{21}$$

Proposition 4. *The optimal time evolution trajectory of low-carbon goodwill under the government dual subsidy model is* $G^{DS}(t) = G_0^{DS}e^{-kt} + \left(1 - e^{-kt}\right)\frac{\mu w}{k(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$*, and the corresponding optimal steady-state strategy and optimal steady-state profit are*

$$\begin{aligned} r^{DS} &= \tfrac{w}{(1-\theta)}\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) \\ s^{DS} &= (p+\eta w)\beta \end{aligned} \tag{22}$$

$$\begin{aligned} V_M^{DS} &= \tfrac{\lambda w}{\rho+k}G(t) + \tfrac{w}{\rho}\left[a - bw + \beta^2(p+\eta w) + \tfrac{w}{2(1-\theta)}\left(\tfrac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \\ V_H^{DS} &= \tfrac{\lambda(p+\eta w)}{\rho+k}G(t) + \tfrac{(p+\eta w)}{\rho}\left[a - bw + \tfrac{\beta^2}{2}(p+\eta w) + \tfrac{w}{(1-\theta)}\left(\delta + \tfrac{\lambda\mu}{(\rho+k)}\right)^2\right] \end{aligned} \tag{23}$$

Proof. See Appendix A. □

In Proposition 4, both pharmaceutical companies and medical institutions hope to gain more profits from government subsidies. In this case, influenced by the policy of centralized drug procurement, although the market demand for low-carbon drugs increases significantly, the two sides have different mechanisms of influence on the market. Subsidies and decisions at one end of the supply chain will not affect decisions at the other end, which also ensures that the price of drug collection will not change significantly due to changes in market demand and decisions at one side, which is one of the purposes of the centralized procurement policy implementation.

The calculation method of social welfare SW^{DS} in the medical institution subsidy model is shown in Appendix A.

$$SW^{DS} = \left\langle \begin{array}{l} \left[\frac{(w+p+\eta w)\lambda}{\rho+k} - \eta w\lambda\right]G(t) + \frac{1}{2}\left[a - bw + \frac{\delta w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) + \beta^2(p+\eta w) + \lambda G(t)\right]^2 \\ +\frac{1}{\rho}\left\{ \begin{array}{l} (a-bw)[w+p+(1-\rho)\eta w] + \beta^2(p+\eta w)\left[w - \rho\eta w + \frac{p+\eta w}{2}\right] \\ +\frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right)\left[\left(\frac{w}{2} + p + \eta w - \frac{\theta\rho w}{2(1-\theta)}\right)\left(\delta + \frac{\lambda\mu}{(\rho+k)}\right) - \rho\eta w\delta\right] \end{array} \right\} \end{array} \right\rangle \tag{24}$$

5. Analysis of Model Results

In this section, we first perform a sensitivity analysis of the relevant parameters and then compare the optimal decisions of pharmaceutical enterprise and medical institution under four subsidy models. Finally, the social welfare under different subsidy models is analyzed. The results of the study show that government subsidies increase the profit (economic) and social welfare (social) of pharmaceutical supply chain members.

Inference 1. $\frac{\partial r^{MS}}{\partial\theta}, \frac{\partial G^{MS}}{\partial\theta}, \frac{\partial V_M^{MS}}{\partial\theta}, \frac{\partial V_H^{MS}}{\partial\theta}$.

When subsidizing pharmaceutical enterprise, low-carbon input r, low-carbon goodwill G, and profit V are positively correlated with the subsidy ratio θ. When pharmaceutical enterprise received low-carbon subsidies from the government, it is equivalent to reducing the cost and risk of low-carbon transformation of the pharmaceutical enterprise, which can effectively promote the pharmaceutical enterprise to improve low-carbon input and accelerate industrial upgrading and improve the profit of pharmaceutical enterprise and medical institution. This indicates that the implementation of this subsidy policy can promote the sustainable development of the pharmaceutical supply chain, while helping to reduce the level of carbon emissions in the pharmaceutical market and provide more low-carbon drugs to patients.

Inference 2. $\frac{\partial s^{HS}}{\partial\eta}, \frac{\partial G^{HS}}{\partial\eta}, \frac{\partial V^{HS}}{\partial\eta}, \frac{\partial V^{HS}}{\partial\eta}$.

When subsidizing medical institution, marketing efforts s and profits V are positively correlated with the subsidy ratio η, and when the government grants revenue subsidies to medical institution, medical institution increase her low-carbon marketing efforts to

attract more patients to use low-carbon drugs. This indicates that the implementation of this subsidy policy can reduce the operational burden of medical institution to a certain extent, respond positively to the achievement of carbon peak and carbon neutral goals, and effectively reduce the level of carbon emissions from medical services and patient access to medical care.

Inference 3. $\frac{\partial V_i^{\mathrm{NS}}}{\partial b} < 0, \frac{\partial V_i^{\mathrm{MS}}}{\partial b} < 0, \frac{\partial V_i^{\mathrm{HS}}}{\partial b} < 0, \frac{\partial V_i^{\mathrm{DS}}}{\partial b} < 0, i = \mathrm{M}, \mathrm{H}.$

Inference 3 shows that under all four subsidy models V_{M} and V_{H} are negatively related to the patient's out-of-pocket ratio b. As the patient's out-of-pocket ratio for drug purchases increases, the profits of pharmaceutical enterprise and medical institution are reduced overall, and due to the influence of health insurance reimbursement ratio and their own income, patients will be more inclined to choose drugs with lower out-of-pocket ratios to reduce the burden of medical care when purchasing drugs; higher deductibles lead to a lower willingness to purchase drugs, which affects the profitability of the entire pharmaceutical supply chain. Thus, the development and implementation of medical insurance reimbursement policies are necessary to reduce the burden of patients and improve their satisfaction with medical care and to increase patients' willingness to purchase drugs and improve the overall profit of the supply chain and promote economic and social development.

Inference 4. *The relationship between the magnitude of low-carbon inputs of pharmaceutical enterprise, marketing efforts of medical institution, and low-carbon goodwill at steady state for each of the four subsidy models are*

$$r^{\mathrm{DS}} = r^{\mathrm{MS}} > r^{\mathrm{HS}} = r^{\mathrm{NS}}; s^{\mathrm{DS}} = s^{\mathrm{HS}} > s^{\mathrm{MS}} = s^{\mathrm{NS}}; G^{\mathrm{DS}} = G^{\mathrm{MS}} > G^{\mathrm{HS}} = G^{\mathrm{NS}}$$

Inference 4 shows that the low-carbon inputs of pharmaceutical enterprise and the low-carbon goodwill of drugs have no effect when the government subsidizes medical institution and increase when the government subsidizes pharmaceutical enterprise, thus showing that government subsidies to pharmaceutical enterprise are more beneficial to the low-carbon goodwill of drugs than subsidies to medical institution. This is because government subsidies to enterprise act on the production of drugs and can ensure the low-carbon goodwill, while subsidies to the medical institution are providing incentives to them, which essentially expands the distribution of drugs and does not affect the low-carbon goodwill.

