Creating a low carbon economy through green supply chain management: Investigation of willingness-to-pay for green products from a consumer's perspective

Abstract

In recent decades, governments have gradually invested in and provided an increasing amount of resources to increase consumers' willingness-to-pay (WTP) for green products, with the aim of improving both the local and global environment rather than primarily concentrating on the economic gains. However, it is argued that the increase in WTP for green products may not always bring the expected benefits for the environment. Some studies have tried to explain this 'special phenomenon' with reference to the green supply chain; however, the effect of WTP on green products remains underexplored, particularly from a consumer perspective. This study therefore investigates how consumers' WTP for green products affects the decisions made by the green supply chain players (retailers and manufacturers) via a green cost-sharing contract, in a context of uncertainty about consumers' perceptions of green products and thus how much utility they could expect to receive from them, in order to contribute to a low carbon economy. Through the application of game theory and uncertainty theory, our findings show that a higher consumer WTP for green products usually leads to a higher retail price and market share of green products, which motivates retailers and manufacturers to invest more in green technology. We also find that an increased WTP for green products can spur retailers to reduce the optimal green cost-sharing rate due to the pressure of increasing costs. This discourages manufacturers from investing more in green technology, which may in turn hinder the further development of environmental initiatives. In addition, we find that retailers are willing to lower the cost sharing rate when the confidence level increases. Regarding the contributions made by this study, it is one of the first to explore the transmission mechanisms involved in the management of the green supply chain by linking consumers' WTP for green products to strategic decisions made by green supply chain players under conditions of uncertainty. Furthermore, our study could help green supply chain players to optimise the cost sharing mechanisms they use to generate more revenue, due to the increase in WTP for green products, which will in turn help to facilitate a low carbon economy.

Keywords

Green supply chain management; Low carbon economy; Cost sharing; Willingness-to-pay; Uncertainty theory; Game theory

1. Introduction

Increased economic activity has been accompanied by growing concerns about climate change, energy security, and the scarcity of natural resources (OECD, 2009). Sustainable consumption and production have emerged as innovative and sustainable ways of addressing these concerns, and have attracted significant attention from customers, industries, and governments around the world (Chen, 2001). Due to the urgency of environmental concerns, many countries have imposed policies, laws, and regulations to promote the development of an environmentally focused economy. In addition, governments have gradually invested in and made an increasing amount of resources available to facilitate green consumption behaviour in order to improve the environment and promote the low carbon economy. For example, in 2009, China launched a new electric vehicle subsidy programme, while Germany introduced a carbon footprint pilot project for new products. Consumers have become increasingly willing to adopt sustainable lifestyles and purchase green products in recent years (Kortelainen et al. 2016; Liu et al. 2017). For example, Zhang et al. (2015) reported that 67 per cent of consumers in the US support the purchase of green products due to environmental considerations, and 51 per cent of them are willing to pay a higher price for those products. In Europe, the proportion of customers willing to pay a higher price for green products increased from 31 per cent in 2005 to 67 per cent in 2008 (Yu et al., 2016). Several studies also show that customers have become more willing to pay a premium for green energy (Clark and Kotchen, 2003; Hartmann, 2012) and food products with a lower carbon impact (Shuai et al., 2016; Chen et al., 2018) over time. In addition, the willingness to buy green products has had a significant positive driving effect on green consumption behaviour, which is vital in the development of a low-carbon economy (Chen et al., 2014; Zhang et al., 2019). Given the shift in consumer preferences towards low-carbon products, segmenting and catering to green consumers creates new opportunities and challenges for firms; not only should they restrategise their products, but they should also consider the competitive operational challenges involved in acquiring and utilising green manufacturing technology and processes. Environmental awareness of the green supply chain has thus become an emergent field of research within operations management (Ghosh and Shah, 2012; Curkovic and Sroufe, 2007). With regard to green supply chain management, consumers' willingness-to-pay (hereafter WTP, meaning the maximum amount that an individual agrees to pay for a green product, in this context) for green products; consumer sensitivity to the degree of so-called greenness (e.g., carbon or energy efficiency labelling); and negotiations between supply chain players via green cost-sharing contracts are regarded as three main factors that influence the optimal decision-making of green supply chain players.

This research is motivated by the fact that large retailers, such as Walmart, Dell, Huawei and JD, produce an array of green products which have increasingly come to be favoured by consumers, but which attract a higher price premium. This study therefore aims to offer insight into the effect of the impact mechanism and degree of consumer WTP for green products on supply chain decisions. There is a growing number of academic research which addresses consumer environmental awareness, consumer sensitivity to the environment, and its relationship to consumer decision-making (see Ghosh and Shah, 2012; Li et al. 2016; Liu et al., 2012). In the early stages of the development of the green product market, the premiums paid by consumers appeared to be relatively low. Therefore, consumers' willingness to pay a premium for green products, as a key factor in the demand function for green products, and its effect on supply chain decisions, has received little attention in the literature. For instance, most studies on the demand function have typically focused on retail prices and sales (Ma et al., 2013b; Wu, 2013), as well as the quality of the environment and consumer environmental awareness (Ghosh and Shah, 2012). As environmental awareness increases, consumers have become more willing to pay a higher price premium for green products, compared to traditional products. For instance, the European Commission stated that 75% of European citizens are willing to buy environmentally-friendly products, even when they cost more (European Commission, 2008, Yu et al., 2016; Zhang et al., 2015). As market participants, consumers are the major determiners of the benefits that can be reaped by an enterprise, so green consumption behaviour by individual consumers directly determines the willingness of an enterprise to produce green products and to invest in and adopt cleaner technology (Yalabik and Fairchild, 2011). In response to these changes that have occurred within the marketplace, enterprises have become more likely to design products with environmentally-friendly features to attract consumers (Gu et al., 2015). Therefore, taking consumer willingness to pay a premium for green products into consideration is not only in line with the current market environment, but can also be regarded as an emerging trend. Doing so can help to shed light on the transmission mechanism that operates between consumers and the supply chain decisions made by supply chain members within the green product market. Consumers are a heterogeneous group and exhibit different behaviours with regard to their willingness to pay a premium for green products. Consequently, enterprises have begun to acknowledge and address this differentiated behaviour and tailor the level of greenness of their products in order to meet consumer demand (Gu et al., 2015; Yu et al., 2016). In this study, we explore the aforementioned issues and model the green product demand function with, respectively, premium payments, the price of goods, consumer environmental awareness, and the quality of green products.

This research focuses on cost-sharing within the supply market from a collaborative perspective (e.g., Bhaskaran and Krishnan, 2009; De Giovanni, 2014; Ghosh and Shah, 2015; Swami and Shah, 2013). In order to produce a greener product, environmentally-friendly materials are needed, which in turn requires a greater level of investment in green technology, thereby generating higher costs and new production methods. For many organisations, implementing improvements in green technology is a costly and challenging undertaking. More importantly, large enterprises frequently expect their suppliers to bear these costs. However, if suppliers have to bear all the associated costs, it becomes difficult for them to sustain their investment in green technology. In order to address this problem, supply chain members have turned to new supply chain strategies, such as green cost-sharing contracts, which allow manufacturers and retailers to negotiate agreements with each other about how the costs of producing green products are to be allocated. As consumer WTP for green products has a direct impact on the demand for green products, changes in demand affect supply chain decisions and have an impact on profits. Thus, it is pertinent to analyse how cost-sharing contracts are formulated from the perspective of consumer WTP for green products. In addition, Liu et al. (2017) and Ma et al. (2020) state that there is a significant degree of uncertainty regarding the external demand for green products and consumer sensitivity to green products. Hence, they may be unobservable to supply chain players, because there is no observed data available with which to forecast these variables in advance for new green products. Therefore, due to the uncertainty surrounding this information, it may be more appropriate to use uncertainty theory to measure it. The concept of uncertainty theory was introduced by Liu (2007), Liu et al. (2017) and Ma et al. (2020) who used the confidence level, which is the degree of belief in a successful result, to reflect consumers' attitude to risk. The value of the confidence level ranges between 0 and 1, and a value close to 1 indidates that the individual is more risk-averse. In contrast, lower confidence level means that individuals are risk-tolerant and willing to bear more potential risks.

