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PACKAGING STRATEGIES OF TEMPERATURE-SENSITIVE FOOD SUPPLY CHAINS CONSIDERING THE INFLUENCES OF DISTRIBUTION CHANNELS AND CONSUMERS' QUALITY CONCERN

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Abstract. With the boom of food delivery worldwide and the emergency of different distribution channels, temperature-sensitive food supply chains need to think about which sort of packages to choose. Compared with disposable packages, reusable packages bring down the deterioration rate of the temperature-sensitive food being delivered and are more environment-friendly; however, they incur more costs. Thus, we model a single-supplier–single-retailer temperature-sensitive food supply chain and investigate its packaging strategies considering the influences of distribution channels and consumers' quality concern. First, we reveal the separate roles of price transmission in the circumstances with quality and non-quality problems, the two-fold effects of reusing reusable packages for more times as well as the recommended environmental policy. Second, it is shown that consumers' quality concern is a critical factor influencing the supply chain's optimal packaging choice, which is explained by reusable packages' preservation advantages over disposable packages and the declining preservation performances of reusable packages over time. Finally, the interaction between the supply chain's packaging strategies and distribution channels is revealed that the geographic concentrations of food producing or processing industries and a more convenient long-distance logistics system will bring about the wide use of reusable packages and the establishment of online channels.

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1. Introduction

The global online food delivery market is booming that it is expected to hit USD 432.32 billion by 2030[1]. In the delivery to consumers, temperature-sensitive food, including frozen food (*e.g.*, seafood and ice-cream) and fresh food (*e.g.*, chicken and beef), easily deteriorates. With the increase of consumers' food-safety awareness, they have begun to pay special attention to the preservation performance of packages within which the food is packed. Reusable packages usually provide better preservation conditions for temperature-sensitive food than disposable packages. However, reusable packages are more expensive than disposable packages and meanwhile

Keywords. Reusable package, supply chain, distribution channel, consumers' quality concern, food delivery.

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[1] https://www.globenewswire.com/news-release/2023/08/28/2732352/0/en/Cosmetics-Market-to-Hit-USD-417-24-Billion-by-2030-With-a-CAGR-of-4-2.html.

additional costs are incurred in their regular maintenance. Considering consumers' demand for better delivery services and the cost-benefit trade-off of reusable packages, temperature-sensitive food sellers need to think about which sort of packages to choose.

Meanwhile, with the development of e-commence, temperature-sensitive food suppliers may establish their direct channels online. A direct channel of distribution defines a condition in which the producer sells a product to a consumer directly without any of the intermediaries[2]. An example is Amazon Fresh providing an online marketplace for suppliers to sell fresh food and offer delivery service in most major U.S. cities and some international cities. By doing so, the suppliers' market coverage will be greatly expanded. If online channels are established, the delivery distance will be much longer, which greatly affects the preservation of temperature-sensitive food. Due to the prolonged delivery distance, the suppliers' choice between disposable packages and reusable packages exerts a growing influence on the quality of food. Such an interaction between the packaging strategies and distribution channels of temperature-sensitive food supply chains has drawn our attention and we will make an investigation on this topic.

Motivated by the above evidence, we model a single-supplier–single-retailer temperature-sensitive food supply chain and study its pricing decisions in different scenarios considering the interaction between packaging strategies and distribution channels and the influences of consumers' quality concern. More precisely, in a traditional channel, the retailer could choose between disposable packages and reusable packages, and in an online channel, the supplier could also choose between disposable packages and reusable packages. We first derive the equilibrium results in each scenario and analyze the influences of some important factors on pricing decisions and profits, including the basic characteristics of packages, the declining preservation performance of reusable packages and environmental policies. As a following step, we investigate supply chain members' optimal packaging strategies and reveal the role of consumers' quality concern. Last but not least, by analyzing the influence of supply chain members' distances from consumers, we identify the interaction between packaging strategies and distribution channels. In this research, we will answer the following research questions:

(1) What are the food supply chain members' optimal pricing decisions considering different packaging choices and distribution channels? How do the basic characteristics of packages, the declining preservation performance of reusable packages and environmental policies affect?
(2) What's the optimal packaging strategy for the fresh food supply chain in scenarios with different distribution channels? What's the influence of consumers' quality concern on the optimal packaging strategy?
(3) What's the interaction between packaging choices and distribution channels? How does the delivery distance from consumers affect such an interaction?

This paper has generated some key findings. First, we reveal the separate roles of price transmission in the circumstances with quality and non-quality problems, the two-fold effects of reusing reusable packages for more times as well as the recommended environmental policy which motivates the green transformation of packages. Second, it is shown that consumers' quality concern is a critical factor influencing the supply chain's optimal packaging choice, which is explained by reusable packages' preservation advantages over disposable packages and the declining preservation performances of reusable packages over time. Last but not least, we analyze the interactions between the packaging strategies and distribution channels of the food supply chain and identify that the geographic concentrations of food producing or processing industries, a more convenient long-distance logistics system and consumers' high quality-preference will bring about the wide use of reusable packages and the establishment of online channels.

The rest of the paper is organized as follows. We provide the contributions of this paper by reviewing the extant research in Section 2. The assumptions, notations and details about different scenarios are provided in Section 3. Then, we derive the equilibrium results, analyze the influences of critical factors, and derive the optimal packaging strategy in scenarios with different distribution channels, as shown in Sections 4 and 5. Section 6 reveals the interactions between the temperature-sensitive food supply chain's optimal

[2] https://www.mbaskool.com/business-concepts/marketing-and-strategy-terms/11794-direct-channel.html.

packaging strategies and distribution channels. The main work and future research directions are provided in Section 7.

2. Literature review

Our research is relevant to two streams of research, *i.e.*, packaging strategies and distribution channels, which has laid a solid foundation for our research.

2.1. Packaging strategies

Logistics service quality is a key factor for the success of many e-commerce platforms. As a non-negligible element of logistics services, package or packaging has drawn much attention from scholars, as pointed out by the review paper of Mahmoudi & Parviziomran [21] and Zhu *et al.* [44].

Since the invention of reusable packages, the management of reusable packages has been emphasized. Some scholars incorporate routing or scheduling issues into the circulation problem, such as Soysal [34] and Soysal *et al.* [35] Some scholars consider inventory issues in packaging management. For example, Accorsi *et al.* [1] investigate how to manage uncertain inventories, washing, and transportation of reusable containers. In addition, other strategic decisions about reusable packages are investigated. Examples include package size decisions in crowdfunding studied by Peng *et al.* [29], a supply chain's production delivery problem with both the profit maximization and carbon emission minimization objectives studied by Sarkar *et al.* [32] and Bhunia *et al.* [7], and the planning problem of a closed-loop food supply chain studied by Zhang *et al.* [42]. In all these studies, the breakdown of reusable packages is usually modeled as a stochastic incident and the distinction is only made between reusable and non-reusable packages. As pointed out by Goh & Varaprasad [16], reusable packages are subject to various sorts of damage (*e.g.*, abrasion and deformation) in their regular circulation. This is consistent with the fact identified by Glock [15] that the preservation performances of reusable packages undergo a declining process and they become completely non-reusable at the end of the lifetime. Based on such facts and following Wang & Zhao [37], we will model the declining preservation performance of reusable packages in the food delivery process.

Our research also pays attention to the comparison between reusable packages and disposable packages. With the development of modern industry, environmental problems are becoming increasingly serious, such as global warming and greenhouse gas emission [6]. Reusable packages bring less waste of packaging, more protection of food and less environmental impact than disposable packages [13]. Sustainable development has become a hot topic in recent years. The use of reusable packaging can contribute to economic, environmental and social sustainability [26]. Meanwhile, the comparatively higher cost of reusable packages is noticeable. In addition, as we mentioned above, the declining preservation performance of reusable packages may further weaken their advantages. With the above considerations, it is necessary to compare reusable packages and disposable packages from more perspectives. Previous research has made some attempt on this topic. For example, McPherson *et al.* [23] find that using reusable packages greatly reduces greenhouse gas, and distance plays a significant role in this process. Choi *et al.* [11] compare the environmental impact of disposable wood pallets and reusable steel cradles. Camps-Posino *et al.* [10] investigate packaging environmental performance based on a Chinese restaurant case study, and they find that if packaging is changed from single-use to reusable, the emissions would potentially be 63% lower than the current situation. Nicolau *et al.* [27] analyze whether consumers are willing to bring a reusable coffee cup under the condition of a monetary incentive and the minimum discount required for individuals to be willing to use a reusable coffee cup. Inspired by their research, we will consider the sellers' distance from consumers, environmental performance of different packages as well as consumers' concerns in comparing reusable packages and disposable packages.

TABLE 1. Comparison with the most relevant studies.

Authors	Packaging strategies	Distribution channels	Declining preservation performance of reusable packages	Consumers' quality concern	Delivery distance	Environmental consideration
Goh & Varaprasad [16]	√		√			
Glock [15]	√		√			
Sarkar *et al.* [32]	√					√
Wang *et al.* [38]		√			√	
Khorshidvand *et al.* [19]		√				√
Nicolau *et al.* [27]	√					√
Gong *et al.* [17]		√		√		
Barman *et al.* [5]		√				√
Wang & Zhao [37]	√		√			√
This paper	√	√	√	√	√	√

2.2. Distribution channels

There has been massive research on distribution channels along with their interaction with supply chain management [9]. Inspired by extant research, we will discuss a temperature-sensitive food supply chain's packaging choices under different distribution channels.

As pointed out by review papers, the topics in the field of channel management in supply chains include the coordination between supply chain members [43], channel selection [5, 17] and so on. Our research lays special emphasis on the sellers' strategy of opening an online channel. The extant research has considered some factors to investigate their specific roles, such as spillovers from online to offline sales [39], vertical differentiation [41], return services [30, 31] and recycling [12].

In addition to the above issues, some scholars consider environmental issues about distribution channels. On the one hand, the green technology investment problem is investigated. For example, Khorshidvand *et al.* [19] explore coordinated decisions regarding a multi-level multi-channel supply chain considering the price of sale channels, the advertisement level, and greenness of the products. For example, Barman *et al.* [4] examine how investing in both preservation and green technologies for perishable commodities can maximise the profitability of the supply chain system in an environment with exceptional demand volatility. Feng *et al.* [14] consider a two-echelon reverse supply chain with dual-recycling channels and study how to strategically design the reverse channel structure and coordinate supply chain members. Taleizadeh & Sadeghi [36] study the return rates in two collecting reverse supply chains considering both internal and external competition. In addition, Mondal & Roy [25] investigated the activation of open- and closed-loop systems through efficient, flexible and resilient supply chain networks in emergency situations. Although our research has some similarities with the above research in terms of the consideration of an online channel, the environmental issues discussed are completely different. We provide a new perspective by focusing on the interactions between a temperature-sensitive food supply chain's packaging strategies and distribution channels and study the influences of environmental policies.

As shown in Table 1, a significant portion of studies on food packaging strategies have not focused on distribution channel factors. Whereas some scholars such as Khorshidvand *et al.* [19], Wang *et al.* [38], Gong *et al.* [17] and Barman *et al.* [5] focused on the distribution channel strategy, their studies were not focused on the packaging strategy of food products. Although Goh & Varaprasad [16] and Glock [15] considered the degradation of preservation performance of reusable packages in their study of packaging strategies for food products, they did not take into account the distance of movement and environmental factors, among others. In addition, some scholars such as Sarkar *et al.* [32], Nicolau *et al.* [27] and Wang & Zhao [37] studied packaging strategies after considering environmental factors without analyzing factors such as distribution channels, consumer concerns about quality and delivery distance.