Inference 5. *The relationship between the profits of pharmaceutical enterprise, medical institution, and the size of social welfare at steady state for each of the four subsidy models are*

$$V_{\mathrm{M}}^{\mathrm{DS}} > V_{\mathrm{M}}^{\mathrm{MS}} > V_{\mathrm{M}}^{\mathrm{HS}} > V_{\mathrm{M}}^{\mathrm{NS}}; V_{\mathrm{H}}^{\mathrm{DS}} > V_{\mathrm{H}}^{\mathrm{HS}} > V_{\mathrm{H}}^{\mathrm{MS}} > V_{\mathrm{H}}^{\mathrm{NS}}; SW^{\mathrm{DS}} > SW^{\mathrm{HS}} > SW^{\mathrm{MS}} > SW^{\mathrm{NS}}$$

Inference 5 shows that the supply chain system under the government dual subsidy model is always the most profitable and has the highest social welfare at this time, and the supply chain system under the no government subsidy model is always the least profitable and has the lowest social welfare. When the government subsidizes pharmaceutical enterprises, the impact of subsidies on low-carbon goodwill is greater than the impact on market demand. Therefore, pharmaceutical enterprises' profits under the low-carbon input subsidy strategy are higher than those under the revenue subsidy strategy, while the opposite is true for a medical institution, but social welfare is always higher when the government subsidizes a medical institution than when it subsidizes a pharmaceutical enterprise. The government's subsidy policy is an important part of guiding pharmaceutical enterprises and medical institutions to reduce carbon emissions, which can promote the transformation of the carbon emission structure of the pharmaceutical supply chain, not only pulling the demand of low-carbon medical market and promoting the development of green economy but also helping to improve patients' satisfaction of medical treatment and social welfare.

6. Numerical Analysis

In this section, we perform numerical analysis to gain more management insights by examining the following questions.

(1) The effect of change in health insurance reimbursement rates and consumer preferences on supply chain members' profits;
(2) The effect of change in the subsidy ratio of pharmaceutical enterprise and the subsidy ratio of medical institution on the profits of supply chain members;
(3) The effect of change in the subsidy rate of pharmaceutical enterprise and the subsidy rate of medical institution on social welfare.

In this section, refer to the assumptions of MA et al. [55]; based on the real context, the basic parameters are set as follows:

$$w = 2; p = 1; a = 1; b = 0.4; \mu = 0.6; k = 0.1; \rho = 0.1;$$
$$\delta = 0.6; \beta = 0.6; \lambda = 0.6; \theta = 0.2; \eta = 0.15; U_0 = 0.1$$

6.1. Low-Carbon Goodwill, Member Decision, and Profit Time Trajectory Chart

Figures 1–3 clearly show that low-carbon goodwill is the same and higher in the MS and DS models than in the other models and that low-carbon goodwill is not affected by marketing efforts. Low-carbon inputs are the same and higher in the MS and DS models than in the NS and HS models, and subsidies to medical institution do not affect the optimal decisions of pharmaceutical enterprise. The marketing efforts under the HS and DS models are the same and higher than the other models, and subsidies for pharmaceutical enterprises do not influence the optimal decision of a medical institution. The profit of a pharmaceutical enterprise and a medical institution is the largest in the DS model; the profit of a pharmaceutical enterprise is higher in the MS model than in the HS model; the profit of a medical institution is higher in the HS model than in the MS model, and the profit of both is the lowest in the NS model. The state variables in the four models are influenced by the equilibrium membership strategy and tend to be stable over time, thus verifying the global asymptotically stable nature of the state variables.

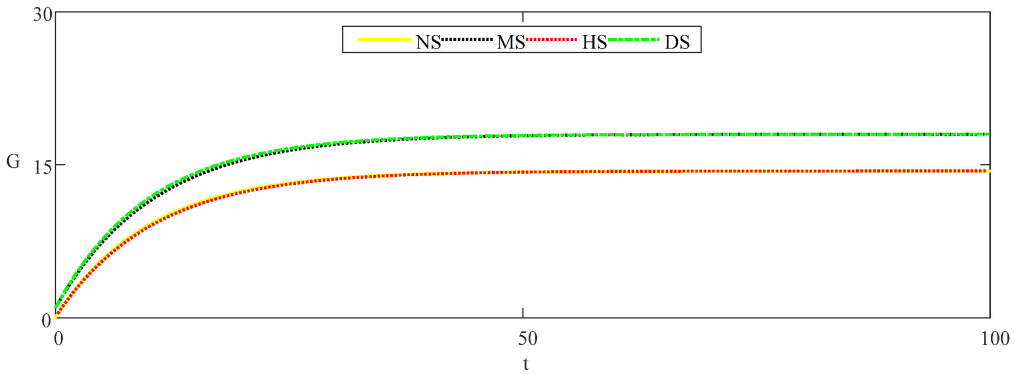


Figure 1. Time trajectory of low-carbon goodwill under four subsidy models.

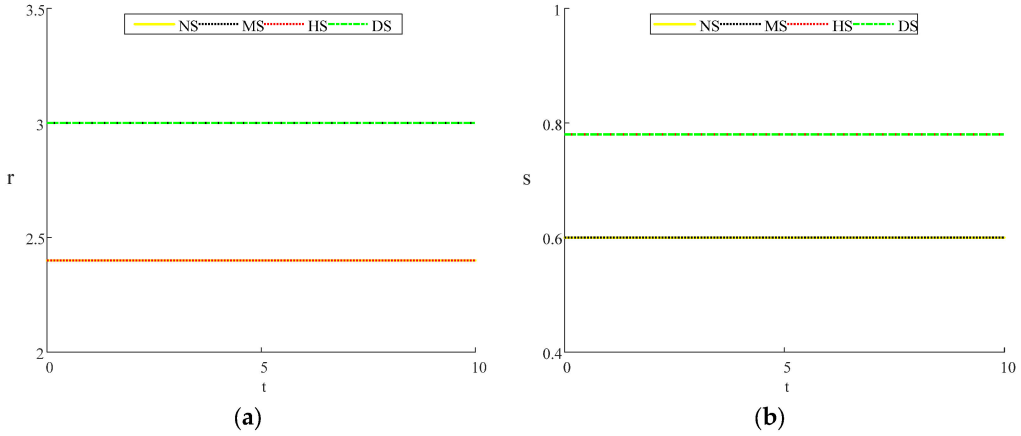


Figure 2. Time trajectory of optimal decision making of a pharmaceutical enterprise and medical institution under four subsidy models ((**a**) pharmaceutical enterprise decisions; (**b**) medical institution decisions).