Motivated by the aforementioned issues, this study aims to reveal the mechanisms that underpin decisions made by consumers, manufacturers and retailers, under conditions of uncertainty, that affect the green supply chain, in order to help achieve the goal of a low carbon economy. Thus, the research is designed to determine the optimal decisions for green supply chain players, taking into account heterogeneous consumers' WTP for green products and the use of cost-sharing contracts. The WTP for green products can be divided into two aspects: 1) the increased willingness to pay for a product because of its 'green', environmentally-friendly features; and 2) the willingness to pay a premium for such products. In order to achieve the research aim, we estimated the impacts of consumers' WTP for green products on cost-sharing contracts under uncertain conditions, based on confidence level; as well as the degree of greenness of products, and product pricing, on the management of the green supply chain.

This study makes three theoretical contributions to the literature. First, it is one of the first to shed light on the transmission mechanism between the demand for green products and the optimal decisions that firms can make within the green supply chain, taking consumers' WTP for green products into account. Second, this study complements research on the classical product demand function by linking consumers' WTP for green products to the demand for green products. Third, it extends the existing literature on green consumption behaviour by investigating the impact of consumers' WTP for green products on decision-making, based on confidence level, and how cost-sharing contracts are negotiated within the management of the green supply chain.

The paper is organised as follows. Section 2 reviews the existing literature on the effect of consumers' WTP on decision-making within the green supply chain, channel coordination and cooperative bargaining. The models and methods used are described in Section 3. Section 4 explains the decision-making process and structure. Subsequently, Section 5 presents the results of our numerical study, and Sections 6 discusses key findings derived from the game theory analysis and offer conclusions.

2. Literature Review

2.1 Consumers' WTP

In terms of green supply chain coordination, the price and the greenness of products are regarded as the main factors that determine the demand for products. However, consumers' WTP for green products as a judgment about the value of products is a topic that has so far attracted little attention in the literature. By ignoring this aspect, firms risk failing to understand consumer demand and thus potentially losing their competitive advantages. Consumers' WTP refers to the maximum price that a buyer is willing to pay for a given quantity of a product (Wertenbroch and Skiera, 2002). Therefore, predicting consumers' WTP for green products is crucial in terms of understanding demand and designing optimal pricing schedules (Wertenbroch and Skiera, 2002). Due to the importance placed on green product development, scholars have begun to estimate WTP using actual market transactions (Silk and Urban 1978) or survey data (Green and Srinivasan, 1990; Mitchell and Carson, 1989). However, the relationship between consumers' WTP for green products and the greenness of the products remains underexplored. Franzen and Vogl (2013) and Shao et al. (2018) found that consumers will pay more for green products mainly due to their personal characteristics and the extent to which they believe a product causes pollution. Many other factors can also influence the WTP, such as educational experience and attainment (Sheehan and Atkinson, 2012; Zhang and Wu, 2012), the egoism of consumers (Bickart and Ruth, 2012), and advertising campaigns (Goldstein et al., 2008). Although consumers' WTP for green products is now attracting considerable attention from researchers, it remains crucial to try to fully understand the relationship between the demand for green products and consumers' WTP in order to promote the development of green products and the future success of such efforts. With regards to the supply chain, Tully and Winer (2014) found that consumers' WTP for green products may vary according to the product type, and such differences in WTP should be taken into account by retailers who stock socially responsible products. This point is also made by Akkucuk (2011). Thus, exploring the influence of consumers' WTP on the demand for green products can provide a theoretical reference for optimising supply chain management. It can also be helpful in guiding firms' production decisions. In recent years, with the rapid increase in consumers' WTP for green products, enterprises have had to operate in a constantly changing market environment - and they are therefore seeking new strategies that can help to maximise their profits.

Due to the development of green products in many industries, some studies have focused on the supply chain and investigated strategic issues relating to green products. These studies have mainly concentrated on examining pricing or the greenness of products using game theory approaches. For example, Zhou (2018) and Li et al. (2016) developed a game theory model with which to examine the optimal pricing decisions for manufacturers. As the concept of sustainable production and consumption has increasingly permeated people's everyday lives, firms have tended to focus on the greenness of products. For instance, Örsdemir et al. (2014) carried out a study into competitive quality choice and remanufacturing. They found that the original equipment manufacturers rely more on quality as a strategic lever when they are in a stronger competitive position. Due to the close relationship between the greenness of products and prices that consumers are willing to pay, a growing number of studies have begun to focus on both pricing and decisions relating to product greenness within the supply chain environment using game theory (see Basiri and Heydari, 2017; Ghosh and Shah, 2012; Liu et al., 2012; Yang and Xiao, 2017; Zhu and He, 2017). As the major driver of demand for green products, consumers' WTP for green products is a key influence on firms' production decisions and on determining the development of the green product market. However, in constructing the demand function, relevant studies have directed their attention towards pricing and the greenness of products, but have overlooked the impact of consumers' WTP for green products. This may have had the effect of preventing optimal decision-making and thus hindering coordination within the supply chain.

Our study builds on prior research and further investigates the impact of consumers' WTP for green products on the demand for green products. Gaining a deeper understanding of the demand function could help to provide a theoretical foundation for decision-making within the green supply chain. The demand function also constitutes a problem in terms of channel coordination, which has provided the motivation for modelling and analysing green supply chains.

2.2 Decision making within the green supply chain

The existing literature on supply chain decision-making has tended to focus on consumer environmental awareness rather than the importance of consumers' WTP for green products, causing the reaction and transmission mechanisms between green consumers and supply chain members to be overlooked. This, in turn, may have resulted in supply chain members making inappropriate or sub-optimal decisions. Therefore, this study sheds light on the motivation behind consumer demand and discloses the transmission mechanism that operates between consumers and supply chain members. Previous studies have focused on the impact of consumer environmental awareness on decisions about green products, such as pricing, the greenness of products, market share and profits (Brécard, 2013; Conrad, 2005; Ma et al., 2018; Roberto, 2007; Xu et al., 2018; Yang et al., 2019). However, knowledge about consumer environmental awareness is of little use in identifying the mechanisms that operate between consumers and manufacturers of green products. This may be due to the relatively low levels of WTP for green products during the early days of green consumption, as it takes time for environmental awareness to be reflected in the buying behaviour of consumers.

However, in recent years, as a result of rising levels of education, concern for the environment and advertising campaigns, consumers have become increasingly willing to pay more for green products (Goldstein et al., 2008; Lee, 2008; Nyborg et al., 2003; Sheehan & Atkinson, 2012; Stern, 1996; Zhang & Wu, 2012). Tully and Winer (2014) applied a Meta-analysis method to test respondents' WTP for socially responsible products. They found that, on average, up to 60% of respondents were willing to pay a premium, and the mean additional amount they would be prepared to pay was 16.8% (Tully and Winer, 2014). By recognising these shifts that have occurred within the marketplace, firms have been able to redesign products to include environmentally-friendly features that may appeal to green consumers (Gu et al., 2015; Yalabik and Fairchild, 2011; Yu et al., 2016). In light of the increasing demand for green products, it has not only become necessary to take consumers' WTP for green products into account in regard to coordinating the green supply chain, but it has also become possible to more accurately predict the optimal decisions that retailers could make.

In this study, we incorporate consumers' WTP for green products into a consumer utility function in order to uncover the underlying mechanism that operates between consumer WTP and supply chain decision-making. Exploring this mechanism could not only provide a theoretical basis on which large retailers and supply chain members can base their decisions, but could also offer a policy reference for governments to promote the development of the green economy.