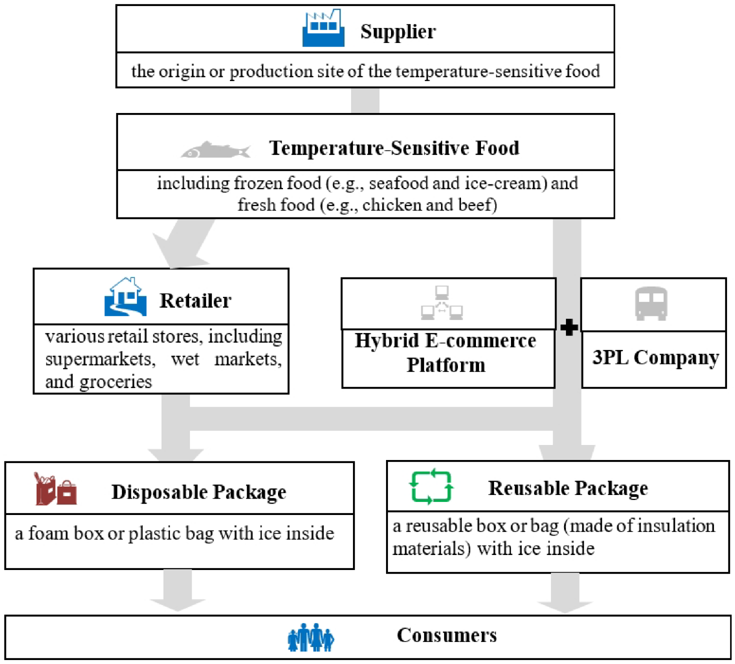

FIGURE 1. Entities involved and their explanations.

According to the above analysis, this paper has both the theoretical and practical contributions. Our research focuses on a temperature-sensitive food supply chain's packaging strategies and distribution channels considering the influences of the declining preservation performance of reusable packages, supply chain members' distance from consumers, consumers' quality concern and environmental policies, which has not been studied previously. In addition, by providing firms with the guidance on reusing packages and distribution channels, our research also has practical significance, and this helps to push forward the wide use of reusable packages and the establishment of online channels.

3. Model setup

In this paper, we study the packaging strategies and distribution channels of a temperature-sensitive food supply chain. The entities involved are presented and explicitly explained in Figure 1. Under the traditional channel, the bulk-packed temperature-sensitive food is transported from the supplier to the retailer in refrigerated trucks and then is temporarily stored in the retailer's refrigerated warehouse. The retailer needs to divide and repackage the food before sale. Under the online channel, the supplier opens its online shop on a hybrid e-commerce platform and signs a logistics contract with a third-party logistics (3PL) company. Once a consumer makes an online order, the supplier prepares the food, and then the 3PL company packages and makes delivery to consumers. As shown in Figure 1, two packaging choices are available for deliveries in both channels, *i.e.*, packaging with disposable packages or reusable packages.

To investigate the interactions between a temperature-sensitive food supply chain's packaging strategies and distribution channels, we consider four scenarios, as shown in Figure 2. In scenario 1, the products are sold through the traditional channel and packed with disposable packages, while in scenario 2, they are packed with reusable packages. In scenarios 3 and 4, the products are sold through the online channel and packed with

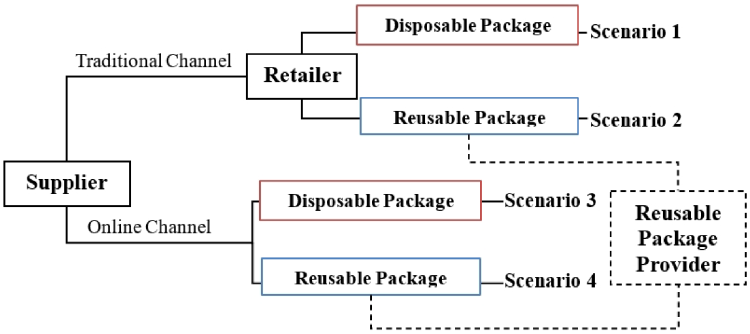

FIGURE 2. Four scenarios about packaging strategies and distribution channels.

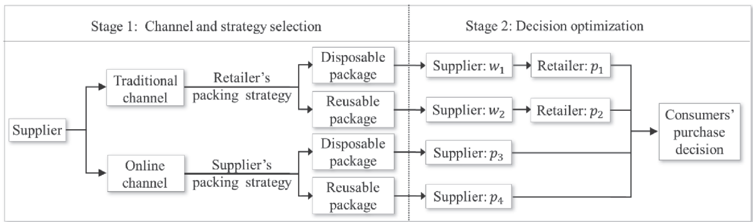

FIGURE 3. Decision sequence in four scenarios.

disposable packages and reusable packages, respectively. Note that the subscripts of notations stand for different scenarios.

This paper considers two stages of decision-making for supply chain members. The first stage is the channel and strategy selection stage and the second stage is the decision-making optimization stage for supply chain members. In the traditional channel structure (scenarios 1 and 2), there is a Stackelberg game between supply chain members, where the supplier is the dominant player and the retailer is the follower. Therefore, in the decision optimization stage, the supplier first decides the wholesale price of the product (scenarios 1 and 2). After observing the supplier's decision, the retailer will set the selling price of the product. Under the online channel (scenarios 3 and 4), the retailer does not participate in the operation of the supply chain, and the supplier needs to decide the selling price of the product. The decision sequence is shown in Figure 3.

3.1. Characteristics of a temperature-sensitive food supply chain

The supply chain we study faces a continuous market demand D_i for the temperature-sensitive food, which has a negative correlation with the food's retail price p_i and a positive correlation with the food's quality q_i $(i = 1, 2, 3, 4)$. We express it as $D_i = v - ap_i + bq_i$ [22], where v is a coefficient measuring the potential market size, a is a coefficient measuring consumers' sensitivity about price, b is a coefficient measuring consumers' sensitivity about quality.

i represents different scenarios (*i.e.*, $i = 1, 2, 3, 4$ denotes the scenarios 1, 2, 3, 4, respectively). To investigate the interaction between packaging strategy and distribution channel in a temperature-sensitive food supply chain, four scenarios are considered.

In scenario 1, products are sold through the traditional channel, *i.e.*, the distribution from the supplier to the retailer, and disposable packages are used, whereas in scenario 2, products are sold through the traditional channel while using reusable packages. In scenario 3, products are sold through an online channel, *i.e.*, directly delivered to consumers by the supplier, and disposable packages are used, while in scenario 4, products are sold through an online channel in reusable packages.

Most of fresh produce items reach their peak quality at the time of production, and then deteriorate substantially over time [2, 8, 40]. As such, the quality of the food is correlated with the distance of delivery and the preservation performance of its package. We express it as $q_i = q_0 - u_i d_i$, where q_0 is the initial quality level of the food, u_i denotes the quality declining rate and d_i denotes the distance from the place of departure to consumers ($i = 1, 2, 3, 4$). Note that $d_i = d_t$ ($i = 1, 2$) and $d_i = d_o$ ($i = 3, 4$).The subscript of the delivery distance "t" represents the scenarios where the traditional channel is established (scenarios 1 and 2), and thus d_t denotes the distance of shipment in the traditional channel from the retailer to consumers. Differently, the subscript of the delivery distance "o" represents the scenarios where the online channel is established (scenarios 3 and 4), and thus d_o is the distance from the supplier to consumers in the online channel. Since the supplier is usually much more remote than the retailer from consumers, we assume $d_t \ll d_o$.

In addition, the wholesale price of the food is denoted as w_i ($i = 1, 2$), and it is a decision variable of the supplier. The retailer's order cycle time is denoted as T, referring to the time period between placing one order and the next order. The retailer's optimal replenishment time for perishable items is unique when the selling price is related to demand [28]. The production cost of the food is denoted as c. Based on the investigation about the quantity of the food that consumers are more likely to buy in a single purchase, the food supply chain will use the package whose capacity is equal to such a quantity. The capacity of a package is denoted as k. Note that k is much smaller than the overall sales quantity.

3.2. Preservation performance of packages

Since disposable packages are designed for just one use, they have stable preservation performance, which means that the quality declining rate of the food being packed is constant. We denote it as $u_i = u_d$ ($i = 1, 3$), and the subscript "d" stands for disposable packages.

Inspired by Levi *et al.* [20] and Wang & Zhao [37], we will pay special attention to the two-fold effects of reusing reusable packages for more times. More precisely, reusing reusable packages for more times will cut down the unit operational cost about reusable packages, and reusing them for less times will cause the decline of food quality and affect market demand. Because the insulation material of reusable packages undergoes natural aging during its lifetime, we assume that the preservation performance of reusable packages declines overtime. Denoting the number of uses of reusable packages as m, we consider a time horizon as mT. In scenario 2, we express the quality declining rate of the food following Wang & Zhao [37]:

$$u_2 = \begin{cases} u_r, & t \in [0, T] \\ u_r + \varphi(j-1), & t \in [(j-1)T, jT] \\ \cdots \\ u_r + \varphi(m-1), & t \in [(m-1)T, mT] \end{cases} \tag{1}$$

where u_r is the initial quality declining rate of the food being packed in reusable packages, and φ is its increasing rate overtime which describes the declining process of preservation performance. Note that the subscript "r" denotes reusable packages. Since reusable packages are much more effective than disposable packages in preserving temperature-sensitive food, we assume $u_r \ll u_d$.

In scenario 4, the reusable package provider possesses numerous reusable packages, incurring the mixed used of reusable packages with different levels of preservation performance. As such, we simply assume that the quality declining rate of food in scenario 4 is on an average level, *i.e.*, $u_4 = u_r + \varphi\frac{m-1}{2}$.

3.3. Operational costs about packages

Previous research has made various assumptions about the ownership and the operational costs about reusable packages. For example, firms purchase reusable packages from a reusable package provider and maintain them on their own [3]. Reusable packages are owned by a reusable package provider and it provides rental services for firms [18]. On this basis, we assume the retailer possesses reusable packages for its own use (scenario 2) and the supplier rents reusable packages (scenario 4). The practical explanations of this assumption are provided as follows. Retailers act as scattering sales points and respectively serve their surrounding area. As such, they are capable to conduct the delivery, collection, and other relevant work about reusable packages. However, suppliers are usually remote from consumers, making it inconvenient for them to undertake the above work. Therefore, the supplier turns to a reusable package provider for professional after-sale services.

Referring to the finding of Menesatti *et al.* [24] and the cost structure in Wang & Zhao [37] that purchasing a reusable package involves an initial investment and annual costs, we assume the possessing cost of a reusable package contains two parts, the procurement cost h and the maintenance cost which is proportional to m and the unit maintenance cost l. The renting cost of a reusable package is denoted as r. In addition to delivery, the collection of reusable packages and other maintenance work are covered in the rental services.

Meanwhile, in contrast to disposable packages, reusable packages are environmentally friendly because their re-usage greatly reduces the waste of packaging materials. To enhance recycling and re-usage, environmental policies have been implemented worldwide, such as environmental taxes and green subsidies [33]. As such, the cost of packages is also affected by environmental policies with both taxes and subsidies [38], *i.e.*, the taxes on the use of disposable packages and the subsidies for the use of reusable packages, where τ denotes the tax rate and s $(0 < s < 1)$ denotes the subsidy rate.

4. Traditional channel

Under the traditional channel, the retailer can pack food with disposable packages or reusable packages. By solving profit maximization problems in scenarios 1 and 2, we will derive the optimal decisions and the maximal profits.