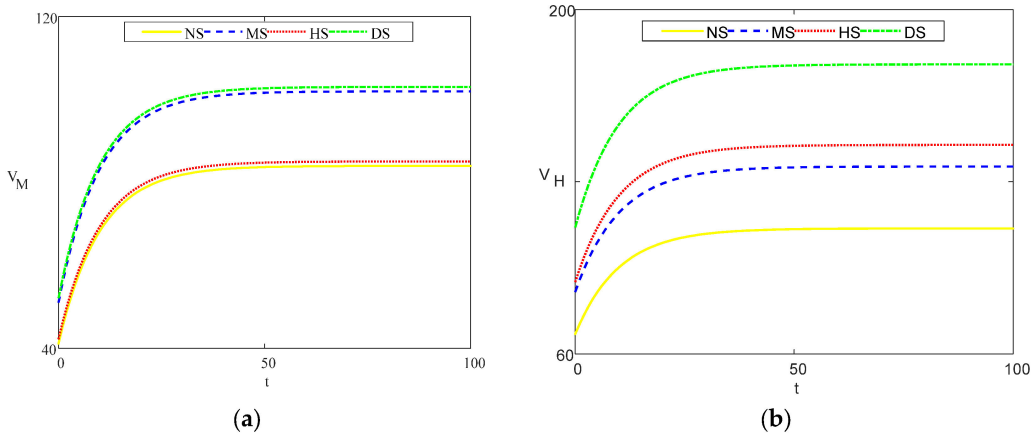
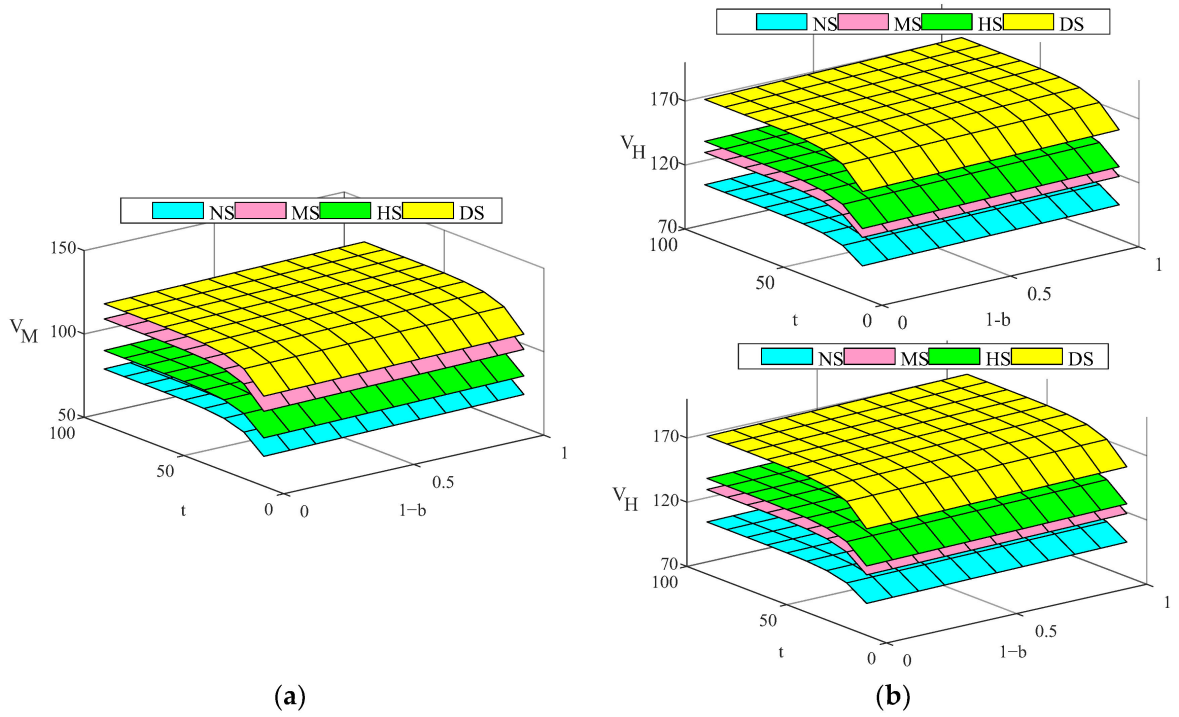


Figure 3. Time trajectory of profits of pharmaceutical enterprise and medical institution under four subsidy models ((**a**) pharmaceutical enterprise profits; (**b**) medical institution profits).

6.2. Impact of Health Insurance Reimbursement Rates on Supply Chain Members' Profits

Figure 4 gives the effect of the steady state of supply chain members' profits regarding the health insurance reimbursement rate $1 - b$. The profits of both the pharmaceutical enterprise and medical institution increase with the increase in the reimbursement rate of health insurance under all four subsidy models. This indicates that drugs entering the national health insurance catalog are more popular among patients due to their quality and price advantages. At the same time, the higher the reimbursement rate of medical insurance, the lower the proportion of personal payment, and the more market demand for drugs, thus increasing the profits of a pharmaceutical enterprise and a medical institution. From a long-term perspective, a pharmaceutical enterprise should increase low-carbon investment, improve the low-carbon goodwill of drugs, and try its best to enter the national medical insurance catalog through medical insurance negotiations to seize market share and gain more profits. Meanwhile, a medical institution should further implement the national health insurance policy and use the market demand for health insurance drugs and state subsidies to further expand its benefits.

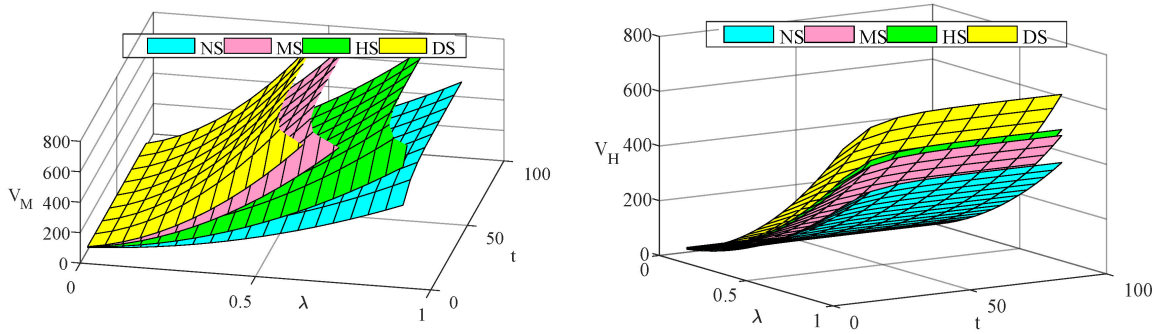


(**a**) (**b**)

Figure 4. Impact of health insurance reimbursement rates on supply chain members' profits under four subsidy models ((**a**) pharmaceutical enterprise profits; (**b**) medical institution profits).

6.3. Impact of Consumer Preferences on the Profitability of Supply Chain Members

Figure 5 shows that as consumers low-carbon preferences increase, the profits of pharmaceutical enterprise and medical institution also increase. The impact of consumers' low-carbon preferences on the profits of pharmaceutical enterprise is greater than that of medical institution; consumers pay more attention to the low-carbon quality of the drugs themselves rather than the marketing of the drugs when purchasing them. Therefore, a medical institution will take the initiative to purchase drugs with higher low-carbon goodwill in order to gain more profits, and a pharmaceutical enterprise will also increase their low-carbon investment in drugs to improve its goodwill due to profit demand and further promote the improvement of consumers' low-carbon preference, thus forming a long-term development of carbon emission reduction in the pharmaceutical supply chain.



(**a**) (**b**)

Figure 5. Impact of consumer preferences on supply chain members' profits ((**a**) pharmaceutical enterprise profits; (**b**) medical institution profits).

6.4. Impact of Government Subsidy Ratio on Supply Chain Members' Profits

Figures 6 and 7 show that as the ratio of subsidies for pharmaceutical enterprise and the ratio of subsidies for medical institution increase, the profits of each member of the

supply chain also rise, and the impact of subsidies for pharmaceutical enterprise on the profits of supply chain members is greater than that of subsidies for medical institution.