2.3 Channel coordination and cooperative bargaining

A growing number of studies have investigated how the coordination of the green supply chain can be improved by the use of cost-sharing contracts. However, the literature on cost-sharing contracts does not pay sufficient attention to consumers' WTP for green products, which may mean that the contract produced is not appropriately designed to meet the supply chain members' requirements or address the actual market situation and thus may even hamper the coordination of the supply chain. This paper uses a cost-sharing contract drawn up between supply chain players to explore the impacts of consumers' WTP for green products on cost-sharing contracts, with the aim of helping supply chain players to better understand consumer behaviour with respect to cost-sharing contracts. Because it requires a large amount of upfront investment, manufacturers usually exercise caution in relation to green technology (Krass et al., 2013). In order to promote the development of the green supply chain, retailers have started to voluntarily share some of the investment costs associated with green technology from the perspective of supply chain coordination. Therefore, increasing attention has been paid to the formulation of cost-sharing contracts within the green supply chain by scholars in recent years.

A series of related contracts, of which cost-sharing contracts constitute one example, are drawn up between supply chain members with the aim of coordinating the supply chain. Via a game theory approach, Ghosh and Shah (2015) developed a model showing how cost-sharing contracts are formulated between supply chain participants in order to examine how such contracts affect the key decisions that they make. Bhaskaran and Krishnan (2009) evaluated the impact of investment and innovation sharing on product development within the framework of negotiations. In an earlier piece of research, Kohli and Park (1989) studied negotiations between the buyer and the seller and their effect on order quantity and the average unit price of products.

However, insufficient attention has been paid to consumers' WTP for green products during the process of formulating contracts. According to research on cost-sharing contracts, market demand is affected by the extent to which consumers are sensitive to green issues. Taking consumers' WTP for green products into consideration when formulating cost-sharing contracts allows the actual market situation to be more accurately reflected, which makes it easier for retailers to bear the costs of investing in technology as well as to invest more rationally. In this study, we incorporate consumers' WTP for green products into the process of drawing up a cost-sharing contract in order to investigate its impact on the way in which the contract is designed.

3. Model Description

3.1. Notations

The notations used in the text are given in full below.

Table 1. Notations

Parameter	Notation
θ	Consumer premium payments
α	Consumer payment coefficient per increased greening level
ϕ	Greening cost-sharing rate borne by the retailer
c	Fixed cost per unit of green product
C	Confidence level
Decision variable	
g	Greening level
p	Retail price
w	Wholesale price
Dependent variable	
U	Consumer utility
q	Quantity of market demand for green products
π	Profit without cost-sharing
π^C	Profit with cost-sharing
Subscript	
D	Decisions in decentralised scenario
I	Decisions in integrated scenario
MD	Manufacturer decisions in decentralised scenario
RD	Retailer decisions in decentralised scenario
SCD	Supply chain decisions in decentralised scenario
MI	Manufacturer decisions in integrated scenario
RI	Retailer decisions in integrated scenario
SCI	Supply chain decisions in integrated scenario

3.2. Model

Based on the framework used by Ghosh and Shah (2015), we broadened the demand function of green products by taking into account heterogeneous consumers' WTP and further investigated the impact of consumers' WTP for green products on the critical decision-making and profits of green supply chain participants under a cost-sharing contract. We considered a vertically-structured supply chain consisting of one manufacturer and one retailer in order to reflect the position of companies such as Walmart, Dell, etc., as accurately as possible The manufacturer produces only one green product and bears the costs associated with greening. The retailer sells the product produced by the manufacturer to consumers. We considered two different cases: the first one with a cost-sharing contract; and the second without a cost-sharing contract. In order to explore the effects of cost-sharing contracts on the optimal strategies that could be employed by green supply chain players, we first investigated the example in which there is no cost-sharing contract within the green supply chain, which consists of two different scenarios: an integrated scenario (I); and a decentralised scenario (D). In the former, the supply chain decides the retail price and the degree of greenness of the product. In the latter scenario, the retailer decides the retail price. The manufacturer bears the costs of greening and determines the degree of greenness of the product as well as the wholesale price by taking into account the retailer's reaction function. Consumers express their demand by purchasing green products based on the retail price and the degree of greenness of the product, and thus determine the demand for the green product. The structure of the problem and the supply chain mechanism are shown in Figure 1, below.

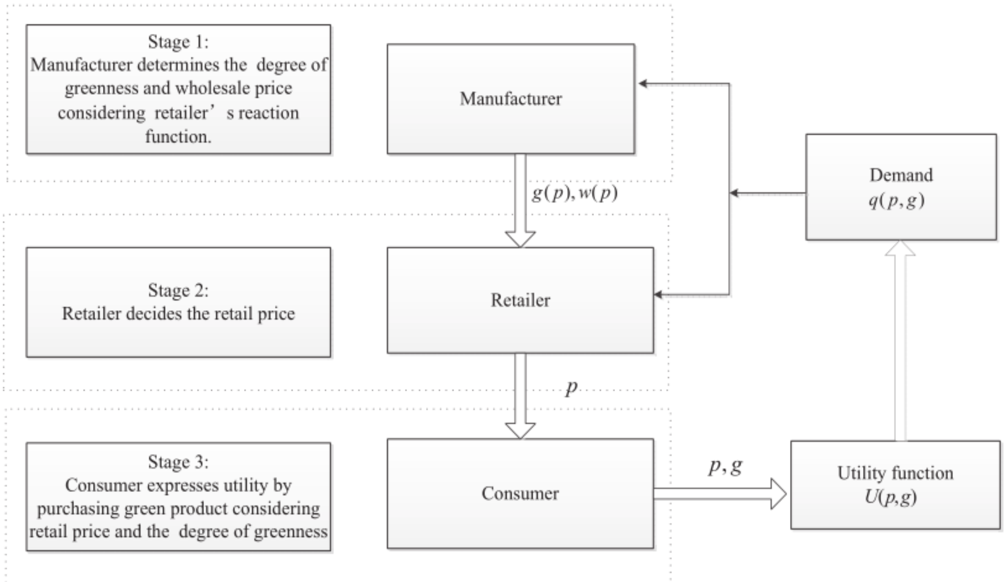


Fig 1. Problem and supply chain structure.

The consumer utility function consists of two parts: the WTP for green products; and the purchasing price (p). The WTP for green products comprises the payment of a premium (θ) and the additional green utility (αg), where αg denotes the increase in utility brought about by the improvement in the greenness of a product, which reflects consumers' objective evaluation of green products. θ is the premium payment that reflects consumers' subjective evaluation of a green product. The consumer utility function is expressed as follows:

$$U = WTP - p\,,\quad WTP = \theta + \alpha g \tag{1}$$

As heterogeneous consumers have different levels of WTP for green products, this affects consumer demand for green products. In order for the analysis to be tractable, we suppose that consumer premium payments are uniformly distributed from 0 to $\bar{\theta}$. Consumer sensitivity to greenness is denoted by α, representing the utility brought about, per unit of improvement in greenness. Consumers will only buy the product when the utility is not negative. In other words, if consumers' premium payment θ is lower than θ^*, they will remain inactive and not purchase green products due to negative utility (in this case, $U < 0$). If consumers' premium payment θ is equal to or greater than θ^*, they will buy green products due to non-negative utility (in this case, $U \geq 0$). Equation (1) is designed to find the indifference point: $\theta^* = \frac{p - \alpha g}{\bar{\theta}}$. Only when $\theta \in \Phi, \Phi = \{\theta \mid \theta^* \leq \theta \leq \bar{\theta}\}$ will consumers buy the product. Figure 2 illustrates the behaviour of heterogeneous consumers. Without losing generality, we assume that $\bar{\theta} > c$:

Fig 2. Behaviour of heterogeneous consumers.