The supplier's profit is its sales revenue minus the purchasing cost. In scenario 1 where disposable packages are used to pack food, the supplier's profit per unit time is:

$$\prod\nolimits_{s1} = \frac{\prod_{s1}^{t}}{mT} = \frac{w_1 D_1 mT - cD_1 mT}{mT} = (w_1 - c)[v - ap_1 + b(q_0 - d_t u_d)]. \tag{2}$$

In scenario 2 where reusable packages are used, the supplier's profit per unit time is:

$$\prod\nolimits_{s2} = \frac{\prod_{s2}^{t}}{mT} = \frac{w_2 \sum_{j=1}^{m} D_{2(j)}T - c\sum_{j=1}^{m} D_{2(j)}T}{mT} = (w_2 - c)\left\{v - ap_2 + b\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\}. \tag{3}$$

Since the capacity of a package is much smaller than the sales quantity, we approximate that the number of packages used in the interval of $[0, mT]$ is $n_1 \approx \frac{D_1 mT}{k}$ (or $n_2 \approx \frac{\max\{D_2\}T}{k}$). Thus, we express the retailer's profit per unit time in scenario 1 as follows:

$$\prod\nolimits_{r1} = \frac{\prod_{r1}^{t}}{mT} = \frac{p_1 D_1 mT - w_1 D_1 mT - \tau n_1}{mT} = \left(p_1 - w_1 - \frac{\tau}{k}\right)[v - ap_1 + b(q_0 - d_t u_d)] \tag{4}$$

where the retailer needs to pay the tax on the use of disposable packages. In scenario 2, since the retailer purchases reusable packages for its own use, it gets the government's subsidy on the purchasing cost of reusable packages. In addition, the retailer's regular maintenance about reusable packages involves certain costs. We express the retailer's profit per unit time in scenario 2 as follows:

$$\begin{aligned}\prod\nolimits_{r2} &= \frac{\prod_{r2}^{t}}{mT} = \frac{p_2 \sum_{j=1}^{m} D_{2(j)}T - w_2 \sum_{j=1}^{m} D_{2(j)}T - [(1-s)h + ml]n_2}{mT} \\ &= (p_2 - w_2)\left\{v - ap_2 + b\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\} - \frac{[(1-s)h + ml][v - ap_2 + b(q_0 - d_t u_r)]}{mk}.\end{aligned} \tag{5}$$

4.1. Optimal decisions and profits

In both scenarios, the supplier and the retailer determine the wholesale price and the retail price of food subsequently. Using backward induction, we first obtain the first-order and second-order derivatives of the retailer's profit functions with respect to the selling prices. Then, by maximizing the retailer's profit in scenarios 1 and 2, we derive the response functions. By plugging the response functions into the supplier's profit functions, we obtain the supplier's profit functions regarding wholesale prices. On this basis, we obtain the first-order and second-order derivatives of the supplier's profits with respect to wholesale prices, where the second derivatives are always less than zero, therefore there always exist maximum profit for the supplier. we derive the optimal solutions, as shown in Lemma 1.

Lemma 1. *The optimal decisions and the maximal profits of supply chain members under a traditional channel include:*

(i) *If disposable packages are used, the optimal wholesale price and retail price are* $w_1^* = \frac{v}{2a} + \frac{c}{2} - \frac{\tau}{2k} + \frac{b}{2a}(q_0 - d_t u_d)$ *and* $p_1^* = \frac{3v}{4a} + \frac{c}{4} + \frac{\tau}{4k} + \frac{3b}{4a}(q_0 - d_t u_d)$*; the maximal profits of the supplier and the retailer are* $\prod_{s1} = \frac{a}{8}[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_t u_d)]^2$ *and* $\prod_{r1} = \frac{a}{16}[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_t u_d)]^2$.

(ii) *If reusable packages are used, the optimal wholesale price and retail price are* $w_2^* = \frac{v}{2a} + \frac{c}{2} + \frac{b}{2a}[q_0 - d_t(u_r + \varphi\frac{m-1}{2})] - \frac{(1-s)h+ml}{2mk}$ *and* $p_2^* = \frac{3v}{4a} + \frac{c}{4} + \frac{3b}{4a}[q_0 - d_t(u_r + \varphi\frac{m-1}{2})] + \frac{(1-s)h+ml}{4mk}$*; supply chain members' maximal profits are* $\prod_{s2} = \frac{a}{8}\{\frac{v}{a} - c + \frac{b}{a}[q_0 - d_t(u_r + \varphi\frac{m-1}{2})] - \frac{(1-s)h+ml}{mk}\}^2$ *and* $\prod_{r2} = \frac{a}{16}\{\frac{v}{a} - c + \frac{b}{a}[q_0 - d_t(u_r + \varphi\frac{m-1}{2})] - \frac{(1-s)h+ml}{mk}\}^2 - \varphi b d_t(m-1)\frac{(1-s)h+ml}{2mk}$.

To guarantee the non-negativity of prices, profit margins and market demand, Condition 1 is needed.

Condition 1. Under the traditional channel, if disposable packages are used, $\frac{k}{3}[c - \frac{v}{a} - \frac{b}{a}(q_0 - d_t u_d)] \leq \tau \leq k[\frac{v}{a} + \frac{b}{a}(q_0 - d_t u_d) - c]$ is essential; if reusable packages are used, $\frac{(1-s)h+ml}{mk} \leq \frac{v}{a} + \frac{b}{a}[q_0 - d_t(u_r - 7\varphi\frac{m-1}{2})] - c - \sqrt{\{\frac{v}{a} - c + \frac{b}{a}[q_0 - d_t(u_r - 3\varphi\frac{m-1}{2})]\}\frac{8\varphi b d_t(m-1)}{a}}$ and $3\{c - \frac{v}{a} - \frac{b}{a}[q_0 - d_t(u_r + \varphi\frac{m-1}{2})]\} \leq \frac{(1-s)h+ml}{mk} \leq \frac{v}{a} + \frac{b}{a}[q_0 - d_t(u_r + \varphi\frac{m-1}{2})] - c$ should be guaranteed.

4.2. Influences of critical factors

In the following content, we will analyze the influences of some critical factors in the scenarios with the traditional channel, including the basic characteristics of packages, the declining preservation performance of reusable packages and environmental policies.

4.2.1. Influences of the basic characteristics of packages

We first analyze the influences of the parameters relevant to the basic characteristics of packages, as shown in Proposition 1.

Proposition 1. *If the initial preservation performance of packages gets worse, meaning that the initial quality declining rate of food increases, the prices and profits of supply chain members decline. With the increase of the purchasing or maintenance cost of a reusable package, the retail price goes up, while the wholesale price and the food supply chain members' profits go down.*

Proposition 1 is explained that with a lower initial quality declining rate of food, the quality of the food at the point of consumption becomes lower, which imposes negative influences on market demand. As such, supply chain members cut down the wholesale price and the retail price, which eventually causes the decline in the profits of supply chain members. Unlike the initial quality declining rate of food, the purchasing or maintenance cost of a reusable package is not related to the quality problems of the food. If the purchasing or maintenance cost of a reusable package increases, meaning that the cost of a package with standard capacity increases, which adds to the retailer's operational cost. Driven by the price transmission, the retailer will transfer the increasing operational cost to downstream consumers. As such, the retailer raises its retail price, which imposes negative influences on market demand. In terms of the wholesale price, it is not directly affected by the retail price. Facing a lower market demand, the supplier cuts down its wholesale price, and supply chain members' profit decline. On this basis, we conclude that the decreasing revenue resulting from lower quality or the increasing packaging cost both lead to profit losses. With the existence of price transmission, the profit losses are jointly undertaken by supply chain members. Proposition 1 corresponds with the reality that when the cost of packaging materials increases, the corresponding supplier will increase its products' price.

The initial quality declining rate of food is directly related with food quality, and the purchasing or maintenance cost of a reusable package is not related with food quality. When the quality of food declines, consumers will purchase less and look for alternatives, and then market demand declines so that the supplier and the retailer will tend to lower their prices in order to maintain their market share and consumer trust. However, when the cost of a reusable package rises, which is unrelated to food quality, supply chain members are more inclined to pass on the cost by increasing prices, and consumers are willing to accept this price adjustment because of environmental protection concepts, trust in quality, and other factors, enabling supply chain members to pass on the loss of profits that are not due to quality issues to consumers through price transmission. On this basis, we make an observation about the separate roles of price transmission in the circumstances with quality and non-quality problems, as shown in Observation 1.

Observation 1. The supply chain cannot transship the profit losses relevant to quality problems to consumers by setting higher retail prices. On the contrary, the profit losses relevant to non-quality problems, such as higher packaging cost, can be transshipped to consumers.

4.2.2. Influences of the declining preservation performance of reusable packages

In the re-usage of reusable packages, their preservation performance undergoes a declining process. As such, we use the number of uses of reusable packages m to analyze the influences of the declining preservation performance of reusable packages in food delivery.

Take the fresh chicken supply chain as an example. A numerical example in real-life operation is given as follows. A fresh chicken supply chain has a potential market size of 500 boxes per day ($v = 500$) and it takes 1 dollar to produce 1 kg fresh chicken ($c = 1$). Consumers are price and quality sensitive, and their sensitivities about price and quality are 2 boxes per dollar ($a = 2$) and 5 boxes per freshness degree ($b = 5$). Fresh chicken at the point of production has the highest freshness level as 10 freshness degrees ($q_0 = 10$). The retailer is located about 1 mile from its consumers ($d_t = 1$). Since its market investigation indicates that the fresh chicken packed in a box having a capacity of 1 kg is the most popular, the retailer chooses the reusable packages whose capacity is 1 kg/box ($k = 1$), and it needs to pay the purchasing cost of 100 dollars ($h = 100$) and the monthly maintenance cost of 10 dollars for each reusable package ($l = 10$). Due to the government's environmental policies, it receives 20% purchasing subsidy ($s = 20\%$). The fresh chicken being packed in reusable packages has an initial quality declining rate as 0.1 freshness degree/mile ($u_r = 0.1$), and in the reusing process of reusable packages, the quality declining rate increases at the rate of 0.005 quality degree per mile per time of use ($\varphi = 0.005$). Using the above dataset, we vary m within the interval of $[5, 100]$ times of uses and plot its influences in scenario 2, as shown in Figure 4.

Figure 4 shows that if the retailer reuses reusable packages for more times, which will cause the decline of the average preservation performance, the retail price will decrease. This finding is also supported by the analytical result that $\frac{\partial p_2^*}{\partial m} = -\frac{3b\varphi d_t}{8a} - \frac{(1-s)h}{4km^2} < 0$. The reason is that with the increase of the number of uses of reusable packages, the preservation performance becomes lower, which causes lower food quality and forces the retailer to reduce the retail price to maintain a stable market demand. In terms of the influences on the wholesale price and profits, it is depicted in Figure 4 that if the retailer reuses reusable packages for more times, the wholesale price and the food supply chain members' profits first increase and then decrease. The reason is that when reusable packages are used less frequently, although the product quality declines, it is still within the acceptable range

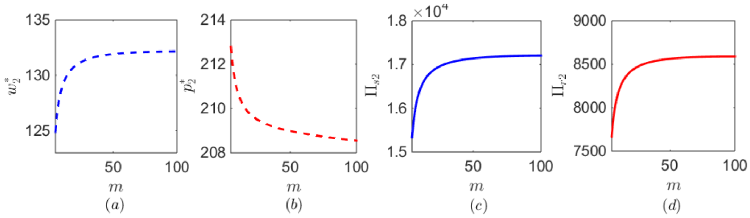

FIGURE 4. Influence of the number of uses of reusable packages in scenario 2. (a) Influence on w_2^*. (b) Influence on p_2^*. (c) Influence on $\prod_{s2}$. (d) Influence on $\prod_{r2}$.

for consumers. As the reusage frequency gradually increases, the product quality will deteriorate, which will lead to a decrease in the wholesale price and profits. It indicates that the retailer does not always have a profit growth if it reuses reusable packages for more times, and the profit of the supplier even declines. In other words, there exists an interval of the number of times within which reusable packages are recommended to be reused. To explore the explicit form of the recommended interval of the number of times, we provide Proposition 2.

Proposition 2. *If* $m > \widetilde{m} = \sqrt{\frac{2(1-s)ah}{kbd_t\varphi}}$, $\frac{\partial w_2^*}{\partial m} < 0$, $\frac{\partial \prod_{s2}}{\partial m} < 0$ *and* $\frac{\partial \prod_{r2}}{\partial m} < 0$*; otherwise,* $\frac{\partial w_2^*}{\partial m} \geq 0$, $\frac{\partial \prod_{s2}}{\partial m} \geq 0$ *and* $\frac{\partial \prod_{r2}}{\partial m} \geq 0$.