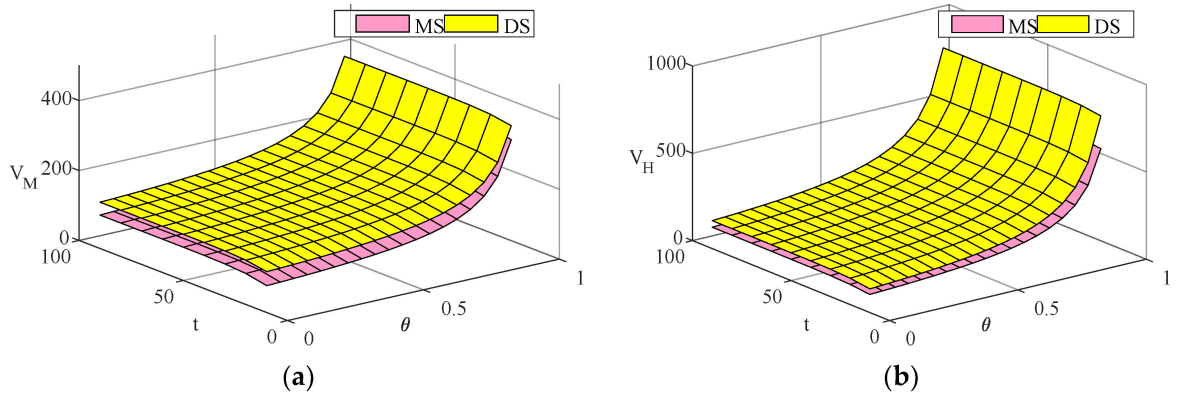


Figure 6. Impact of pharmaceutical enterprise subsidies on supply chain members' profits ((**a**) pharmaceutical enterprise profits; (**b**) medical institution profits).

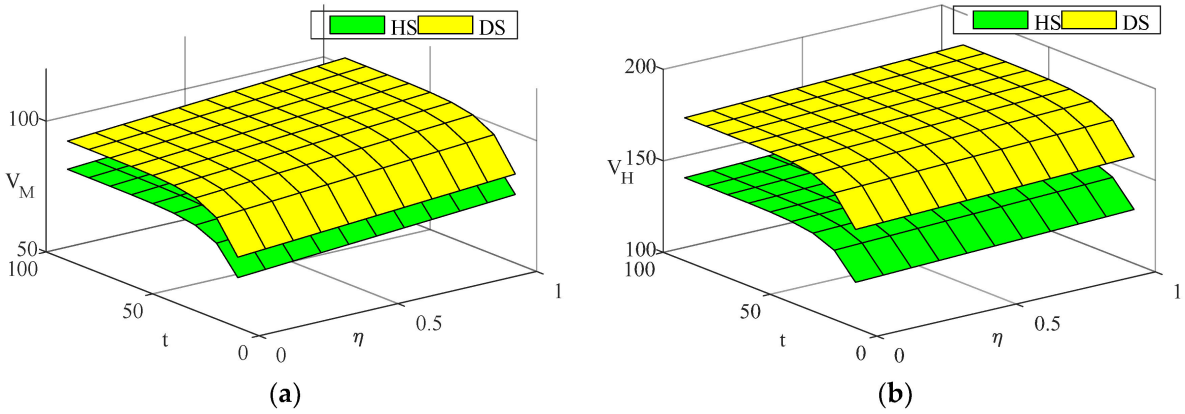


Figure 7. Impact of subsidies for a medical institution on supply chain members' profits ((**a**) pharmaceutical enterprise profits; (**b**) medical institution profits).

Therefore, the government should consider the impact of different subsidy ratios on the profits of supply chain members when formulating subsidy policies and strive to obtain the highest benefits at the lowest subsidy cost, which can reduce the government's financial expenditure and also promote the low-carbon investment of a pharmaceutical enterprise and the marketing efforts of a medical institution and promote the low-carbon and green development of the social medical system and pharmaceutical market to better serve society.

6.5. Impact of Government Subsidies on Social Welfare

Figure 8 shows that pharmaceutical enterprise subsidies and medical institution subsidies positively influence the trend of social welfare, and the single institution subsidy policy can improve social welfare to some extent, but its impact is much lower compared to the government's dual subsidy policy. With the increasing ratio of pharmaceutical enterprise subsidies and medical institution subsidies, the social welfare brought about by the government's dual subsidy model is much more than the effect of a single subsidy. Based on this, the government should consider the supply chain dual subsidy model based on reasonable expenditure and determine the optimal subsidy ratio to maximize social welfare.

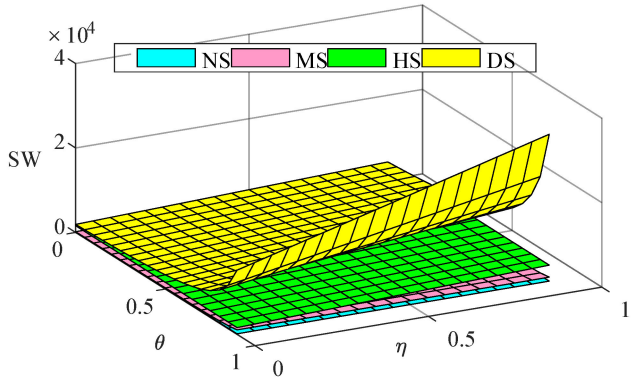


Figure 8. Impact of changes in the proportion of pharmaceutical enterprise subsidies and medical institution subsidies on social welfare.

7. Conclusions

Different macro-regulatory approaches of the government will have different policy effects. In this paper, we construct a two-level pharmaceutical supply chain with pharmaceutical enterprises in a dominant position in the context of centralized drug procurement policy and compare and analyze the low-carbon feedback equilibrium strategies of no government subsidy, a pharmaceutical enterprise subsidy, a medical institution subsidy and government dual subsidy decisions to explore the impact of government subsidies on pharmaceutical low-carbon goodwill, supply chain profits, and social welfare. The main conclusions drawn are the following.

Government subsidy behavior has a significant impact on pharmaceutical enterprises' low-carbon inputs and medical institution marketing efforts. The higher the patients' low-carbon preference, the more motivated pharmaceutical enterprises' technological innovation and low-carbon investment, and government subsidies can reduce the cost and risk of low-carbon transition for enterprises. Meanwhile, in order to accelerate the transformation of the energy structure of the pharmaceutical industry, government subsidies increase the revenue of medical institutions, which makes them accelerate the transformation and encourages medical institutions to achieve their carbon reduction goals.

Government subsidies are more effective in improving the profitability and sustainability of enterprises in supply chain nodes. Government subsidies can significantly increase the profitability of pharmaceutical enterprises, and providing subsidies to first movers in the low-carbon transition is a key part of guiding enterprises to strengthen their low-carbon investment, which is essential to promote the development of low-carbon drugs. In addition, government subsidies promote the implementation of the "zero-rate" policy and the achievement of emission reduction targets under the centralization policy of medical institutions, which increases the market demand for low-carbon drugs and thus generates more profits.

Compared with the single subsidy model, government social welfare is better in the dual subsidy model. The government should give priority to the dual subsidy model under a reasonable fiscal budget target and set a reasonable subsidy ratio for both pharmaceutical enterprises and medical institutions, which can accelerate the pace of low-carbon transformation of the pharmaceutical supply chain and better achieve a high level of development of the pharmaceutical supply chain and social welfare.

The management insights derived from this paper are as follows.

For pharmaceutical enterprises, achieving carbon emission reduction in drug production is an important part of their low-carbon transformation. First, pharmaceutical enterprises need to achieve carbon reduction from raw materials; pharmaceutical enterprises can share information with their supply chain partners (raw material providers, logistics service providers) to improve the supply chain capacity effect. Second, in terms of production technology, pharmaceutical enterprises should strengthen horizontal cooperation with research institutes and universities for pharmaceutical talent and technology sharing. The

input cost of low-carbon technology can be reduced through industry–university–research integration, which can realize the rapid breakthrough of carbon reduction technology in the pharmaceutical industry. Third, pharmaceutical enterprises need to reasonably set carbon emission reduction targets and programs, take advantage of government subsidies to accelerate the development of industrial scale, improve the low-carbon goodwill of drugs, and try their best to enter the national health insurance catalog through health insurance negotiations to quickly seize market share and gain more profits. Finally, pharmaceutical enterprises should have the responsibility to cultivate the low-carbon consumption concept of the public and improve consumers low-carbon preference, which is also beneficial to the marketing of their products.