We can then determine the proportion of consumers who buy green products. We assume that the potential market capacity is A, and then the demand function for the green product is:

$$q = A \int_{\theta \in \Phi} \frac{1}{\theta} d\theta = A \frac{\bar{\theta} - p + \alpha g}{\bar{\theta}} \tag{2}$$

In the base model, the manufacturer bears the costs of greening products. Thus, the profit functions of the manufacturer (M), retailer (R), and the supply chain are derived as follows:

$$\pi_M = (w - c)q - \beta g^2, \tag{3}$$

$$\pi_R = (p - w)q, \tag{4}$$

$$\pi_{SC} = (p - c)q - \beta g^2. \tag{5}$$

As the market scale and consumer sensitivity to greenness may be unobservable, with reference to Liu et al. (2017) and Ma et al. (2020), we assume that A and α are mutually independent uncertain variables with uncertain distributions, $\Theta(x)$ and $\Psi(x)$, respectively. $C \in [0,1]$ is the confidence level of the manufacturer and retailer under the condition of full information. Note that because $\pi_M(w,p,g;A,\alpha)$, $\pi_R(w,p,g;A,\alpha)$ and $\pi_{SC}(w,p,g;A,\alpha)$ contain uncertain variables A and α, they are also uncertain variables.

Before examining the profits of supply chain members under conditions of uncertainty, we first need to establish some preliminary knowledge. Following Liu (2007) and Liu et al. (2017), we denote Ω as a nonempty set and $\mathcal{F}$ an σ-algebra over Ω. The uncertain measure $\mathcal{M}$ is a set function which satisfies the following conditions:

(1) (Normality) $\mathcal{M}\{\Omega\} = 1$.

(2) (Self-Duality) $\mathcal{M}\{\Lambda\} + \mathcal{M}\{\Lambda^c\} = 1$ for any event Λ.

(3) (Countable Subadditivity) For any countable sequence of events $\{\Lambda_i\}$, we have

$$\mathcal{M}\left\{\bigcup_{i=1}^{\infty} \Lambda_i\right\} \le \sum_{i=1}^{\infty} \mathcal{M}\{\Lambda_i\}.$$

$(\Omega, \mathcal{F}, \mathcal{M})$ is known as an uncertainty space. The uncertain variable ξ is a function of the uncertainty space $(\Omega, \mathcal{F}, \mathcal{M})$ to the set of real numbers. The uncertainty distribution Ψ of the uncertain variable ξ is defined as:

$$\Psi(x) = \mathcal{M}\{\gamma \in \Omega \mid \xi(\gamma) \le x\}, \forall x \in \Re, \Re \to [0,1].$$

Again, following Liu et al. (2017) and Ma et al. (2020), we assume that the uncertain variable ξ has a linear uncertainty distribution $\mathcal{F}(a,b)$ as:

$$\Psi(x) = \begin{cases} 0, & \text{if } x < a \\ \dfrac{x-a}{b-a}, & \text{if a} \le x < b. \\ 1, & \text{if } x \ge b \end{cases}$$

where a and b are real numbers and $a < b$.

The unique inverse uncertainty distribution of the linear variable $\mathcal{F}(a,b)$ for each $C \in [0,1]$ is:

$$\Psi^{-1}(C) = a(1-C) + bC, \quad 0 \le C \le 1,$$

and the expected value is:

$$E[\xi] = \int_0^1 \Psi^{-1}(C)dC = \frac{a+b}{2}.$$

Given the confidence level C, the net profit of a manufacturer can be denoted as π_{M0}, which belongs to $\{\pi_{M0} \mid \mathrm{M}\ \{\pi_M(w,p,g;A,\alpha) \ge \pi_{M0}\} \ge C\}$ under the condition of full information. The above set is the net profit that the manufacturer earned under confidence level C. The maximum profit of the manufacturer under confidence level C can then be written as:

$$\Pi_M(w,p,g;A,\alpha) = \max\{\pi_{M0} \mid \mathrm{M}\ \{\pi_M(w,p,g;A,\alpha) \ge \pi_{M0}\} \ge C\}. \quad (6)$$

Similarly, the the maximum profit of the retailer and supply chain under confidence level C can be denoted as:

$$\Pi_R(w,p,g;A,\alpha) = \max\{\pi_{R0} \mid \mathrm{M}\ \{\pi_R(w,p,g;A,\alpha) \ge \pi_{R0}\} \ge C\}, \quad (7)$$

$$\Pi_{SC}(w,p,g;A,\alpha) = \max\{\pi_{SC0} \mid \mathrm{M}\ \{\pi_{SC}(w,p,g;A,\alpha) \ge \pi_{SC0}\} \ge C\}. \quad (8)$$

4. Decision-Making Structure

In this section, we first examine the key decisions when consumer WTP for green products is taken into account in the integrated scenario and the decentralised scenario without a cost-sharing contract. Next, we explore the impact of WTP for green products on the optimal strategies and profits of supply chain participants. Finally, we compare the optimal strategies and profits in the integrated scenario with those in the decentralised scenario. The purpose of the steps described above is to establish a clearer understanding of the green supply chain in order to further analyse the cost-sharing contract model. In the cost-sharing contract scenario, we assess how consumers' WTP for green products and the cost-sharing contract affect decisions regarding the greenness of products, pricing, and profits made by green supply chain participants. We then investigate the optimal cost-sharing rate. This is followed by a discussion of the decentralised scenario, the integrated scenario, and the cost-sharing contract scenario. The deduction process and its corresponding verifications can be found in the appendix.

4.1. Integrated scenario

In the integrated case, the entire profit of the supply chain under confidence level C is calculated as follows:

$$\Pi_{SCI}(p,g) = (p-c)q - \beta g^2 \quad (9)$$

where $q=\Theta^{-1}(1-C)\frac{\bar{\theta}-p+\Psi^{-1}(1-C)g}{\bar{\theta}}$, $\Theta^{-1}(1-C)$ denotes the degree of belief in the market capacity of the manufacturer and retailer. $\Psi^{-1}(1-C)$ denotes the degree of belief in the consumer's sensitivity to greenness.

Theorem 1: *In the integrated case, the supply chain profit* Π_{SCI} under confidence level c *is concave in* p_I *and* g_I *simultaneously if* $\beta>\frac{\left(\Psi^{-1}(1-C)\right)^2\Theta^{-1}(1-C)}{4\bar{\theta}}$. *There are unique optimal strategies that can be used to maximise* Π_{SCI} *:*

$$p_I=\frac{2\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{10}$$

$$g_I=\frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)\left(\bar{\theta}-c\right)}{4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}. \tag{11}$$

By plugging the optimal values of the price and the degree of greenness into equations (2) and (9), the market share and probability of the supply chain are calculated as follows:

$$q_I=\frac{2\beta\left(\bar{\theta}-c\right)^2\Theta^{-1}(1-C)}{\left[4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2}, \tag{12}$$

$$\pi_{SCI}=\frac{\Theta^{-1}(1-C)\beta\left(\bar{\theta}-c\right)^2}{4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}. \tag{13}$$

Proposition 1: *In the integrated scenario with confidence level* C *, a higher consumer WTP a premium for green products increases the retail price, improves the degree of greenness, and broadens the market share. Thus, enhancing the profitability of the supply chain; and increasing the degree of belief in consumer sensitivity to greenness will decrease the retail price, enhance the degree of greenness, broaden the market share, and improve the profitability of the supply chain. The equilibrium values are shown in the following order:*

$$\frac{\partial p_I}{\partial\bar{\theta}}>0,\frac{\partial g_I}{\partial\bar{\theta}}>0,\frac{\partial q_I}{\partial\bar{\theta}}>0,\frac{\partial\Pi_{SCI}}{\partial\bar{\theta}}>0,\frac{\partial p_I}{\partial\Psi^{-1}(1-C)}<0,\frac{\partial g_I}{\partial\Psi^{-1}(1-C)}>0,\frac{\partial q_I}{\partial\Psi^{-1}(1-C)}>0,\frac{\partial\Pi_{SCI}}{\partial\Psi^{-1}(1-C)}>0 \tag{14}$$

Proposition 1 indicates that a higher WTP for green products enables participants to increase a product's level of greenness and raise market demand. The results shown above have the effect of jointly increasing supply chain profits.