The result of Proposition 2 is consistent with that shown in Figure 4. This finding corresponds with that of Levi *et al.* [20] and Wang & Zhao [37], which highlights the trade-off between the two-fold effects of reusing reusable packages for more times, the effect of declining packaging cost and the effect of declining preservation performance. When the effect of declining packaging cost outweighs, we will see an increase; otherwise, a decrease will be observed. Different from Levi *et al.* [20], our research incorporates the influence of the declining preservation performance into the cost-benefit analysis about reusable packages. Based on the packaging choice within the supply chain studied by Wang & Zhao [37], we further study the food delivery to end consumers and assess how the delivery distance affects. In addition, we find that consumers' concern about quality affects the recommended number of uses of reusable packages and thus it is an essential consideration in the food supply chain's usage of reusable packages.

4.2.3. Influences of environmental policies

Next, we will analyze the influences of environmental policies, including the tax rate for disposable packages and subsidy rate for reusable packages.

Proposition 3. *With the increase of the tax rate for disposable packages (or the decrease of the subsidy rate for reusable packages), the retail price in scenario 1 (or scenario 2) increases, and the wholesale price and supply chain members' profits in scenario 1 (or scenario 2) decline.*

Proposition 3 is explained that the increase of the tax rate for disposable packages or the decrease of the subsidy rate for reusable packages will cause the increase of the retailer's operational cost. As such, the retailer raises its retail price, leading to lower market demand. Facing a lower market demand, the supplier cuts down its wholesale price, and thus supply chain members' profit show a declining trend. This finding corresponds with the reality that the government usually adopts the policy of high tax rate or the policy of high subsidy rate to motivate the green transformation of packages.

4.3. Retailer's optimal packaging strategy

The packaging strategy bringing higher profit will be chosen. By comparing the retailer's profits in scenarios 1 and 2, we obtain the retailer's optimal packaging strategy. Using the basic dataset in Section 4.2.2, the

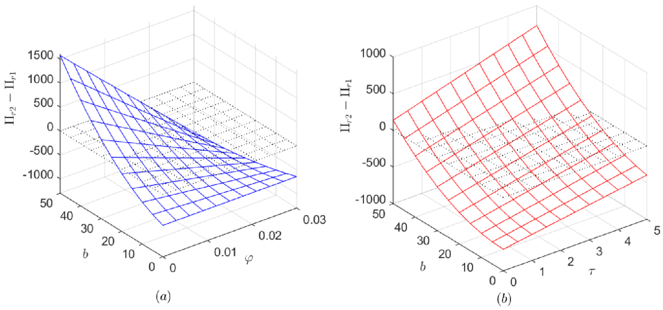

FIGURE 5. Influence of consumers' quality concern on the retailer's optimal packaging strategy. (a) Varying φ. (b) Varying τ.

initial quality declining rate in disposable packages is 1 freshness degree/mile ($u_d = 1$), the number of uses of reusable packages is 50 ($m = 50$) and varying b within the interval of $[0, 50]$ in the cases with different φ and τ, we present numerical results in Figure 5 to reveal the influences of consumers' quality concern.

As shown in Figure 5, with the increase of consumers' quality concern, the retailer's profit difference in scenarios 1 and 2 becomes larger, which affects the retailer's optimal packaging strategy. More precisely, if consumers' quality concern is below a certain threshold, the retailer is recommended to adopt disposable packages; otherwise, reusable packages should be adopted. In addition, the values of φ and τ impose a nonnegligible influences. If φ is low enough, making that $u_d \gg u_r + \varphi\frac{m-1}{2}$, or if τ is large enough, making that $\tau \gg \frac{(1-s)h+ml}{m}$, the retailer is recommended to adopt reusable packages. This is supported by the analytical results that $\sqrt{\prod_{r2} + A} - \sqrt{\prod_{r1}} = \frac{m\tau-((1-s)h+ml)}{mk} + \frac{bd_t}{a}(u_d - (u_r + \varphi\frac{m-1}{2}))$, where $A = \varphi bd_t(m-1)\frac{(1-s)h+ml}{2mk} > 0$. This finding is explained that when the quality of food declines fast in reusable packages (larger φ), the quality of the food at the point of consumption becomes lower, which causes the shrink in market demand. As such, the retailer has to cut down its retail price ($\frac{\partial p_2^*}{\partial \varphi} < 0$), and eventually its profit in scenario 2 becomes lower than that in scenario 1. Unlike the declining rate of preservation performance in reusable packages, the tax rate on the use of disposable packages is not related to the quality problems of the food. If the tax rate on the use of disposable packages increases, meaning that the cost of a disposable package increases, which adds to the retailer's operational cost in scenario 1. Driven by the price transmission, the retailer will transfer the increasing operational cost to downstream consumers. As such, the retailer raises its retail price ($\frac{\partial p_1^*}{\partial \tau} > 0$), which imposes negative influences on market demand, and eventually its profit in scenario 1 becomes lower than that in scenario 2. The above explanation for Figure 5 also corresponds to Observation 1.

In summary, when the quality of food declines slowly or disposable packages are heavily taxed, meaning that reusable packages are gaining advantages over disposable packages, the retailer is more likely to prefer reusable packages. In addition, this finding also corresponds with the reality that the retailer will adopt reusable packages when the government set a higher tax for disposable packages.

5. ONLINE CHANNEL

The supplier makes direct delivery to consumers under the online channel, and it can use disposable packages or rent reusable packages. By solving the profit maximization problems in scenarios 3 and 4, we will derive the supplier's optimal decisions and maximal profits.

Under the online channel, the supplier's profit is its sales revenue minus the procurement cost of food and the cost relevant to packaging. We approximate the number of packages used in the interval of $[0, mT]$ as $n_3 \approx \frac{D_3 mT}{k}$

and then express the supplier's profit per unit time in scenario 3 as follows:

$$\prod_{s3} = \frac{\prod_{s3}^{t}}{mT} = \frac{p_3 D_3 mT - cD_3 mT - \tau n_3}{mT} = \left(p_3 - c - \frac{\tau}{k}\right)[v - ap_3 + b(q_0 - d_o u_d)], \tag{6}$$

where the supplier needs to pay the tax on the use of disposable packages. With the number of packages used in scenario 4 derived as $n_4 \approx \frac{D_4 mT}{k}$, we express the profit of the supplier per unit time in scenario 4 as follows:

$$\begin{aligned}\prod_{s4} &= \frac{\prod_{s4}^{t}}{mT} = \frac{p_4 D_4 mT - cD_4 mT - (1-s)rn_4}{mT} \\ &= \left[p_4 - c - (1-s)\frac{r}{k}\right]\left\{v - ap_4 + b\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\}\end{aligned} \tag{7}$$

where the supplier needs to pay the post-subsidy renting cost of reusable packages.

5.1. Optimal decisions and profits

The optimal solutions and essential conditions under the online channel are presented in Lemma 2 and Condition 2.

Lemma 2. *The optimal retail prices in scenarios 3 and 4 are* $p_3^* = \frac{v}{2a} + \frac{c}{2} + \frac{\tau}{2k} + \frac{b}{2a}(q_0 - d_o u_d)$ *and* $p_4^* = \frac{v}{2a} + \frac{c}{2} + \frac{(1-s)r}{2k} + \frac{b}{2a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right]$. *The supplier's maximal profits are* $\prod_{s3} = \frac{a}{4}\left[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_o u_d)\right]^2$ *and* $\prod_{s4} = \frac{a}{4}\left\{\frac{v}{a} - c - \frac{(1-s)r}{k} + \frac{b}{a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\}^2$.

According to equations (6) and (7), we obtain the first-order and second-order derivatives of the supplier's profits with respect to the selling prices, where the second-order derivatives are less than zero ($\frac{\partial^2 \prod_{s3}}{\partial p_3^2} = -2a < 0$ and $\frac{\partial^2 \prod_{s4}}{\partial p_4^2} = -2a < 0$). Therefore, the supplier's profit has the maximum value. Let the first-order derivatives ($\frac{\partial \prod_{s3}}{\partial p_3}$ and $\frac{\partial \prod_{s4}}{\partial p_4}$) be equal to zero. The optimal retail prices can be derived. Then, by substituting the retail prices into the supplier's profit functions, the maximum profits of the supplier are derived.

Condition 2. Under the online channel, if disposable packages are used, $\tau \le k[\frac{v}{a} + \frac{b}{a}(q_0 - d_o u_d) - c]$ is essential. If reusable packages are used, $\frac{(1-s)r}{k} \le \frac{v}{a} + \frac{b}{a}[q_0 - d_o(u_r + \varphi\frac{m-1}{2})] - c$ should be guaranteed.

5.2. Impact of critical factors

The influences of some critical factors in the scenarios with the online channel, including the basic characteristics of packages, the declining preservation performance of reusable packages and environmental policies will be revealed.

5.2.1. Influences of basic characteristics of packages

Under the online channel, we pay special attention to the initial preservation performance and capacity of packages and analyze their influences in Proposition 4.

Proposition 4. *If the initial preservation performance of packages gets worse, meaning that the initial quality declining rate of food increases, the retail price and the supplier's profit decline. With the increase of the capacity of a reusable package, the retail price declines, and the supplier's profit increases.*

The finding about the initial preservation performance of packages in Proposition 4 is consistent with that in Proposition 1. In addition, the finding about the capacity of a reusable package is explained that if the capacity of a package becomes smaller, the government charges more taxes or provides less subsidies. Thus, the purchasing or maintenance cost of a reusable package increases, meaning that the cost of a package with standard capacity increases. Facing the higher packaging cost, the supplier raises the retail price, and its profit declines.

Based on the above observations, we find that the roles of price transmission in the circumstances with quality and non-quality problems still exist under the online channel. In combination with Section 4.2.1, we conclude that only after a seller has solved its quality problems, its costs associated with non-quality problems can be transshipped to consumers.

5.2.2. Influences of the declining preservation performance of reusable packages

Next, we will analyze the influences of the declining preservation performance of reusable packages. Results are shown in Proposition 5.

Proposition 5. *If reusable packages are reused for more times, the retail price decreases, and the supplier's profit declines.*

According to Proposition 5, if reusable packages are reused for more times, the retail price and the supplier's profit under the online channel decrease, which matches the reality that the food with low quality targets at the low-end market and does not bring a high profit margin. As such, we recommend the supplier to rent reusable packages from a reusable package provider with newer infrastructure so that its food is packed with better preservation conditions and its profit margin becomes higher. Alternatively, the supplier is recommended to purchase and possess reusable packages as the retailer does so that reusing reusable packages for more times may bring the increase in its profit. In this circumstance, it needs to turn to professional reusable packaging operators for the recycling and maintaining services.

5.2.3. Influences of environmental policies

Proposition 6. *With the increase of the tax rate for disposable packages (or the decrease of the subsidy rate for reusable packages), the retail price in scenario 3 (or scenario 4) increases, and the supplier's profit in scenario 3 (or scenario 4) declines.*

It is manifest that the results in Proposition 6 are consistent with those in Proposition 3, and thus its explanation is omitted here. In addition, we find that the policy of high tax rate for using disposable packages or the policy of high subsidy rate for using reusable packages helps to encourage the supplier's usage of reusable package. This is supported by the analytical result that a sufficiently high tax rate (*i.e.*, $\tau > \frac{bkd_o}{a}\left[\varphi\frac{m-1}{2} - (u_d - u_r)\right] + (1-s)r$) is needed to motivate the supplier's usage of reusable packages. It is shown that with the increase of the subsidy rate, the threshold of the tax rate decreases, reflecting the relationship between the recommended tax rate and subsidy rate and indicating the optimal combination of environmental policies under the online channel.