For medical institutions, reducing carbon emissions in drug distribution is a key step in achieving their emission reduction goals. First, medical institutions need to develop sustainable procurement policies and methods and use procurement decision-making power to require their procurement supply chain to make carbon emission reduction activities. Second, medical institutions should reasonably procure low-carbon drugs according to the health insurance catalog and use this to obtain low-carbon subsidies from the government to help their own low-carbon transformation. Third, the recycling of medical waste is also a key issue for carbon emission reduction in the pharmaceutical industry. Medical institutions can cooperate with third-party recycling companies; medical institutions can achieve high-efficiency waste recycling by paying part of the abatement costs of the abatement materials, and when recycling companies and medical institutions jointly carry out low-carbon transformation, they can increase the speed of transformation with the hitchhiking effect. Finally, medical institutions should also play the advantage of public institutions to guide the public to green and healthy living, gradually cultivate patients' awareness of low-carbon medical care, and incorporate both medical insurance reimbursement rates and patients low-carbon preferences into the selection criteria of medical products.

For government, the stimulating effect of adopting different subsidy policies varies greatly. The government should actively promote the collection and collation of carbon reduction costs and profits of supply chain members and provide appropriate subsidies to specific supply chain members. When the government aims to improve the low-carbon goodwill of drugs, reduce prices, and encourage pharmaceutical enterprises to increase low-carbon investment, the government should give more low-carbon subsidies to pharmaceutical enterprises. If the government focuses more on improving the low-carbon level of medical institutions, improving patient satisfaction with medical care, and promoting the low-carbon transformation and upgrading of medical institutions, the government can give more revenue subsidies to medical institutions. If the government's goal is to achieve a high level of development of the healthcare supply chain and social welfare with the highest subsidy efficiency, it should give preference to the dual subsidy model. Government plays a crucial role in low-carbon development, and it guides the direction of low carbon development for the whole society. Under the condition of sufficient financial resources, we hope that the government can promote the low-carbon transformation and development of the pharmaceutical supply chain through the double subsidy model to achieve better economic, social, and environmental development.

In the future, we can consider increasing the competitive relationship between supply chain members and expanding the complex supply chain network system, which is the next research direction.

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Appendix A

Proof of Proposition 1. We use inverse induction to solve this strategy, and, according to the theory of continuum dynamics, the continuously differentiable value function $V_{\mathrm{H}}^{\mathrm{NS}}$ satisfies the Hamilton–Jacobi–Bellman (HJB) equation as:

$$\rho V_{\mathrm{H}}^{\mathrm{NS}} = p(a - bw + \delta r + \beta s + \lambda G) - \frac{1}{2}s^2 + \frac{\partial V_{\mathrm{H}}^{\mathrm{NS}}}{\partial G^{\mathrm{NS}}}(\mu r - kG) \tag{A1}$$

where $\frac{\partial V_{\mathrm{H}}^{\mathrm{NS}}}{\partial G^{\mathrm{NS}}}$ is the first-order partial derivative of the medical institution optimal value function with respect to low-carbon goodwill G^{NS}. By the first-order optimality condition, the marketing effort $s(t)$ is obtained as $s^{\mathrm{NS}} = p\beta$. Substituting it into the pharmaceutical enterprise's objective generalized function, we obtain the Hamilton–Jacobi–Bellman (HJB) equation that the pharmaceutical enterprise should satisfy.

$$\rho V_{\mathrm{M}}^{\mathrm{NS}} = w\Big(a - bw + \delta r + \beta^2 p + \lambda G\Big) - \frac{1}{2}r^2 + \frac{\partial V_{\mathrm{M}}^{\mathrm{NS}}}{\partial G^{\mathrm{NS}}}(\mu r - kG) \tag{A2}$$

where $\frac{\partial V_{\mathrm{M}}^{\mathrm{NS}}}{\partial G^{\mathrm{NS}}}$ is the first-order partial derivative of the pharmaceutical enterprise optimal value function with respect to low-carbon goodwill G^{NS}. According to the first-order optimality condition, the low-carbon input $r(t)$ is obtained as $r^{\mathrm{NS}} = w\Big(\delta + \frac{\mu\lambda}{\rho+k}\Big)$. Bringing $s^{\mathrm{NS}} = p\beta$, $r^{\mathrm{NS}} = w\Big(\delta + \frac{\mu\lambda}{\rho+k}\Big)$ into the HJB equation for the pharmaceutical enterprise and the medical institution yields:

$$\begin{aligned}
\rho V_{\mathrm{M}}^{\mathrm{NS}} &= w\Big[a - bw + \delta w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2 p + \lambda G\Big] - \tfrac{1}{2}w^2\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big)^2 + \tfrac{\partial V_{\mathrm{M}}^{\mathrm{NS}}}{\partial G^{\mathrm{NS}}}\Big[\mu w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big] \\
\rho V_{\mathrm{H}}^{\mathrm{NS}} &= p\Big[a - bw + \delta w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2 p + \lambda G\Big] - \tfrac{1}{2}\beta^2 p^2 + \tfrac{\partial V_{\mathrm{H}}^{\mathrm{NS}}}{\partial G^{\mathrm{NS}}}\Big[\mu w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big]
\end{aligned} \tag{A3}$$

The optimal value function of pharmaceutical enterprise and medical institution is assumed to be

$$V_{\mathrm{M}}^{\mathrm{NS}} = f_1^{\mathrm{NS}} G^{\mathrm{NS}} + f_2^{\mathrm{NS}}, \;\; V_{\mathrm{H}}^{\mathrm{NS}} = g_1^{\mathrm{NS}} G^{\mathrm{NS}} + g_2^{\mathrm{NS}}$$

where $f_1^{\mathrm{NS}}, f_2^{\mathrm{NS}}$ and $g_1^{\mathrm{NS}}, g_2^{\mathrm{NS}}$ are the corresponding constant coefficients to be determined, respectively, which are substituted into (A3) to obtain the set of equations to be determined as

$$\begin{aligned}
\rho\big(f_1^{\mathrm{NS}} G^{\mathrm{NS}} + f_2^{\mathrm{NS}}\big) &= w\Big[a - bw + \delta w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2 p + \lambda G\Big] - \tfrac{1}{2}w^2\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big)^2 + f_1^{\mathrm{NS}}\Big[\mu w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big] \\
\rho\big(g_1^{\mathrm{NS}} G^{\mathrm{NS}} + g_2^{\mathrm{NS}}\big) &= p\Big[a - bw + \delta w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2 p + \lambda G\Big] - \tfrac{1}{2}\beta^2 p^2 + g_1^{\mathrm{NS}}\Big[\mu w\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big]
\end{aligned} \tag{A4}$$

According to the system of equations to be solved, we can obtain:

$$\begin{cases}
f_1^{\mathrm{NS}} = \frac{\lambda w}{\rho+k} \\
f_2^{\mathrm{NS}} = \frac{w}{\rho}\Big[a - bw + \beta^2 p + \frac{w}{2}\Big(\frac{\lambda\mu}{\rho+k} + \delta\Big)^2\Big] \\
g_1^{\mathrm{NS}} = \frac{\lambda p}{\rho+k} \\
g_2^{\mathrm{NS}} = \frac{p}{\rho}\Big[a - bw + \frac{\beta^2 p}{2} + w\Big(\frac{\lambda\mu}{\rho+k} + \delta\Big)^2\Big]
\end{cases} \tag{A5}$$