4.2. Decentralised scenario

An integrated scenario requires a central decision-maker to make choices on behalf of supply chain members. However, when supply chain players are independent, the solution obtained by centralised decision-making may benefit one member and harm another. Consequently, supply chain participants do not participate in integrated decision-making (Basiri and Heydari, 2017). Under these circumstances, it is appropriate to establish a decentralised model to represent the relationships between channel members. In a decentralised scenario with confidence level C, the aim of each supply chain member is to maximise their respective profits. The retailer first determines the selling price to maximise its profit function. The manufacturer then decides the degree of greenness and the wholesale price by taking into account the retailer's optimal pricing strategy that can be used to achieve maximum profit.

The supply chain members' profits under confidence level C are formulated as follows:

$$\Pi_{MD}\left(w,g\right)=(w-c)q-\beta g^{2}, \tag{15}$$

$$\Pi_{RD}\left(p\left(w,g\right)\right)=(p-w)q, \tag{16}$$

$$\Pi_{SCD}=(p-c)q-\beta g^{2}, \tag{17}$$

where $q=\Theta^{-1}(1-C)\dfrac{\bar{\theta}-p+\Psi^{-1}(1-C)g}{\bar{\theta}}$.

Theorem 2: *In the decentralised scenario with confidence level* C, Π_{MD} *is concave in* w_D *and* g_D *simultaneously if* $\beta>\dfrac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^{2}}{8c}$. π_{RD} *is also concave in* p_D. *There are unique optimal values for* w_D, g_D, *and* p_D *that maximise* Π_{MD} *and* Π_{RD} *which can be represented as follows:*

$$p_D=\frac{2\beta\bar{\theta}\left(3\bar{\theta}+c\right)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^{2}c}{8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^{2}}, \tag{18}$$

$$g_D=\frac{\left(\bar{\theta}-c\right)\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^{2}}, \tag{19}$$

$$w_D=\frac{4\beta\bar{\theta}\left(\bar{\theta}+c\right)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^{2}c}{8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^{2}}. \tag{20}$$

By plugging the optimal retail price, the wholesale price and degree of greenness into equations (2) and (15) – (17), the market share and profits are calculated using the following formulae:

$$q_D = \frac{2\beta\left(\bar{\theta}-c\right)\Theta^{-1}(1-C)}{8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{21}$$

$$\Pi_{MD} = \frac{\beta\left(\bar{\theta}-c\right)^2\Theta^{-1}(1-C)}{8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{22}$$

$$\Pi_{RD} = \frac{4\beta^2\bar{\theta}\left(\bar{\theta}-c\right)^2\Theta^{-1}(1-C)}{\left[8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2}, \tag{23}$$

$$\Pi_{SCD} = \frac{\Theta^{-1}(1-C)\beta\left(\bar{\theta}-c\right)^2\left[12\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2}. \tag{24}$$

Proposition 2: *In the decentralised scenario with confidence level C, a higher consumer WTP a premium for green products and the degree of belief in consumer sensitivity to greenness have a positive effect on the retail price, the degree of greenness, the market share, and the profitability of supply chain players, respectively. The equilibrium values are shown in the following order:*

$$\frac{\partial p_D}{\partial \Phi} > 0, \frac{\partial g_D}{\partial \Phi} > 0, \frac{\partial w_D}{\partial \Phi} > 0, \frac{\partial q_D}{\partial \Phi} > 0, \frac{\partial \Pi_{MD}}{\partial \Phi} > 0, \frac{\partial \Pi_{RD}}{\partial \Phi} > 0, \frac{\partial \Pi_{SCD}}{\partial \Phi} > 0 \quad . \tag{25}$$

Proposition 2 suggests that a higher consumer WTP a premium for green products and the degree of belief in consumer sensitivity to greenness will cause the manufacturer to enhance the greenness of the product, and thus increase its wholesale price. An increase in wholesale prices will prompt the retailer to increase the retail price. It is worth mentioning that a higher consumer WTP a premium for green products will increase consumer demand for green products, while the proportion of consumers who remain inactive will decrease. The results shown above will have the effect of jointly increasing the profits of the supply chain.

The results obtained in the integrated scenario and the decentralised scenario *with confidence level* C show that a higher consumer WTP a premium for green products and a greater degree of belief in consumer sensitivity to greenness will promote the development of the green economy and increase the profits of the green supply chain. This result is closely related to green consumption, and provides a useful reference with which supply chain participants and the government could explore incentivising mechanisms for raising the premium that consumers are willing to pay for green products and the degree of belief in consumer sensitivity to greenness.

Proposition 3: *The equilibrium values of the decentralised scenario and the centralised scenario under confidence level C are compared as follows:*

$$p_I > p_D, g_I > g_D, q_I > q_D. \tag{26}$$

Proposition 3 claims that the retail prices of green products, the greenness of products, and the equilibrium quantity will all increase, as the decision-making structure shifts from a decentralised scenario to a centralised scenario.

Proposition 4: *Compared to the decentralised supply chain under confidence level C, the integrated supply chain under confidence level C produces greater whole-channel profits.*

$$\Delta_{\Pi_{SCI}-\Pi_{SCD}} = \frac{\beta\Theta^{-1}(1-C)(\bar{\theta}-c)^2\left[32\beta^2\bar{\theta}+4\beta\bar{\theta}^2\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]\left[8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]} > 0. \quad (27)$$

In the integrated scenario, the supply chain acts as the central decision-maker which is able to optimise profits. However, in the decentralised scenario, each player maximises profits independently. Therefore, the integrated supply chain generates a higher level of whole-channel profit than the decentralised supply chain.

Although the integrated scenario produces greater profits than the decentralised scenario, integrated decision-making is unapproved. Therefore, an alternative decision-making process may be needed to maximise the supply chain profit on the basis of ensuring the profits of manufacturers and retailers.

4.3. Cost-sharing contract case

In the scenarios described above, the manufacturer bears all the costs of greening the product. In this section, we first examine the impact of cost-sharing contracts on participants in the green supply chain under confidence level C. Because a cost-sharing contract can reduce the greening costs borne by the manufacturer, it plays an important role in motivating manufacturers to participate in the green economy (Kaya and Caner, 2018). Secondly, we investigate the optimal cost-sharing rate within the contract. Finally, we evaluate how consumer WTP for green products impacts on the optimal cost-sharing rate and the optimal strategies that can be used by supply chain players. In the cost-sharing contracts case, the game structure is as follows:

1. The retailer sets the retail price (p).

2. The manufacturer sets the level of greenness (g) and the wholesale price (w) by taking the retailer's reaction function into account.

3. Consumer decisions affect demand by taking the retail price and degree of greenness into account in the utility function.

4. The retailer decides the optimal cost-sharing proportion (ϕ^*). By taking the optimal retail price ($p(\phi)$), the degree of greenness ($g(\phi)$), and the wholesale price ($w(\phi)$) into account, the retailer decides the optimal cost-sharing proportion (ϕ^*) that will maximise the profit.

The profit functions of the supply chain players under confidence level C can be formulated as follows:

$$\Pi_M^C = (w-c)q - (1-\phi)\beta g^2, \tag{28}$$

$$\Pi_R^C = (p-w)q - \phi\beta g^2, \tag{29}$$

$$\Pi_{SC}^C = (p-c)q - \beta g^2, \tag{30}$$

where $q = \Theta^{-1}(1-C)\dfrac{\bar{\theta} - p + \Psi^{-1}(1-C)g}{\bar{\theta}}$.

and ϕ represents the greening costs borne by the retailers, $0 < \phi \le 1$.