More precisely, if the average quality decline of the food in a reusable package is large enough to offset the difference between the initial quality declining rates of the food in a disposable package and a reusable package, the tax tool is essential and its rate should be sufficiently high. In this case, the increase of consumers' sensitivity to food quality, the capacity of a package along with the supplier's distance from consumers all push up the threshold of the tax rate. On the contrary, if the average increase of the quality declining rate of the food in a reusable package is too slight, meaning that reusable packages have better preservation performance, even if the government doesn't tax the usage of disposable packages, the supplier is willing to adopt reusable packages.

5.3. Supplier's optimal packaging strategy

Next, we will investigate the supplier's optimal packaging strategy under the online channel by comparing the supplier's profits in scenarios 3 and 4. Results are shown in Proposition 7.

Proposition 7. *The influences of b and φ on the supplier's optimal packaging strategy include:*

(i) *In the circumstance where $\varphi < \frac{2(u_d-u_r)}{m-1}$, if $b < \frac{2a((1-s)r-\tau)}{kd_o(2u_d-2u_r-\varphi(m-1))}$, the supplier will use disposable packages; otherwise, it will use reusable packages.*

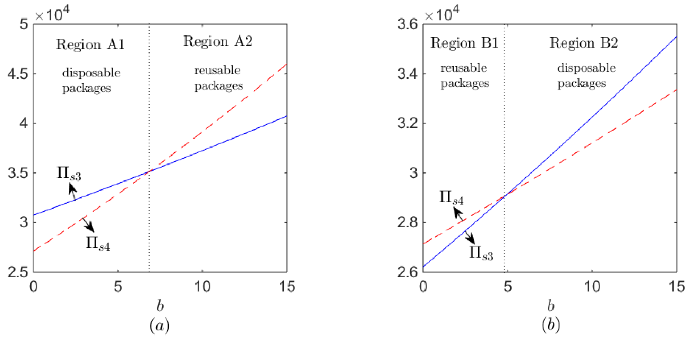

FIGURE 6. Influence of consumers' quality concern on the supplier's optimal packaging strategy. (a) $\varphi = 0.001$, $\tau = 1$. (b) $\varphi = 0.05$, $\tau = 20$.

(ii) *In the circumstance where* $\varphi \geq \frac{2(u_d-u_r)}{m-1}$*, if* $b < \frac{2a(\tau-(1-s)r)}{kd_o(2u_r-2u_d+\varphi(m-1))}$*, the supplier will use reusable packages; otherwise, it will use disposable packages.*

As shown in Proposition 7, consumers' quality concern has an inconsistent influence on the supplier's optimal packaging strategy. More precisely, if the average quality decline of the food in a reusable package is too slight and cannot offset the difference between the initial quality declining rates of the food in a disposable package and a reusable package, the increase in consumers' quality concern will motivate the use of reusable packages; and in other cases, the increase in consumers' quality concern imposes an opposite influence. This is explained that disposable packages gain their advantages over reusable packages if the preservation conditions of reusable packages decline too much over time, which is in line with the explanations in Section 4.3. Since consumers are concerned about food quality, disposable packages may be chosen when they provide better preservation conditions. In the supplier's strategic packaging choice, the price transmission also plays a significant role. When the quality of food declines slowly, the increase in consumers' quality concern further increases the market demand in scenario 4, allowing the supplier to raise its retail price, and eventually the supplier's profit in scenario 4 exceeds that in scenario 3. Thus, the supplier will prefer reusable packages rather than disposable packages in this circumstance.

Using the basic dataset in Section 4.3, considering that the supplier is located about 5 miles from its consumers ($d_o = 5$), the renting cost of a reusable package is 20 dollars ($r = 20$), and varying b within the interval of $[0, 15]$ in the cases with different φ and τ, we plot Figure 6 to reveal how critical factors affect the supplier's optimal packaging strategy.

As shown in Figure 6, the supplier's profit increases with b regardless of the value of φ. In other words, in either circumstance of Proposition 5, the increase in consumers' quality concern brings the supplier more profits. This is explained by the pricing decision of the supplier and the market demand for products. Since $\frac{\partial p_i^*}{\partial b} > 0$ and $\frac{\partial D_i^*}{\partial b} > 0$ $(i = 3, 4)$, consumers' increasing concern about quality will lead to the increase of the retail price and market demand, which is consistent with the market segmentation of "high price and high quality" and "low price and low quality" in reality. Since the supplier's profit is positively related with the retail price and market demand, it shows an increasing trend when consumers concern more about quality.

We also see from Figure 6 that the slope of the curve of $\prod_{s3}$ is gentler than that of $\prod_{s4}$ in the circumstance where $\varphi < \frac{2(u_d-u_r)}{m-1}$, and it becomes steeper than that of $\prod_{s4}$ in the circumstance where $\varphi \geq \frac{2(u_d-u_r)}{m-1}$. The reason lies in the relationship between the average quality decline of the food in a reusable package and the difference between the initial quality declining rates of the food in a disposable package and a reusable package, as aforementioned. In addition, Figure 6 shows that the value of τ affects the thresholds about b. In the circumstance where $\varphi < \frac{2(u_d-u_r)}{m-1}$, meaning that reusable packages always perform better in food preservation. However, the supplier's profit is affected by the cost and the usage number of disposable package and reusable package. Thus, the supplier, for cost reduction reasons, will choose disposable packages or reusable packages alternatively when facing a sufficiently low tax rate for using disposable packages (Regions A1 and A2). While in the circumstance where $\varphi \geq \frac{2(u_d-u_r)}{m-1}$, only if the tax rate for using disposable packages is sufficiently high, the supplier has two packaging alternatives (Regions B1 and B2). Under the circumstance where $\varphi \geq \frac{2(u_d-u_r)}{m-1}$, the declining rate of preservation performance for reusable package is high, which means that product quality will deteriorate over time and lead to the food preservation advantages of disposable packages over reusable packages. With the increasing cost for using disposable packages, the supplier will make their trade-off.

6. Interaction between packaging strategies and distribution channels

In this section, we will discuss packaging strategies and distribution channels of a temperature-sensitive food supply chain and will reveal their interaction by analyzing the influences of supply chain members' distance from consumers.

6.1. Critical thresholds of delivery distances

Since the channel choice greatly affects delivery distances, we pay special attention to the influence of supply chain members' distances from consumers. Under the traditional channel, the retailer's packaging choice affects the market demand as well as the supplier's profits. As such, the supplier needs to consider the retailer's packaging choice before determining its channel. The critical thresholds of d_t satisfying $G(d_t) = \prod_{r2} - \prod_{r1} = 0$ are needed to define the circumstances about the retailer's packaging choice, and they are denoted as $\underline{d_t}$ and $\overline{d_t}$ ($\overline{d_t} > \underline{d_t}$), respectively.

Proposition 8. *If* $d_t \in (0, \max\{\underline{d_t}, 0\}]$ *or* $d_t \in [\max\{0, \overline{d_t}\}, +\infty)$, *the retailer will choose disposable packages; and if* $d_t \in (\max\{\underline{d_t}, 0\}, \max\{0, \overline{d_t}\})$, *the retailer will choose reusable packages.*

The critical threshold of d_o making $F(d_o) = \prod_{s4} - \prod_{s3} = 0$ is needed to define the circumstances about the supplier's packaging choice, and it is denoted as $\overline{\overline{d_o}}$.

Proposition 9. *If* $d_o \in (0, \max\{\overline{\overline{d_o}}, 0\}]$, *the supplier will choose disposable packages; and if* $d_o \in (\max\{\overline{\overline{d_o}}, 0\}, +\infty)$, *the supplier will choose reusable packages.*

By comparing $\prod_{s1}$ and $\prod_{s3}$ and comparing $\prod_{s1}$ and $\prod_{s4}$, we obtain the equations reflecting the relationships between the distances from consumers:

$$d_o = \left(1 - \frac{1}{\sqrt{2}}\right)\frac{a}{bu_d}\left(\frac{v}{a} - c + \frac{b}{a}q_0 - \frac{\tau}{k}\right) + \frac{1}{\sqrt{2}}d_t, \tag{8}$$

$$d_o = \left(1 - \frac{1}{\sqrt{2}}\right)\frac{a}{bu_r}\left(\frac{v}{a} - c + \frac{b}{a}q_0\right) + \left[\frac{\tau}{\sqrt{2}} - (1-s)r\right]\frac{a}{bu_r k} + \frac{u_d}{\sqrt{2}u_r}d_t. \tag{9}$$

By comparing $\prod_{s2}$ and $\prod_{s3}$ and comparing $\prod_{s2}$ and $\prod_{s4}$, we obtain the following functions:

$$d_o = \frac{a}{bu_d}\left(1 - \frac{1}{\sqrt{2}}\right)\left(\frac{v}{a} - c + \frac{b}{a}q_0\right) + \frac{a}{bu_d k}\left[\frac{(1-s)h + ml}{\sqrt{2}m} - \tau\right] + \frac{u_r + \varphi\frac{m-1}{2}}{\sqrt{2}u_d}d_t, \tag{10}$$

$$d_o = \frac{a}{bu_r}\left(1 - \frac{1}{\sqrt{2}}\right)\left(\frac{v}{a} - c + \frac{b}{a}q_0\right) + \frac{a}{bu_r k}\left[\frac{(1-s)h + ml}{\sqrt{2}m} - (1-s)r\right] + \frac{u_r + \varphi\frac{m-1}{2}}{\sqrt{2}u_r}d_t. \tag{11}$$

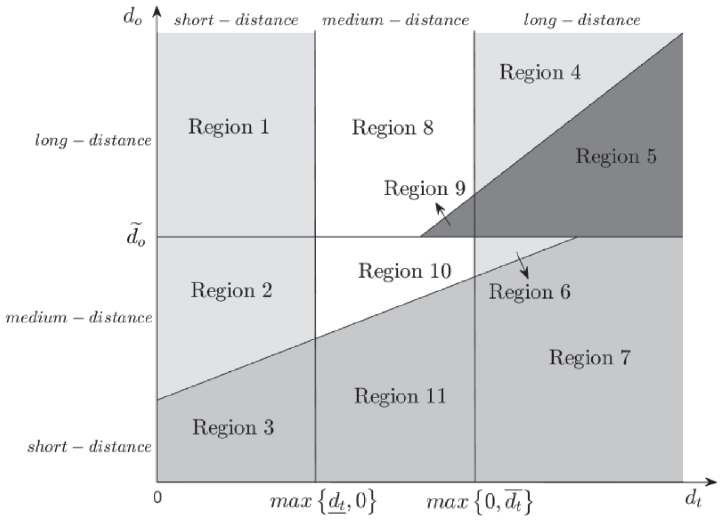

FIGURE 7. Regions divided based on the distances from consumers.

TABLE 2. Regions and their corresponding packaging strategy and distribution channel.

Distribution channel	Packaging strategy	Regions
Traditional channel	Disposable packages	8, 10
	Reusable packages	1, 2, 4, 6
Online channel	Disposable packages	3, 7, 11
	Reusable packages	5, 9

6.2. Influence of delivery distances

Based on Propositions 8 and 9 and equations (9)–(11), we divide regions according to the relationships between the distances from consumers, as shown in Figure 7.

As shown in Table 2, we correspond the regions of Figure 7 with the supplier chain members' packaging strategies and distribution channels.

According to Figure 7 and Table 2, if the supplier is at a long or medium distance from consumers and the retailer is much closer than the supplier, the supplier should retain its traditional channel for distributing products to the retailer, otherwise the supplier needs to establish an online channel. This implies that for areas with high population density where retailers can serve a large number of consumers while are remote for the supplier, it is strongly recommended that the supplier retains the traditional channel, which reduces the cost of long-distance transport directly from the supplier to consumers and improves the overall supply chain's operational efficiency. On the contrary, if the supplier is close to consumers or consumers are located in an area with low population density, then choosing the online channel and shipping directly to consumers brings cost reduction and efficiency improvement to the supplier.