Substituting $r^{NS} = w\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$ into the state equation for low-carbon goodwill yields:

$$\dot{G}^{NS}(t) = \mu w\left(\delta + \frac{\mu\lambda}{\rho+k}\right) - kG^{NS}(t) \tag{A6}$$

The differential equation can be solved to obtain the low-carbon goodwill as:

$$G^{NS}(t) = G_0^{NS}e^{-kt} + \left(1 - e^{-kt}\right)\frac{\mu w}{k}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) \tag{A7}$$

The corresponding optimal strategic steady-state strategies and optimal steady-state profits can therefore be derived as follows.

$$\begin{array}{l} r^{NS} = w\left(\delta + \frac{\mu\lambda}{\rho+k}\right) \\ s^{NS} = p\beta \end{array} \tag{A8}$$

$$\begin{array}{l} V_M^{NS}(t) = \frac{\lambda w}{\rho+k}G(t) + \frac{w}{\rho}\left[a - bw + \beta^2 p + \frac{w}{2}\left(\frac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \\ V_H^{NS}(t) = \frac{\lambda p}{\rho+k}G(t) + \frac{p}{\rho}\left[a - bw + \frac{\beta^2 p}{2} + w\left(\frac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \end{array} \tag{A9}$$

Proposition 1 is proved. □

Proof of Proposition 2. We use inverse induction to solve this strategy, and, according to the theory of continuum dynamics, the continuously differentiable value function V_H^{MS} satisfies the Hamilton–Jacobi–Bellman (HJB) equation as:

$$\rho V_H^{MS} = p(a - bw + \delta r + \beta s + \lambda G) - \frac{1}{2}s^2 + \frac{\partial V_H^{MS}}{\partial G^{MS}}(\mu r - kG) \tag{A10}$$

where $\frac{\partial V_H^{MS}}{\partial G^{MS}}$ is the first-order partial derivative of the medical institution optimal value function with respect to low-carbon goodwill G^{MS}. By the first-order optimality condition, the marketing effort $s(t)$ is obtained as $s^{MS} = p\beta$. Substituting it into the pharmaceutical enterprise's objective generalized function, we obtain the Hamilton–Jacobi–Bellman (HJB) equation that the pharmaceutical enterprise should satisfy.

$$\rho V_M^{MS} = w\left(a - bw + \delta r + \beta^2 p + \lambda G\right) - \frac{1}{2}(1-\theta)r^2 + \frac{\partial V_M^{MS}}{\partial G^{MS}}(\mu r - kG) \tag{A11}$$

where $\frac{\partial V_M^{MS}}{\partial G^{MS}}$ is the first-order partial derivative of the pharmaceutical enterprise optimal value function with respect to low-carbon goodwill G^{MS}. According to the first-order optimality condition, the low-carbon input $r(t)$ is obtained as $r^{MS} = \frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$. Bringing $s^{MS} = p\beta$, $r^{MS} = \frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$ into the HJB equation for the pharmaceutical enterprise and the medical institution yields:

$$\begin{array}{l} \rho V_M^{MS} = w\left[a - bw + \delta\frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) + \beta^2 p + \lambda G\right] - \frac{1}{2}(1-\theta)\left(\frac{w}{(1-\theta)}\right)^2\left(\delta + \frac{\mu\lambda}{\rho+k}\right)^2 + \frac{\partial V_M^{MS}}{\partial G^{MS}}\left[\mu\frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) - kG\right] \\ \rho V_H^{MS} = p\left[a - bw + \delta\frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) + \beta^2 p + \lambda G\right] - \frac{1}{2}\beta^2 p^2 + \frac{\partial V_H^{MS}}{\partial G^{MS}}\left[\mu\frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) - kG\right] \end{array} \tag{A12}$$

The optimal value function of pharmaceutical enterprise and medical institution is assumed to be

$$V_M^{MS} = f_3^{MS}G^{MS} + f_4^{MS}, \;\; V_H^{MS} = g_3^{MS}G^{MS} + g_4^{MS}$$

where f_3^{MS}, f_4^{MS} and g_3^{MS}, g_4^{MS} are the corresponding constant coefficients to be determined, respectively, which are substituted into (A12) to obtain the set of equations to be determined as

$$\begin{aligned}\rho\left(f_3^{\mathrm{MS}}G^{\mathrm{MS}}+f_4^{\mathrm{MS}}\right)&=w\left[a-bw+\delta\tfrac{w}{(1-\theta)}\left(\delta+\tfrac{\mu\lambda}{\rho+k}\right)+\beta^2p+\lambda G\right]-\tfrac{1}{2}(1-\theta)\left(\tfrac{w}{(1-\theta)}\right)^2\left(\delta+\tfrac{\mu\lambda}{\rho+k}\right)^2+f_3^{\mathrm{MS}}\left[\mu\tfrac{w}{(1-\theta)}\left(\delta+\tfrac{\mu\lambda}{\rho+k}\right)-kG\right]\\ \rho\left(g_3^{\mathrm{MS}}G^{\mathrm{MS}}+g_4^{\mathrm{MS}}\right)&=p\left[a-bw+\delta\tfrac{w}{(1-\theta)}\left(\delta+\tfrac{\mu\lambda}{\rho+k}\right)+\beta^2p+\lambda G\right]-\tfrac{1}{2}\beta^2p^2+g_3^{\mathrm{MS}}\left[\mu\tfrac{w}{(1-\theta)}\left(\delta+\tfrac{\mu\lambda}{\rho+k}\right)-kG\right]\end{aligned}\tag{A13}$$

According to the system of equations to be solved, we can obtain:

$$\begin{cases} f_3^{\mathrm{MS}}=\frac{\lambda w}{\rho+k}\\ f_4^{\mathrm{MS}}=\frac{w}{\rho}\left[a-bw+\beta^2p+\frac{w}{2(1-\theta)}\left(\frac{\lambda\mu}{\rho+k}+\delta\right)^2\right]\\ g_3^{\mathrm{MS}}=\frac{\lambda p}{\rho+k}\\ g_4^{\mathrm{MS}}=\frac{p}{\rho}\left[a-bw+\frac{\beta^2p}{2}+\frac{w}{(1-\theta)}\left(\frac{\lambda\mu}{\rho+k}+\delta\right)^2\right]\end{cases}\tag{A14}$$

Substituting $r^{\mathrm{MS}}=\frac{w}{(1-\theta)}\left(\delta+\frac{\mu\lambda}{\rho+k}\right)$ into the state equation for low-carbon goodwill yields:

$$\dot{G}^{\mathrm{MS}}(t)=\mu\frac{w}{(1-\theta)}\left(\delta+\frac{\mu\lambda}{\rho+k}\right)-kG^{\mathrm{MS}}(t)\tag{A15}$$

The differential equation can be solved to obtain the low-carbon goodwill as:

$$G^{\mathrm{MS}}(t)=G_0^{\mathrm{MS}}e^{-kt}+\left(1-e^{-kt}\right)\frac{\mu w}{k(1-\theta)}\left(\delta+\frac{\mu\lambda}{\rho+k}\right)\tag{A16}$$

The corresponding optimal strategic steady-state strategies and optimal steady-state profits can therefore be derived as follows.