The reverse-solution method is applied to maximise profits in the following order: $\max\limits_{p^C(w^C,g^C)} \Pi_R^C$, $\max\limits_{w^C,g^C} \Pi_M^C$, and $\max\limits_{\phi(p^C,w^C,g^C)} \Pi_R^C$.

Theorem 3: *In the case of decentralised decision-making with a cost-sharing contract,* Π_{MD}^C *is concave in* w_D^C *and* g_D^C *simultaneously if* $\beta > \dfrac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{8c\left(1-\phi^*\right)}$, *and* Π_{RD}^C *is concave in* p_D^C. *There are unique optimal values for* w_D^C, g_D^C, *and* p_D^C *that can be used to maximise* Π_{MD}^C *and* Π_{RD}^C *and which can be represented as follows:*

$$p_D^C = \frac{2\beta\bar{\theta}\left(1-\phi^*\right)\left(3\bar{\theta}+c\right) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 c}{8\beta\bar{\theta}\left(1-\phi^*\right) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{31}$$

$$g_D^C = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)\left(\bar{\theta}-c\right)}{8\beta\bar{\theta}\left(1-\phi^*\right) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{32}$$

$$w_D^C = \frac{4\beta\bar{\theta}\left(1-\phi^*\right)\left(\bar{\theta}+c\right) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 c}{8\beta\bar{\theta}\left(1-\phi^*\right) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{33}$$

$$\phi^* = \frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta\bar{\theta}}. \tag{34}$$

where $\phi^* = \dfrac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta\bar{\theta}} < \dfrac{1}{3}$ for $\beta > \dfrac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{8\bar{\theta}\left(1-\phi^*\right)}$.

The equilibrium market share and profitability are calculated as follows:

$$q_D^C = \frac{2\beta\Theta^{-1}(1-C)(1-\phi^*)(\bar{\theta}-c)}{8\beta\bar{\theta}(1-\phi^*)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{35}$$

$$\Pi_{MD}^C = \frac{\beta\Theta^{-1}(1-C)(1-\phi^*)(\bar{\theta}-c)^2}{8\beta\bar{\theta}(1-\phi^*)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}, \tag{36}$$

$$\Pi_{RD}^C = \frac{\beta\Theta^{-1}(1-C)(\bar{\theta}-c)^2\left[4\beta\bar{\theta}(1-\phi^*)^2-\phi\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[8\beta\bar{\theta}(1-\phi^*)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2}, \tag{37}$$

$$\Pi_{SCD}^C = \frac{\beta\Theta^{-1}(1-C)(\bar{\theta}-c)^2\left[12\beta\bar{\theta}(1-\phi^*)^2-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[8\beta\bar{\theta}(1-\phi^*)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2}. \tag{38}$$

Proposition 5: *In the case with a cost-sharing contract, a higher consumer WTP a premium for green products and consumer sensitivity to greenness have a positive effect on the retail price, the degree of greenness, the market share, and the profits of supply chain players, respectively. The equilibrium values are shown in the following order:*

$$\frac{\partial p_D^C}{\partial \Phi} > 0, \frac{\partial g_D^C}{\partial \Phi} > 0, \frac{\partial w_D^C}{\partial \Phi} > 0, \frac{\partial \Pi_{MD}^C}{\partial \Phi} > 0, \frac{\partial \Pi_{RD}^C}{\partial \Phi} > 0, \frac{\partial \Pi_{SCD}^C}{\partial \Phi} > 0. \tag{39}$$

Proposition 5 suggests that consumer WTP a premium for green products and the degree of belief in consumer sensitivity to greenness have a positive effect on the retail price, the degree of greenness, the market share, and the profits of supply chain players when there is a cost-sharing contract in place, as the decentralised scenario does not include a cost-sharing contract.

However, there is a mismatch between the increase in the level of greenness of a product and increasing the premium that consumers are willing to pay for green products. In other words, although consumers are willing to spend more money, they cannot buy greener products. This is because investment in technology causes a rapid increase in costs, so the manufacturer will keep the increase in the greenness of a product to a minimum.

Proposition 6: $\frac{\partial \phi}{\partial \beta} < 0$, $\frac{\partial \phi}{\partial \Psi^{-1}(1-C)} > 0$, $\frac{\partial \phi}{\partial \bar{\theta}} < 0$.

Proof: $\frac{\partial \phi}{\partial \beta} = -\frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta^2\bar{\theta}} < 0$, $\frac{\partial \phi}{\partial \Psi^{-1}(1-C)} = \frac{A\Psi^{-1}(1-C)}{8\beta\bar{\theta}} > 0$,

$\frac{\partial \phi}{\partial \bar{\theta}} = -\frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta\bar{\theta}^2} < 0$.

Proposition 6 shows that, when the cost of greening products (β) increases, the retailer will contribute a lower proportion of ϕ to maintain profitability. At the same time, if there is a high consumer WTP a premium for green products, the retailer will also pay a lower proportion of ϕ, because when the consumer WTP for green products increases, the manufacturer will improve the degree of greenness of their products, thereby incurring an increase in greening costs. To maintain profitability, the retailer will pay a lower proportion of the costs. However, when the degree of belief in consumer sensitivity to greenness $\Psi^{-1}(1-C)$ increases, the retailer will contribute a larger share of ϕ. This is because, when the consumer is willing to pay more for a greener product, the utility for consuming the green product increases, thus raising the demand for the green product. This increase in demand can increase the profit obtained by the retailer. Thus, a retailer will be willing to offer to pay a higher proportion of ϕ when $\Psi^{-1}(1-C)$ increases.

These results imply that supply chain decision-makers and policymakers can improve consumer sensitivity to green products through appropriate policies. This, in turn, will contribute to promoting the development of the green product market.

Proposition 7: *Compared to the decentralised equilibrium values, the values in the case with a cost-sharing contract are as follows:*

$$p_D^C > p_D,\ w_D^C > w_D,\ g_D^C > g_D\ . \tag{40}$$

These results indicate that the cost-sharing contract case has a higher degree of greenness than the decentralised model. However, a greater level of greenness will raise the wholesale price and the retail price, which will increase the purchase cost for consumers.

Proposition 8: Compared to the amount of profit generated in the decentralised scenario under confidence level C, the case with a cost-sharing contract produces higher profit values:

$$\Pi_{MD}^C > \Pi_{MD}, \Pi_{RD}^C > \Pi_{RD}, \Pi_{SCD}^C > \Pi_{SCD}\ . \tag{41}$$

The results indicate that the profit obtained in the decentralised scenario is lower than that in the cost-sharing contract case. Interestingly, this implies that the retailer can obtain greater profits by sharing the greening costs. This finding serves to facilitate the use of cost-sharing contracts, because a retailer who bears part of the greening costs will reduce the costs for the manufacturer, thus prompting the manufacturer to increase the level of greenness of a product. A higher level of greenness is likely to lead to a higher retail price and a greater share of the market, thus enabling the manufacturer and the retailer to obtain more profit than they could without a cost-sharing contract. This may also explain why retailers are generally willing to bear the costs of greening products. The finding is relevant to green production and provides a meaningful reference that supply chain participants and policymakers can use to encourage manufacturers to produce greener products.