We also find that reusable packages are particularly favoured where the supplier is at a long or medium distance from consumers and the retailer is at a long or short distance from consumers. Reusable packages are also preferred when the retailer is at a medium distance from consumers and meanwhile much closer than the supplier. This is explained by the fact that reusable packages help to improve the preservation conditions for medium and long distance transport and ensure a greater extent of the safety and hygiene of the food product, which in turn enhances the consumers' willingness to buy. In addition, under the above distance conditions, the profit of the overall supply chain is greater compared to the scenarios with disposable packages due to the multiple-use and environmentally friendly nature of reusable packages and the implementation of environmental policies. Based on the above study, we conclude that the geographical concentration of the food production or processing industry, convenient long-distance logistics system and consumers' high concern for quality will promote the widespread use of reusable packages.

7. Conclusions

With the boom of food delivery and the emergency of different distribution channels, temperature-sensitive food sellers need to think about which sort of packages to choose. Under different distribution channels, delivery distances impose different influences on food preservation and thus they affect sellers' packaging choices. Considering the interaction between packaging strategies and distribution channels, we model a single-supplier—single-retailer temperature-sensitive food supply chain and study its decision-making. The important results can be presented as follows.

7.1. Main results

By analyzing the influences of some critical factors, we reveal the separate roles of price transmission in the circumstances with quality and non-quality problems. More precisely, the supply chain cannot transship the profit losses relevant to quality problems to consumers by setting higher retail prices; on the contrary, the profit losses relevant to non-quality problems, such as higher packaging cost, can be transshipped to consumers. It is also noteworthy that reusing reusable packages for more times does not always benefit supply chain members, which is explained by the two-fold effects of reusing reusable packages for more times, the effect of declining packaging cost and the effect of declining preservation performance. In addition, the finding regarding environmental policies corresponds with the reality that the government usually adopts the policy of high tax rate for disposable packages or the policy of high subsidy rate for reusable packages to motivate the green transformation of packages.

To derive the optimal packaging choice for supply chain members, we compare the profits in different scenarios and find that if consumers' quality concern is below a certain threshold, the retailer is recommended to adopt disposable packages; otherwise, reusable packages should be adopted. This is explained that disposable packages gain their advantages over reusable packages if the preservation conditions of reusable packages decline too much over time. Since consumers are concerned about food quality, disposable packages may be chosen when they provide better preservation conditions. Moreover, it is shown that when the quality of food declines slowly or disposable packages are heavily taxed, meaning that reusable packages are gaining their advantages over disposable packages, the retailer is more likely to prefer reusable packages.

In addition to packaging strategies, our research provides some insights into the supplier's distribution channel and identifies the significant influences of the distance from consumers. For a remote region with high population density where a retailer can serve a large number of consumers in their area, the supplier is highly recommended to keep its traditional channel. On the contrary, if the supplier is close to consumers or consumers are located in the region with low population density, the supplier should establish an online channel. By analyzing the interactions between the packaging strategies and distribution channels of the food supply chain, we conclude that the geographic concentrations of food producing or processing industries, a more convenient long-distance logistics system and consumers' high quality-concern will push forward the wide use of reusable packages and the establishment of online channels.

7.2. Managerial insights

Our research provides some managerial insights for supply chain members and the government. For supply chain members, we recommend that:

(1) When supply chain members adopt reusable packages, they should raise consumers' awareness of environmental protection *via* public education programmes, such as promoting the positive effects of reusable packages on environmental protection, to enhance consumers' acceptance of the increased cost of reusable packages.
(2) Due to the two-fold effect of reusable packages, supply chain members need to pay attention to its re-usage frequency and cost over time to avoid the impact of quality degradation on consumer purchasing behavior.

Specifically, for the suppliers, we recommend that:

(1) Suppliers need to consider the geographical concentration level of product distribution areas when making decisions on distribution channels and packaging strategies. When the distribution areas are relatively scattered, *i.e.*, their geographical concentration is low, suppliers should sell products through online e-commerce platforms.
(2) Suppliers could maintain the advantage of online sales by improving their long-distance logistics system. Due to the long delivery distance of online sales products, to avoid a decrease in product quality during transportation, suppliers need to improve the delivery speed of their logistics system.

In terms of the government, we recommend that:

(1) To motivate supply chain members' choice of reusable packages, the government needs to design appropriate tax and subsidy policies.
(2) The government needs to help supply chains in fulfilling their environmental education role for consumers. More precisely, it can increase consumer awareness of environmental protection by setting up environmental protection publicity days or organizing advertising activities.

7.3. Limitations and future research

Several extensions of the model can be envisaged. Future research may relax the assumptions to allow less-than-truckload deliveries and the retailer's payment by installments. In addition, the perspective of social welfare maximization may be included to optimize the tax rate and subsidy rate for the government. Finally, the reusable packaging recycling systems and the corresponding costs can be considered.

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Conflicts of interest

The authors report there are no competing interests to declare.

Data availability statement

The data that supports the findings of this study are available in the main content of this paper.

References

[1] R. Accorsi, S. Cholette, R. Manzini and L. Mucci, Managing uncertain inventories, washing, and transportation of reusable containers in food retailer supply chains. *Sustain. Prod. Consum.* **31** (2022) 331–345.
[2] S.S. Ali, H. Barman, R. Kaur, H. Tomaskova and S.K. Roy, Multi-product multi echelon measurements of perishable supply chain: Fuzzy non-linear programming approach. *Mathematics* **9** (2021) 2093.

[3] B. Atamer, İ.S. Bakal and Z.P. Bayındır, Optimal pricing and production decisions in utilizing reusable containers. *Int. J. Prod. Econ.* **143** (2013) 222–232.

[4] H. Barman, M. Pervin and S.K. Roy, Impacts of green and preservation technology investments on a sustainable epq model during covid-19 pandemic. *RAIRO-Oper. Res.* **56** (2022) 2245–2275.

[5] H. Barman, M. Pervin, S.K. Roy and G.-W. Weber, Analysis of a dual-channel green supply chain game-theoretical model under carbon policy. *Int. J. Syst. Sci. Oper. Logistics* **10** (2023) 2242770.

[6] H. Barman, S.K. Roy, L. Sakalauskas and G.-W. Weber, Inventory model involving reworking of faulty products with three carbon policies under neutrosophic environment. *Adv. Eng. Inf.* **57** (2023) 102081.

[7] S. Bhunia, S.K. Das, J. Jablonsky and S.K. Roy, Evaluating carbon cap and trade policy effects on a multi-period bi-objective closed-loop supply chain in retail management under mixed uncertainty: towards greener horizons. *Expert Syst. App.* **250** (2024) 123889.

[8] J. Blackburn and G. Scudder, Supply chain strategies for perishable products: the case of fresh produce. *Prod. Oper. Manage.* **18** (2009) 129–137.

[9] Y.-J. Cai and C.K.Y. Lo, Omni-channel management in the new retailing era: a systematic review and future research agenda. *Int. J. Prod. Econ.* **229** (2020) 107729.

[10] L. Camps-Posino, L. Batlle-Bayer, A. Bala, G. Song, H. Qian, R. Aldaco, R. Xifré and P. Fullana-i Palmer, Potential climate benefits of reusable packaging in food delivery services. A Chinese case study. *Sci. Total Environ.* **794** (2021) 148570.

[11] B. Choi, S. Yoo, K.-D. Lee and S.-I. Park, An environmental impact comparison of disposable wood pallets and reusable steel cradles: a case study on rolled steel coils in container shipping in South Korea. *Int. J. Sustain. Transp.* **14** (2020) 335–342.

[12] S.K. Dey and B.C. Giri, Corporate social responsibility in a closed-loop supply chain with dual-channel waste recycling. *Int. J. Syst. Sci. Oper. Logistics* **10** (2023) 2005844.

[13] S. Dhanorkar, Environmental benefits of internet-enabled C2C closed-loop supply chains: a quasi-experimental study of craigslist. *Manage. Sci.* **65** (2018) 660–680.

[14] L. Feng, K. Govindan and C. Li, Strategic planning: design and coordination for dual-recycling channel reverse supply chain considering consumer behavior. *Eur. J. Oper. Res.* **260** (2017) 601–612.

[15] C.H. Glock, Decision support models for managing returnable transport items in supply chains: a systematic literature review. *Int. J. Prod. Econ.* **183** (2017) 561–569.

[16] T.N. Goh and N. Varaprasad, A statistical methodology for the analysis of the life-cycle of reusable containers. *IIE Trans.* **18** (1986) 42–47.

[17] B. Gong, H. Zhang, Y. Gao and Z. Liu, Blockchain adoption and channel selection strategies in a competitive remanufacturing supply chain. *Comput. Ind. Eng.* **175** (2023) 108829.

[18] M. Hariga, C.H. Glock and T. Kim, Integrated product and container inventory model for a single-vendor single-buyer supply chain with owned and rented returnable transport items. *Int. J. Prod. Res.* **54** (2016) 1964–1979.

[19] B. Khorshidvand, H. Soleimani, S. Sibdari and M.M.S. Esfahani, Revenue management in a multi-level multi-channel supply chain considering pricing, greening, and advertising decisions. *J. Retail. Cons. Serv.* **59** (2021) 102425.

[20] M. Levi, S. Cortesi, C. Vezzoli and G. Salvia, A comparative life cycle assessment of disposable and reusable packaging for the distribution of italian fruit and vegetables. *Packaging Technol. Sci.* **24** (2011) 387–400.

[21] M. Mahmoudi and I. Parviziomran, Reusable packaging in supply chains: a review of environmental and economic impacts, logistics system designs, and operations management. *Int. J. Prod. Econ.* **228** (2020) 107730.

[22] T. Maiti and B.C. Giri, A closed loop supply chain under retail price and product quality dependent demand. *J. Manuf. Syst.* **37** (2015) 624–637.

[23] B. McPherson, M. Sharip and T. Grimmond, The impact on life cycle carbon footprint of converting from disposable to reusable sharps containers in a large us hospital geographically distant from manufacturing and processing facilities. *PeerJ* **7** (2019) e6204.

[24] P. Menesatti, E. Canali, G. Sperandio, G. Burchi, G. Devlin and C. Costa, Cost and waste comparison of reusable and disposable shipping containers for cut flowers. *Packaging Technol. Sci.* **25** (2012) 203–215.

[25] A. Mondal and S.K. Roy, Multi-objective sustainable opened-and closed-loop supply chain under mixed uncertainty during covid-19 pandemic situation. *Comput. Ind. Eng.* **159** (2021) 107453.

[26] A. Mondal, B.K. Giri, S.K. Roy, M. Deveci and D. Pamucar, Sustainable-resilient-responsive supply chain with demand prediction: an interval type-2 robust programming approach. *Eng. App. Artif. Intell.* **133** (2024) 108133.

[27] J.L. Nicolau, K.A. Stadlthanner, L. Andreu and X. Font, Explaining the willingness of consumers to bring their own reusable coffee cups under the condition of monetary incentives. *J. Retail. Consum. Serv.* **66** (2022) 102908.

[28] A. Paul, M. Pervin, S.K. Roy, G.-W. Weber and A. Mirzazadeh, Effect of price-sensitive demand and default risk on optimal credit period and cycle time for a deteriorating inventory model. *RAIRO-Oper. Res.* **55** (2021) S2575–S2592.

[29] J. Peng, J. Zhang, T. Nie, Y. Zhu and S. Du, Pricing and package size decisions in crowdfunding. *Transp. Res. Part E: Logistics Transp. Rev.* **143** (2020) 102091.

[30] M. Saha and R.N. Giri, Consumers' purchasing decisions of a dual-channel supply chain system under return and warranty policies. *Int. J. Syst. Sci. Oper. Logistics* **10** (2023) 2173990.

[31] A. Sarkar and B. Pal, Pricing and service strategies in a dual-channel supply chain under return–refund policy. *Int. J. Syst. Sci. Oper. Logistics* **9** (2022) 281–301.

[32] B. Sarkar, M. Tayyab, N. Kim and M.S. Habib, Optimal production delivery policies for supplier and manufacturer in a constrained closed-loop supply chain for returnable transport packaging through metaheuristic approach. *Comput. Ind. Eng.* **135** (2019) 987–1003.