$$\begin{aligned}r^{\mathrm{MS}}&=\tfrac{w}{(1-\theta)}\left(\delta+\tfrac{\mu\lambda}{\rho+k}\right)\\ s^{\mathrm{SS}}&=\beta p\end{aligned}\tag{A17}$$

$$\begin{aligned}V_{\mathrm{M}}^{\mathrm{MS}}&=\tfrac{\lambda w}{\rho+k}G(t)+\tfrac{w}{\rho}\left[a-bw+\beta^2p+\tfrac{w}{2(1-\theta)}\left(\tfrac{\lambda\mu}{\rho+k}+\delta\right)^2\right]\\ V_{\mathrm{H}}^{\mathrm{MS}}&=\tfrac{\lambda p}{\rho+k}G(t)+\tfrac{p}{\rho}\left[a-bw+\tfrac{\beta^2p}{2}+\tfrac{w}{(1-\theta)}\left(\tfrac{\lambda\mu}{\rho+k}+\delta\right)^2\right]\end{aligned}\tag{A18}$$

Proposition 2 is proved. □

Proof of Proposition 3. We use inverse induction to solve this strategy, and, according to the theory of continuum dynamics, the continuously differentiable value function $V_{\mathrm{H}}^{\mathrm{HS}}$ satisfies the Hamilton–Jacobi–Bellman (HJB) equation as:

$$\rho V_{\mathrm{H}}^{\mathrm{HS}}=(p+\eta w)(a-bw+\delta r+\beta s+\lambda G)-\frac{1}{2}s^2+\frac{\partial V_{\mathrm{H}}^{\mathrm{HS}}}{\partial G^{\mathrm{HS}}}(\mu r-kG)\tag{A19}$$

where $\frac{\partial V_{\mathrm{H}}^{\mathrm{HS}}}{\partial G^{\mathrm{HS}}}$ is the first-order partial derivative of the medical institution optimal value function with respect to low-carbon goodwill G^{HS}. By the first-order optimality condition, the marketing effort $s(t)$ is obtained as $s^{\mathrm{HS}}=\beta(p+\eta w)$. Substituting it into the pharmaceutical enterprise's objective generalized function, we obtain the Hamilton–Jacobi–Bellman (HJB) equation that the pharmaceutical enterprise should satisfy.

$$\rho V_{\mathrm{M}}^{\mathrm{HS}}=w\left[a-bw+\delta r+\beta^2(p+\eta w)+\lambda G\right]-\frac{1}{2}r^2+\frac{\partial V_{\mathrm{M}}^{\mathrm{HS}}}{\partial G^{\mathrm{HS}}}(\mu r-kG)\tag{A20}$$

where $\frac{\partial V_{\mathrm{M}}^{\mathrm{HS}}}{\partial G^{\mathrm{HS}}}$ is the first-order partial derivative of the pharmaceutical enterprise optimal value function with respect to low-carbon goodwill G^{HS}. According to the first-order optimality condition, the low-carbon input $r(t)$ is obtained as $r^{\mathrm{HS}}=w\left(\delta+\frac{\mu\lambda}{\rho+k}\right)$. Bring-

ing $s^{HS} = \beta(p + \eta w)$, $r^{HS} = w\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$ into the HJB equation for the pharmaceutical enterprise and the medical institution yields:

$$\begin{aligned}\rho V_M^{HS} &= w\left[a - bw + \delta w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) + \beta^2(p + \eta w) + \lambda G\right] - \tfrac{1}{2}w^2\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right)^2 + \tfrac{\partial V_M^{HS}}{\partial G^{HS}}\left[\mu w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) - kG\right] \\ \rho V_H^{HS} &= (p + \eta w)\left[a - bw + \delta w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) + \beta^2(p + \eta w) + \lambda G\right] - \tfrac{1}{2}\beta^2(p + \eta w)^2 + \tfrac{\partial V_H^{HS}}{\partial G^{HS}}\left[\mu w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) - kG\right]\end{aligned} \tag{A21}$$

The optimal value function of pharmaceutical enterprise and medical institution is assumed to be

$$V_M^{HS} = f_5^{HS} G^{HS} + f_6^{HS}, \;\; V_H^{HS} = g_5^{HS} G^{HS} + g_6^{HS}$$

where f_5^{HS}, f_6^{HS} and g_5^{HS}, g_6^{HS} are the corresponding constant coefficients to be determined, respectively, which are substituted into (A21) to obtain the set of equations to be determined as

$$\begin{aligned}\rho\left(f_5^{HS} G^{HS} + f_6^{HS}\right) &= w\left[a - bw + \delta w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) + \beta^2(p + \eta w) + \lambda G\right] - \tfrac{1}{2}w^2\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right)^2 + f_5^{HS}\left[\mu w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) - kG\right] \\ \rho\left(g_5^{HS} G^{HS} + g_6^{HS}\right) &= (p + \eta w)\left[a - bw + \delta w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) + \beta^2(p + \eta w) + \lambda G\right] - \tfrac{1}{2}\beta^2(p + \eta w)^2 + g_5^{HS}\left[\mu w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) - kG\right]\end{aligned} \tag{A22}$$

According to the system of equations to be solved, we can obtain:

$$\begin{cases} f_1^{NS} = \frac{\lambda w}{\rho+k} \\ f_2^{NS} = \frac{w}{\rho}\left[a - bw + \beta^2\eta w + \beta^2(p + \eta w) + \frac{w}{2}\left(\frac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \\ g_1^{NS} = \frac{\lambda(p+\eta w)}{\rho+k} \\ g_2^{NS} = \frac{(p+\eta w)}{\rho}\left[a - bw + \frac{1}{2}\beta^2(p + \eta w) + w\left(\delta + \frac{\lambda\mu}{(\rho+k)}\right)^2\right] \end{cases} \tag{A23}$$

Substituting $r^{HS} = w\left(\delta + \frac{\mu\lambda}{\rho+k}\right)$ into the state equation for low-carbon goodwill yields:

$$\dot{G}^{NS}(t) = \mu w\left(\delta + \frac{\mu\lambda}{\rho + k}\right) - kG^{HS}(t) \tag{A24}$$

The differential equation can be solved to obtain the low-carbon goodwill as:

$$G^{HS}(t) = G_0^{HS} e^{-kt} + (1 - e^{-kt})\frac{\mu w}{k}\left(\delta + \frac{\mu\lambda}{\rho + k}\right)G \tag{A25}$$

The corresponding optimal strategic steady-state strategies and optimal steady-state profits can therefore be derived as follows.

$$\begin{aligned} r^{HS} &= w\left(\delta + \tfrac{\mu\lambda}{\rho+k}\right) \\ s^{HS} &= \beta(p + \eta w)\end{aligned} \tag{A26}$$

$$\begin{aligned} V_M^{HS}(t) &= \tfrac{w\lambda}{\rho+k}G(t) + \tfrac{w}{\rho}\left[a - bw + \beta^2(p + \eta w) + \tfrac{w}{2}\left(\tfrac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \\ V_H^{HS} &= \tfrac{\lambda(p+\eta w)}{\rho+k}G(t) + \tfrac{(p+\eta w)}{\rho}\left[a - bw + \tfrac{1}{2}\beta^2(p + \eta w) + w\left(\delta + \tfrac{\lambda\mu}{(\rho+k)}\right)^2\right]\end{aligned} \tag{A27}$$