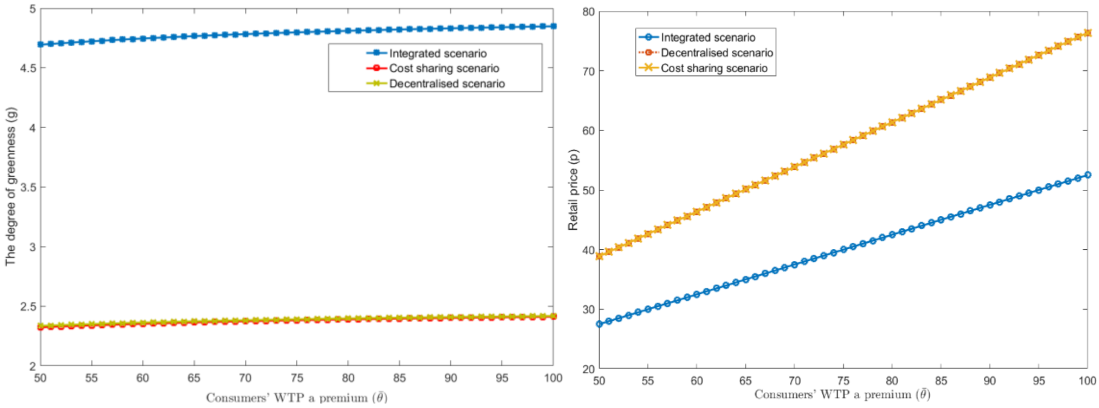
5. Numerical Study

In this section, we explain the numerical simulations that were carried out to support parts of the theoretical analysis described above. We assumed that $A = \mathrm{F}\left(1000,2000\right)$, $\alpha = \mathrm{F}\left(0.2,1\right)$, $c = 4$. Then $A = \Theta^{-1}\left(1-C\right) = 2000-1000C$, $\alpha = \Psi^{-1}\left(1-C\right) = 1-0.8C$. The value of $\bar{\theta}$ was varied from 50 to 100. The value of β had to satisfy the following requirement: $\beta > \dfrac{A\alpha^2}{8\bar{\theta}(1-\phi)}$. As described in the first subsection, we analysed the influence of consumer WTP for green products, the cost of greening, and consumer sensitivity to the degree of greenness on the decision variables, the market demand and supply chain profits under the condition of absolute risk aversion with *C*=1. We then compared the effects of these factors in different scenarios. The second subsection desceibes how we investigated the impact of the confidence level on the equilibrium results with a confidence level of less than 1.

5.1. Analysis of results under condition of absolute risk aversion with C=1

5.1.1. Impact of consumers' WTP a premium for green products

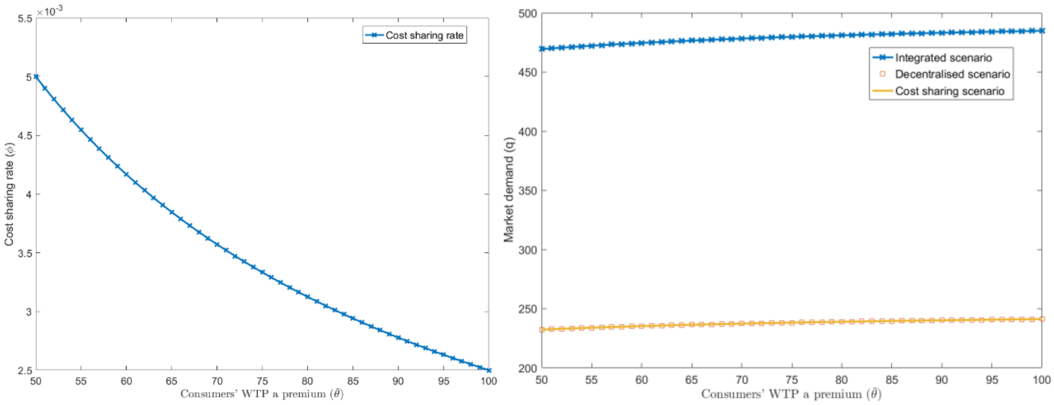
As a key factor that affects the demand for green products, consumer WTP for green products has attracted considerable attention from supply chain players. Thus, we first examined the effect of consumers' WTP a premium for green products on the optimal strategies that could be used by supply chain players, as well as on market demand and supply chain profits. Figure 3 shows that consumers' WTP a premium for green products has an increasing impact on the degree of greenness of a product and the retail price. Furthermore, the level of greenness of the product is highest in the integrated channel scenario and lowest in the decentralised channel scenario. More importantly, the cost-sharing rate borne by the retailer decreases with consumers' WTP a premium for green products. This can provide a reference that retailers could use for sharing the greening costs, which may be substantial in the sensitive green economy (see Fig. 4(a)). The market demand and supply chain profits increase with an increase in consumer WTP for green products (see Fig. 2 (b)) and Fig. 5). Interestingly, the integrated channel scenario has the largest market demand, and the decentralised channel scenario has the smallest market demand, a finding which is similar to that for the degree of greenness. In the case with a cost-sharing contract scenario, supply chain profits are higher than in the decentralised case, and 34% more profit on average can be obtained via the integrated supply chain than is the case with a cost-sharing contract.



(a) The impact of consumers' WTP a premium on the degree of greenness

(b) The impact of consumers' WTP a premium on the retail price

Fig 3. The impact of consumers' WTP a premium for green products on the degree of greenness and the retail price.



(a) The impact of consumers' WTP a premium on the cost-sharing rate

(b) The impact of consumers' WTP a premium on the quantity of market demand

Fig 4. The impact of consumers' WTP a premium for green products on the cost-sharing rate and the quantity of market demand.

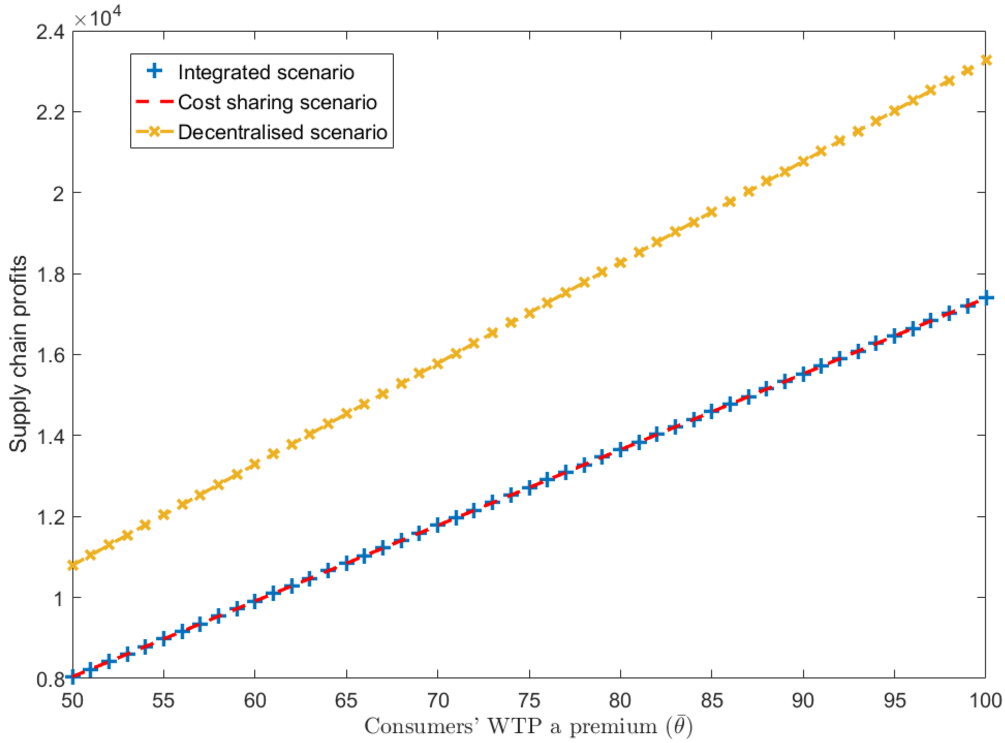
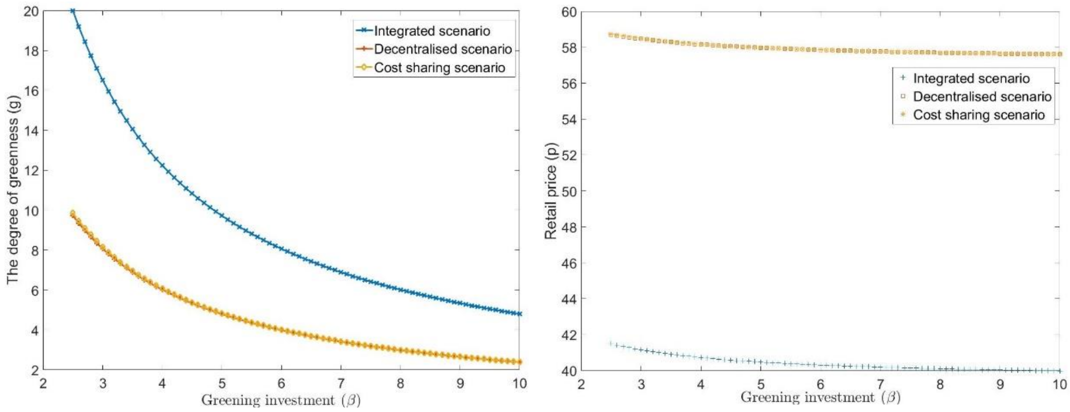