[33] H. Song, J. Zhang and J. Li, The impacts of subsidy strategies and recycling modes on the closed-loop supply chain. *Manage. Decis. Econ.* **43** (2022) 4106–4123.

[34] M. Soysal, Closed-loop inventory routing problem for returnable transport items. *Transp. Res. Part D Transp. Environ.* **48** (2016) 31–45.

[35] M. Soysal, Ç. Koç, M. Çimen and M. İbiş, Managing returnable transport items in a vendor managed inventory system. *Soc.-Econ. Planning Sci.* **86** (2022) 101504.

[36] A.A. Taleizadeh and R. Sadeghi, Pricing strategies in the competitive reverse supply chains with traditional and e-channels: a game theoretic approach. *Int. J. Prod. Econ.* **215** (2019) 48–60.

[37] M. Wang and L. Zhao, Disposable or reusable? Packaging strategy and pricing decision for fresh food considering environmental policies. *Int. Trans. Oper. Res.* **31** (2024) 1149–1177.

[38] W. Wang, S. Yang, L. Xu and X. Yang, Carrot/stick mechanisms for collection responsibility sharing in multi-tier closed-loop supply chain management. *Transp. Res. Part E Logistics Transp. Rev.* **125** (2019) 366–387.

[39] Y. Yan, R. Zhao and Z. Liu, Strategic introduction of the marketplace channel under spillovers from online to offline sales. *Eur. J. Oper. Res.* **267** (2018) 65–77.

[40] M. Yu and A. Nagurney, Competitive food supply chain networks with application to fresh produce. *Eur. J. Oper. Res.* **224** (2013) 273–282.

[41] T. Zhang, X. Feng and N. Wang, Manufacturer encroachment and product assortment under vertical differentiation. *Eur. J. Oper. Res.* **293** (2021) 120–132.

[42] Y. Zhang, A. Che and F. Chu, Improved model and efficient method for bi-objective closed-loop food supply chain problem with returnable transport items. *Int. J. Prod. Res.* **60** (2022) 1051–1068.

[43] B. Zhu, B. Wen, S. Ji and R. Qiu, Coordinating a dual-channel supply chain with conditional value-at-risk under uncertainties of yield and demand. *Comput. Ind. Eng.* **139** (2020) 106181.

[44] Z. Zhu, W. Liu, S. Ye and L. Batista, Packaging design for the circular economy: a systematic review. *Sustain. Prod. Consum.* **32** (2022) 817–832.

Appendix A.

A.1. Proof of Lemma 1 and Condition 1

Using backward induction, we first obtain the reaction function by maximizing the retailer's profit in scenario 1. According to equation (4), $\frac{\partial \prod_{r1}}{\partial p_1} = v - 2ap_1 + b(q_0 - d_t u_d) + aw_1 + \frac{a\tau}{k}$ and $\frac{\partial^2 \prod_{r1}}{\partial {p_1}^2} = -2a < 0$. With $\frac{\partial^2 \prod_{r1}}{\partial {p_1}^2} < 0$, the relationship between the optimal wholesale price and the optimal retail price is derived by equating $\frac{\partial \prod_{r1}}{\partial p_1}$ with zero:

$$p_1^* = \frac{w_1^*}{2} + \frac{v}{2a} + \frac{b}{2a}(q_0 - d_t u_d) + \frac{\tau}{2k}\cdot \tag{A.1}$$

By plugging equation (A.1) into equation (2), we obtain:

$$\prod\nolimits_{s1} = (w_1 - c)\left[\frac{v}{2} - \frac{aw_1}{2} + \frac{b}{2}(q_0 - d_t u_d) - \frac{a\tau}{2k}\right]\cdot \tag{A.2}$$

According to equation (A.2), $\frac{\partial \prod_{s1}}{\partial w_1} = \frac{v}{2} - aw_1 + \frac{b}{2}(q_0 - d_t u_d) - \frac{a\tau}{2k} + \frac{ac}{2}$ and $\frac{\partial^2 \prod_{s1}}{\partial {w_1}^2} = -a < 0$. With $\frac{\partial^2 \prod_{s1}}{\partial {w_1}^2} < 0$, the optimal wholesale price is derived by equating $\frac{\partial \prod_{s1}}{\partial w_1}$ with zero:

$$w_1^* = \frac{v}{2a} + \frac{b}{2a}(q_0 - d_t u_d) - \frac{\tau}{2k} + \frac{c}{2}\cdot \tag{A.3}$$

By plugging equation (A.3) into equation (A.1), equations (2) and (4), we obtain:

$$p_1^* = \frac{3v}{4a} + \frac{3b}{4a}(q_0 - d_t u_d) + \frac{\tau}{4k} + \frac{c}{4} \tag{A.4}$$

$$\prod\nolimits_{s1} = \frac{a}{8}\left[\frac{v}{a} + \frac{b}{a}(q_0 - d_t u_d) - \frac{\tau}{k} - c\right]^2 \tag{A.5}$$

$$\prod\nolimits_{r1} = \frac{a}{16}\left[\frac{v}{a} + \frac{b}{a}(q_0 - d_t u_d) - \frac{\tau}{k} - c\right]^2. \tag{A.6}$$

According to the constraints in equation (6), the condition

$$\frac{k}{3}\left[c - \frac{v}{a} - \frac{b}{a}(q_0 - d_t u_d)\right] \le \tau \le k\left[\frac{v}{a} + \frac{b}{a}(q_0 - d_t u_d) - c\right]$$

is needed to guarantee the non-negativity of prices, profit margins and market demand. According to equation (5),

$$\frac{\partial \prod_{r2}}{\partial p_2} = v - 2ap_2 + b\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] + aw_2 + a\frac{(1-s)h + ml}{mk}$$

and $\frac{\partial^2 \prod_{r2}}{\partial {p_2}^2} = -2a < 0$. With $\frac{\partial^2 \prod_{r2}}{\partial {p_2}^2} < 0$, the relationship between the optimal wholesale price and the optimal retail price is derived by equating $\frac{\partial \prod_{r2}}{\partial p_2}$ with zero:

$$p_2^* = \frac{w_2^*}{2} + \frac{v}{2a} + \frac{b}{2a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] + \frac{(1-s)h + ml}{2mk}\cdot \tag{A.7}$$

By plugging equation (A.7) into equation (3), we obtain:

$$\prod\nolimits_{s2} = (w_2 - c)\left\{\frac{v}{2} - \frac{aw_2}{2} + \frac{b}{2}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - a\frac{(1-s)h + ml}{2mk}\right\}\cdot \tag{A.8}$$

According to equation (A.8),

$$\frac{\partial\prod_{s2}}{\partial w_2} = \frac{v}{2} - aw_2 + \frac{b}{2}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - a\frac{(1-s)h+ml}{2mk} + \frac{ac}{2}$$

and $\frac{\partial^2\prod_{s2}}{\partial {w_2}^2} = -a < 0$. With $\frac{\partial^2\prod_{s2}}{\partial {w_2}^2} < 0$, the optimal wholesale price is derived by equating $\frac{\partial\prod_{s2}}{\partial w_2}$ with zero:

$$w_2^* = \frac{v}{2a} + \frac{b}{2a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{2mk} + \frac{c}{2}\cdot \tag{A.9}$$

By plugging equation (A.3) into equations (A.1), (3) and (5), we obtain:

$$p_2^* = \frac{3v}{4a} + \frac{3b}{4a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] + \frac{(1-s)h+ml}{4mk} + \frac{c}{4} \tag{A.10}$$

$$\prod_{s2} = \frac{a}{8}\left\{\frac{v}{a} + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk} - c\right\}^2 \tag{A.11}$$

$$\prod_{r2} = \frac{a}{16}\left\{\frac{v}{a} + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk} - c\right\}^2 - \frac{bd_t\varphi(m-1)[(1-s)h+ml]}{2mk}\cdot \tag{A.12}$$

According to Lemma 1 and Section 4.1, the conditions

$$\frac{(1-s)h+ml}{mk} \le \frac{v}{a} + \frac{b}{a}\left[q_0 - d_t\left(u_r - 7\varphi\frac{m-1}{2}\right)\right] - c - \sqrt{\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r - 3\varphi\frac{m-1}{2}\right)\right]\right\}\frac{8\varphi bd_t}{a}(m-1)}$$

and

$$3\left\{c - \frac{v}{a} - \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\} \le \frac{(1-s)h+ml}{mk} \le \frac{v}{a} + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - c$$

are needed to guarantee the non-negativity of prices, profit margins, market demand and profits.

A.2. Proof of Proposition 1

$\frac{\partial w_1^*}{\partial u_d} = -\frac{bd_t}{2a} < 0$, $\frac{\partial w_2^*}{\partial u_r} = -\frac{bd_t}{2a} < 0$, $\frac{\partial w_2^*}{\partial h} = -\frac{1-s}{2mk} < 0$, $\frac{\partial w_2^*}{\partial l} = -\frac{1}{2k} < 0$, $\frac{\partial p_1^*}{\partial u_d} = -\frac{3bd_t}{4a} < 0$, $\frac{\partial p_2^*}{\partial u_r} = -\frac{3bd_t}{4a} < 0$, $\frac{\partial p_2^*}{\partial h} = \frac{1-s}{4mk} > 0$, $\frac{\partial p_2^*}{\partial l} = \frac{1}{4k} > 0$

$$\frac{\partial\prod_{s1}}{\partial u_d} = 2\frac{\partial\prod_{r1}}{\partial u_d} = -\frac{bd_t}{4}\left[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_t u_d)\right] = -\frac{bd_t}{a}D_1 < 0$$

$$\frac{\partial\prod_{s2}}{\partial u_r} = -\frac{bd_t}{4}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\} = -\frac{bd_t}{a}D_2 < 0$$

$$\frac{\partial\prod_{s2}}{\partial h} = -\frac{a(1-s)}{4mk}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\} = -\frac{(1-s)}{mk}D_2 < 0$$

$$\frac{\partial\prod_{s2}}{\partial l} = -\frac{a}{4k}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\} = -\frac{1}{k}D_2 < 0$$

$$\frac{\partial\prod_{r2}}{\partial u_r} = -\frac{bd_t}{8}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_r\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\} = -\frac{bd_t}{2a}D_2 < 0$$

$$\frac{\partial\prod_{r2}}{\partial h} = -\frac{a(1-s)}{8mk}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\} - \frac{\varphi bd_t(m-1)(1-s)}{2mk}$$
$$= -\frac{(1-s)[D_2 + \varphi bd_t(m-1)]}{2mk} < 0$$
$$\frac{\partial\prod_{r2}}{\partial l} = -\frac{a}{8k}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\} - \frac{\varphi bd_t(m-1)}{2k}$$
$$= -\frac{1}{2k}[D_2 + \varphi bd_t(m-1)] < 0.$$

A.3. Proof of Proposition 2

$$\frac{\partial w_2^*}{\partial m} = -\frac{bd_t\varphi}{4a} + \frac{(1-s)h}{2m^2k}$$
$$\frac{\partial\prod_{s2}}{\partial m} = \frac{a}{2}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\}\left[-\frac{bd_t\varphi}{4a} + \frac{(1-s)h}{2m^2k}\right] = 2D_2\frac{\partial w_2^*}{\partial m}$$

and

$$\frac{\partial\prod_{r2}}{\partial m} = \frac{a}{8}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\}\left[-\frac{bd_t\varphi}{2a} + \frac{(1-s)h}{m^2k}\right]$$
$$- \frac{bd_t\varphi\left[(1-s)h + lm^2\right]}{2km^2} = \frac{1}{2}\frac{\partial\prod_{s2}}{\partial m} - \frac{bd_t\varphi\left[(1-s)h + lm^2\right]}{2km^2}.$$

As such, if $m > \widetilde{m} = \sqrt{\frac{2(1-s)ah}{kbd_r\varphi}}$, $\frac{\partial w_2^*}{\partial m} < 0$, $\frac{\partial\prod_{s2}}{\partial m} < 0$ and $\frac{\partial\prod_{r2}}{\partial m} < 0$; otherwise, $\frac{\partial w_2^*}{\partial m} \geq 0$, $\frac{\partial\prod_{s2}}{\partial m} \geq 0$ and $\frac{\partial\prod_{r2}}{\partial m} \geq 0$.