Proposition 3 is proved. □

Proof of Proposition 4. We use inverse induction to solve this strategy, and, according to the theory of continuum dynamics, the continuously differentiable value function V_H^{DS} satisfies the Hamilton–Jacobi–Bellman (HJB) equation as:

$$\rho V_H^{DS} = (p + \eta w)(a - bw + \delta r + \beta s + \lambda G) - \frac{1}{2}s^2 + \frac{\partial V_H^{DS}}{\partial G^{DS}}(\mu r - kG) \tag{A28}$$

where $\frac{\partial V_{\mathrm{H}}^{\mathrm{DS}}}{\partial G^{\mathrm{DS}}}$ is the first-order partial derivative of the medical institution optimal value function with respect to low-carbon goodwill G^{DS}. By the first-order optimality condition, the marketing effort $s(t)$ is obtained as $s^{\mathrm{DS}} = \beta(p + \eta w)$. Substituting it into the pharmaceutical enterprise's objective generalized function, we obtain the Hamilton–Jacobi–Bellman (HJB) equation that the pharmaceutical enterprise should satisfy.

$$\rho V_{\mathrm{M}}^{\mathrm{DS}} = w\Big[a - bw + \delta r + \beta^2(p + \eta w) + \lambda G\Big] - \frac{1}{2}(1-\theta)r^2 + \frac{\partial V_{\mathrm{M}}^{\mathrm{DS}}}{\partial G^{\mathrm{DS}}}(\mu r - kG) \tag{A29}$$

where $\frac{\partial V_{\mathrm{M}}^{\mathrm{DS}}}{\partial G^{\mathrm{DS}}}$ is the first-order partial derivative of the pharmaceutical enterprise optimal value function with respect to low-carbon goodwill G^{DS}. According to the first-order optimality condition, the low-carbon input $r(t)$ is obtained as $r^{\mathrm{DS}} = \frac{w}{(1-\theta)}\Big(\delta + \frac{\mu\lambda}{\rho+k}\Big)$. Bringing $s^{\mathrm{DS}} = \beta(p + \eta w)$, $r^{\mathrm{DS}} = \frac{w}{(1-\theta)}\Big(\delta + \frac{\mu\lambda}{\rho+k}\Big)$ into the HJB equation for the pharmaceutical enterprise and the medical institution yields:

$$\begin{aligned}
\rho V_{\mathrm{M}}^{\mathrm{DS}} &= w\Big[a - bw + \delta\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2(p + \eta w) + \lambda G\Big] - \tfrac{1}{2}(1-\theta)\Big(\tfrac{w}{(1-\theta)}\Big)^2\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big)^2 + \tfrac{\partial V_{\mathrm{M}}^{\mathrm{DS}}}{\partial G^{\mathrm{DS}}}\Big[\mu\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big] \\
\rho V_{\mathrm{H}}^{\mathrm{DS}} &= (p + \eta w)\Big[a - bw + \delta\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2(p + \eta w) + \lambda G\Big] - \tfrac{1}{2}\beta^2(p + \eta w)^2 + \tfrac{\partial V_{\mathrm{H}}^{\mathrm{DS}}}{\partial G^{\mathrm{DS}}}\Big[\mu\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big]
\end{aligned} \tag{A30}$$

The optimal value function of pharmaceutical enterprise and medical institution is assumed to be

$$V_{\mathrm{M}}^{\mathrm{DS}} = f_7^{\mathrm{DS}} G^{\mathrm{DS}} + f_8^{\mathrm{DS}}, \;\; V_{\mathrm{H}}^{\mathrm{DS}} = g_7^{\mathrm{DS}} G^{\mathrm{DS}} + g_8^{\mathrm{DS}}$$

where $f_7^{\mathrm{DS}}, f_8^{\mathrm{DS}}$ and $g_7^{\mathrm{DS}}, g_8^{\mathrm{DS}}$ are the corresponding constant coefficients to be determined, respectively, which are substituted into (A30) to obtain the set of equations to be determined as

$$\begin{aligned}
\rho\big(f_7^{\mathrm{DS}} G^{\mathrm{DS}} + f_8^{\mathrm{DS}}\big) &= w\Big[a - bw + \delta\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2(p + \eta w) + \lambda G\Big] - \tfrac{1}{2}(1-\theta)\Big(\tfrac{w}{(1-\theta)}\Big)^2\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big)^2 + f_7^{\mathrm{DS}}\Big[\mu\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big] \\
\rho\big(g_7^{\mathrm{DS}} G^{\mathrm{DS}} + g_8^{\mathrm{DS}}\big) &= (p + \eta w)\Big[a - bw + \delta\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) + \beta^2(p + \eta w) + \lambda G\Big] - \tfrac{1}{2}\beta^2(p + \eta w)^2 + g_7^{\mathrm{DS}}\Big[\mu\tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) - kG\Big]
\end{aligned} \tag{A31}$$

According to the system of equations to be solved, we can obtain:

$$\begin{cases}
f_7^{\mathrm{DS}} = \frac{\lambda w}{\rho+k} \\
f_8^{\mathrm{DS}} = \frac{w}{\rho}\left[a - bw + \beta^2(p + \eta w) + \frac{w}{2(1-\theta)}\left(\frac{\lambda\mu}{\rho+k} + \delta\right)^2\right] \\
g_7^{\mathrm{DS}} = \frac{\lambda(p+\eta w)}{\rho+k} \\
g_8^{\mathrm{DS}} = \frac{(p+\eta w)}{\rho}\left[a - bw + \frac{1}{2}\beta^2(p + \eta w) + \frac{w}{(1-\theta)}\left(\delta + \frac{\lambda\mu}{(\rho+k)}\right)^2\right]
\end{cases} \tag{A32}$$

Substituting $r^{\mathrm{DS}} = \frac{w}{(1-\theta)}\Big(\delta + \frac{\mu\lambda}{\rho+k}\Big)$ into the state equation for low-carbon goodwill yields:

$$\dot{G}^{\mathrm{DS}}(t) = \mu\frac{w}{(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) - kG^{\mathrm{DS}}(t) \tag{A33}$$

The differential equation can be solved to obtain the low-carbon goodwill as:

$$G^{\mathrm{DS}}(t) = G_0^{\mathrm{DS}} e^{-kt} + \left(1 - e^{-kt}\right)\frac{\mu w}{k(1-\theta)}\left(\delta + \frac{\mu\lambda}{\rho+k}\right) \tag{A34}$$

The corresponding optimal strategic steady-state strategies and optimal steady-state profits can therefore be derived as follows.

$$\begin{aligned}
r^{\mathrm{DS}} &= \tfrac{w}{(1-\theta)}\Big(\delta + \tfrac{\mu\lambda}{\rho+k}\Big) \\
s^{\mathrm{DS}} &= (p + \eta w)\beta
\end{aligned} \tag{A35}$$

$$V_{\mathrm{M}}^{\mathrm{DS}} = \frac{\lambda w}{\rho+k} G(t) + \frac{w}{\rho}\left[a - bw + \beta^2(p+\eta w) + \frac{w}{2(1-\theta)}\left(\frac{\lambda\mu}{\rho+k} + \delta\right)^2\right]$$
$$V_{\mathrm{H}}^{\mathrm{DS}} = \frac{\lambda(p+\eta w)}{\rho+k} G(t) + \frac{(p+\eta w)}{\rho}\left[a - bw + \frac{\beta^2}{2}(p+\eta w) + \frac{w}{(1-\theta)}\left(\delta + \frac{\lambda\mu}{(\rho+k)}\right)^2\right] \quad \text{(A36)}$$

Proposition 4 is proved. □

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