A.4. Proof of Proposition 3

$\frac{\partial w_1^*}{\partial \tau} = -\frac{1}{2k} < 0$; $\frac{\partial w_2^*}{\partial s} = \frac{h}{2mk} > 0$. $\frac{\partial p_1^*}{\partial \tau} = \frac{1}{4k} > 0$; $\frac{\partial p_2^*}{\partial s} = -\frac{h}{4mk} < 0$.

$$\frac{\partial\prod_{s1}}{\partial \tau} = 2\frac{\partial\prod_{r1}}{\partial \tau} = -\frac{a}{4k}\left[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_tu_d)\right] = -\frac{1}{k}D_1 < 0$$
$$\frac{\partial\prod_{s2}}{\partial s} = \frac{ah}{4mk}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\} = \frac{h}{mk}D_2 > 0$$
$$\frac{\partial\prod_{r2}}{\partial s} = \frac{ah}{8mk}\left\{\frac{v}{a} - c + \frac{b}{a}\left[q_0 - d_t\left(u_r + \varphi\frac{m-1}{2}\right)\right] - \frac{(1-s)h+ml}{mk}\right\}$$
$$+ \frac{h\varphi bd_t(m-1)}{2mk} = \frac{h[D_2 + \varphi bd_t(m-1)]}{2mk} > 0.$$

A.5. Proof of Lemma 2 and Condition 2

According to equation (6), $\frac{\partial\prod_{s3}}{\partial p_3} = v - 2ap_3 + b(q_0 - d_ou_d) + ac + \frac{a\tau}{k}$ and $\frac{\partial^2\prod_{s3}}{\partial {p_3}^2} = -2a < 0$. With $\frac{\partial^2\prod_{s3}}{\partial {p_3}^2} < 0$, the optimal retail price is derived by equating $\frac{\partial\prod_{s3}}{\partial p_3}$ with zero:

$$p_3^* = \frac{v}{2a} + \frac{b}{2a}(q_0 - d_ou_d) + \frac{c}{2} + \frac{\tau}{2k}. \tag{A.13}$$

By plugging equation (A.13) into equation (6), we obtain:

$$\prod_{s3} = \frac{a}{4}\left[\frac{v}{a} + \frac{b}{a}(q_0 - d_ou_d) - c - \frac{\tau}{k}\right]^2. \tag{A.14}$$

According to Lemma 2 and Section 4.1, the condition $\tau \leq k[\frac{v}{a} + \frac{b}{a}(q_0 - d_o u_d) - c]$ is needed to guarantee the non-negativity of the retail price, profit margin, market demand and profit. According to equation (7),

$$\frac{\partial \prod_{s4}}{\partial p_4} = v - 2ap_4 + b\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right] + ac + \frac{a(1-s)r}{k}$$

and $\frac{\partial^2 \prod_{s4}}{\partial {p_4}^2} = -2a < 0$. With $\frac{\partial^2 \prod_{s4}}{\partial {p_4}^2} < 0$, the optimal retail price is derived by equating $\frac{\partial \prod_{s4}}{\partial p_4}$ with zero:

$$p_4^* = \frac{v}{2a} + \frac{b}{2a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right] + \frac{c}{2} + \frac{(1-s)r}{2k}. \tag{A.15}$$

By plugging equation (A.15) into equation (7), we obtain:

$$\prod\nolimits_{s4} = \frac{a}{4}\left\{\frac{v}{a} + \frac{b}{a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right] - c - \frac{(1-s)r}{k}\right\}^2. \tag{A.16}$$

According to equations (A.15) and (A.16), the condition

$$\frac{(1-s)r}{k} \leq \frac{v}{a} + \frac{b}{a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right] - c$$

is needed to guarantee the non-negativity of the retail price, profit margin, market demand and profit.

A.6. Proof of Proposition 4

$\frac{\partial p_3^*}{\partial u_d} = -\frac{bd_o}{2a} < 0$, $\frac{\partial p_3^*}{\partial k} = -\frac{\tau}{2k^2} < 0$. $\frac{\partial p_4^*}{\partial u_r} = -\frac{bd_o}{2a} < 0$, $\frac{\partial p_4^*}{\partial k} = -\frac{(1-s)r}{2k^2} < 0$.

$$\frac{\partial \prod_{s3}}{\partial u_d} = -\frac{bd_o}{2}\left[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_o u_d)\right] = -\frac{2bd_o}{a}D_3 < 0$$

$$\frac{\partial \prod_{s3}}{\partial k} = \frac{a\tau}{2k^2}\left[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_o u_d)\right] = \frac{2\tau D_3}{k^2} > 0$$

$$\frac{\partial \prod_{s4}}{\partial u_r} = -\frac{bd_o}{2}\left\{\frac{v}{a} - c - \frac{(1-s)r}{k} + \frac{b}{a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\} = -\frac{2bd_o D_4}{a} < 0$$

$$\frac{\partial \prod_{s4}}{\partial k} = \frac{a(1-s)r}{2k^2}\left\{\frac{v}{a} - c - \frac{(1-s)r}{k} + \frac{b}{a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\} = \frac{2D_4(1-s)r}{k^2} > 0.$$

A.7. Proof of Proposition 5

$$\frac{\partial p_4^*}{\partial m} = -\frac{b\varphi d_o}{4a} < 0$$

$$\frac{\partial \prod_{s4}}{\partial m} = -\frac{bd_o\varphi}{4}\left\{\frac{v}{a} - c - \frac{(1-s)r}{k} + \frac{b}{a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\} = -\frac{bd_o\varphi}{4a}D_4 < 0.$$

A.8. Proof of Proposition 6

$\frac{\partial p_3^*}{\partial \tau} = \frac{1}{2k} > 0$; $\frac{\partial p_4^*}{\partial s} = -\frac{r}{2k} < 0$.

$$\frac{\partial \prod_{s3}}{\partial \tau} = -\frac{a}{2k}\left[\frac{v}{a} - c - \frac{\tau}{k} + \frac{b}{a}(q_0 - d_o u_d)\right] = -\frac{2D_3}{k} < 0$$

$$\frac{\partial \prod_{s4}}{\partial s} = \frac{ar}{2k}\left\{\frac{v}{a} - c - \frac{(1-s)r}{k} + \frac{b}{a}\left[q_0 - d_o\left(u_r + \varphi\frac{m-1}{2}\right)\right]\right\} = \frac{2rD_4}{k} > 0.$$

A.9. Proof of Proposition 7

According to Lemma 2, we obtain:

$$\prod_{s4}-\prod_{s3}=\frac{a}{4}\left(\frac{2v}{a}-2c-\frac{\tau}{k}-\frac{(1-s)r}{k}+\frac{b}{a}\left[q_0-d_o\left(u_r+\varphi\frac{m-1}{2}\right)\right]+\frac{b}{a}(q_0-d_ou_d)\right)$$
$$\left\{\frac{\tau}{k}-\frac{(1-s)r}{k}+\frac{bd_o}{a}\left[u_d-\left(u_r+\varphi\frac{m-1}{2}\right)\right]\right\}=\frac{4(D_3+D_4)}{a}\left\{\frac{\tau}{k}-\frac{(1-s)r}{k}+\frac{bd_o}{a}\left[u_d-\left(u_r+\varphi\frac{m-1}{2}\right)\right]\right\}.$$

As such, in the circumstance where $\varphi<\frac{2(u_d-u_r)}{m-1}$, if $b<\frac{2a((1-s)r-\tau)}{kd_o(2u_d-2u_r-\varphi(m-1))}$, $\prod_{s4}<\prod_{s3}$ and in the circumstance where $\varphi\geq\frac{2(u_d-u_r)}{m-1}$, if $b<\frac{2a(\tau-(1-s)r)}{kd_o(2u_r-2u_d+\varphi(m-1))}$, $\prod_{s4}>\prod_{s3}$.

A.10. Proof of Proposition 8

According to Lemma 1, we obtain:

$$\begin{aligned}\prod_{r2}-\prod_{r1}&=\frac{b^2}{16a}\left[\left(u_r+\varphi\frac{m-1}{2}\right)^2-{u_d}^2\right]{d_t}^2\\&\quad+\frac{b}{8}\left\{\begin{array}{l}\left(\frac{v}{a}-c-\frac{\tau}{k}+\frac{b}{a}q_0\right)u_d-\left(u_r+\varphi\frac{m-1}{2}\right)\left(\frac{v}{a}-c+\frac{b}{a}q_0\right)\\+\left[u_r-\varphi\frac{7(m-1)}{2}\right]\frac{(1-s)h+ml}{mk}\end{array}\right\}d_t\\&\quad+\frac{a}{16}\left[\frac{2v}{a}-2c+\frac{2b}{a}q_0-\frac{(1-s)h+ml}{mk}-\frac{\tau}{k}\right]\left[\frac{\tau}{k}-\frac{(1-s)h+ml}{mk}\right]\\&=A_2{d_t}^2+B_2d_t+C_2.\end{aligned}$$

On this basis, we obtain that $\underline{d_t}=\frac{-B_2-\sqrt{{B_2}^2-4A_2C_2}}{2A_2}$ and $\overline{d_t}=\frac{-B_2+\sqrt{{B_2}^2-4A_2C_2}}{2A_2}$. Since $u_r\ll u_d$, we assume $(u_r+\varphi\frac{m-1}{2})-u_d<0$, that is $A_2<0$. We infer that if $d_t\in(-\infty,\underline{d_t}]$ or $d_t\in[\overline{d_t},+\infty)$, $\prod_{r2}\leq\prod_{r1}$; and if $d_t\in(\underline{d_t},\overline{d_t})$, $\prod_{r2}>\prod_{r1}$. Considering the constraint that $d_t>0$, we conclude that if $d_t\in(0,\max\{\underline{d_t},0\}]$ or $d_t\in[\max\{0,\overline{d_t}\},+\infty)$, the retailer will choose disposable packages; and if $d_t\in(\max\{\underline{d_t},0\},\max\{0,\overline{d_t}\})$, the retailer will choose reusable packages.

A.11. Proof of Proposition 9

According to Lemma 2, we obtain:

$$\prod_{s4}-\prod_{s3}=\frac{a}{4}\left[\frac{2v}{a}-2c-\frac{(1-s)r}{k}+\frac{2b}{a}q_0-\frac{b}{a}d_o\left(u_r+\varphi\frac{m-1}{2}\right)-\frac{\tau}{k}-\frac{b}{a}d_ou_d\right]$$
$$\left\{\frac{\tau}{k}-\frac{(1-s)r}{k}+\frac{b}{a}d_o\left[u_d-\left(u_r+\varphi\frac{m-1}{2}\right)\right]\right\}=\frac{4(D_3+D_4)}{a}\left\{\frac{\tau}{k}-\frac{(1-s)r}{k}+\frac{b}{a}d_o\left[u_d-\left(u_r+\varphi\frac{m-1}{2}\right)\right]\right\}.$$

Since $D_3>0$ and $D_4>0$, we obtain that $\overline{\overline{d_o}}=\frac{a[(1-s)r-\tau]}{bk[u_d-(u_r+\varphi\frac{m-1}{2})]}$. With $u_d>(u_r+\varphi\frac{m-1}{2})$ and $d_o>0$, we infer that if $d_o\in(0,\max\{\overline{\overline{d_o}},0\}]$, $\prod_{s4}\leq\prod_{s3}$, the supplier will choose disposable packages; and if $d_o\in(\max\{\overline{\overline{d_o}},0\},+\infty)$, $\prod_{s4}>\prod_{s3}$, the supplier will choose reusable packages.