Fig 5. Impact of consumers' WTP a premium for green products on the profits of supply chain players.

5.1.2. Impact of greening investment

According to the following figures, investments in greening have an impact upon the decision variables, the cost-sharing rate, the market demand, and the profits of the supply chain participants (see Fig. 6 - Fig. 8). Furthermore, the level of greenness of a product is highest in the integrated channel scenario while the opposite is true for the decentralised channel scenario. More importantly, the cost-sharing rate offered by the retailer decreases with the level of investment in greening, which indicates that the retailer will reduce the cost-sharing rate in order to maximise profits as the manufacturer's investment in greening increases (see Fig. 8).



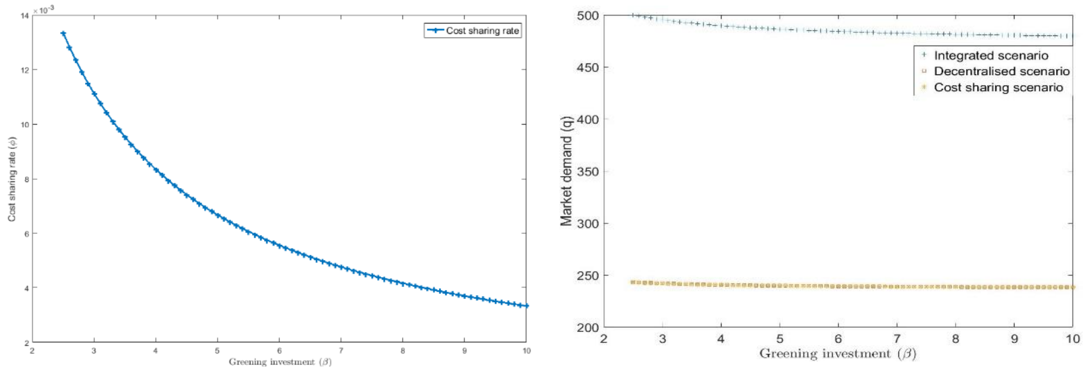
(a) The impact of greening investment on the

(b) The impact of greening investment

degree of greenness

on the retail price

Fig 6. The impact of greening investment on the degree of greenness and the retail price



(a) The impact of greening investment on the cost-sharing rate

(b) The impact of greening investment on the quantity of market demand

Fig 7. The impact of greening investment on the cost-sharing rate and the quantity of market demand.

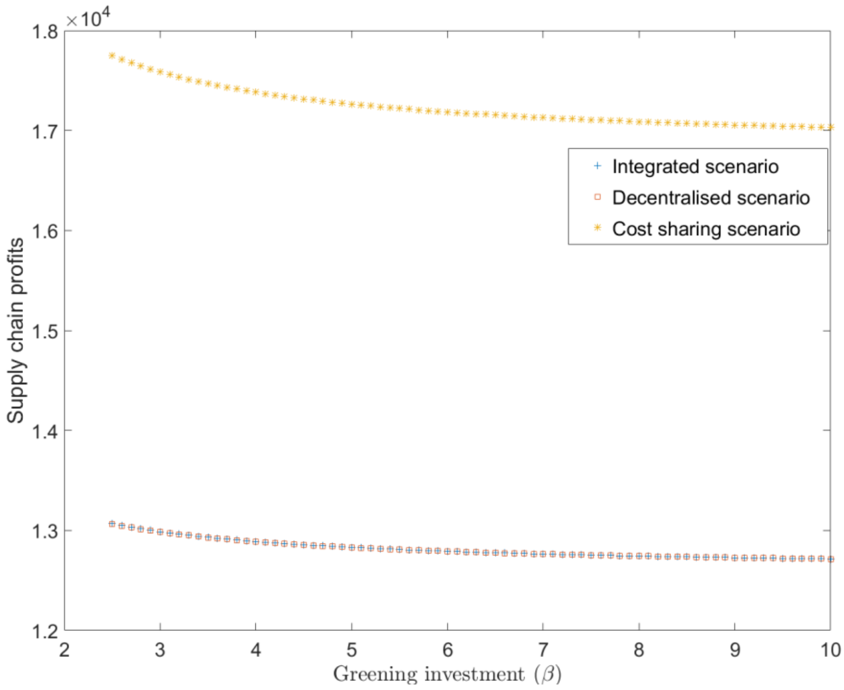
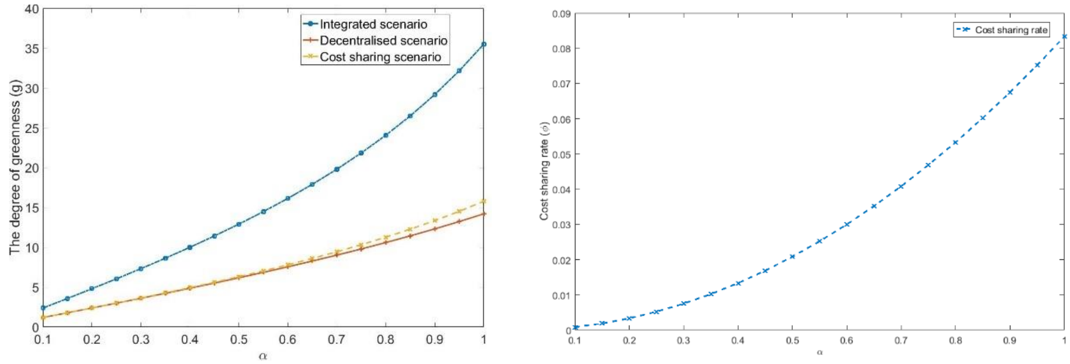


Fig 8. The impact of greening investment on the profits of the supply chain participants.

5.1.3. Influence of consumer sensitivity to the degree of greenness

Consumer sensitivity to the degree of greenness is another factor that can affect the demand for green products. We investigated the influence of consumer sensitivity to greenness using the degree of greenness and the cost-sharing rate. Fig. 9 (a) illustrates the equilibrium value of the degree of greenness under three scenarios. Compared to the other two scenarios, the integrated scenario has the highest degree of greenness with changes to α. This means that an integrated scenario can create a greener channel. Furthermore, according to Fig. 9 (b), increasing α can increase the retailer's cost-sharing rate with regard to green products. This is because an increase in α means that consumers are more concerned with the greenness of a product. A retailer that offers a higher cost-sharing rate can decrease the greening costs incurred by the manufacturer, thereby prompting the manufacturer to improve the degree of greenness of a product. This finding implies that supply chain participants and policymakers can enhance consumer sensitivity to green products through appropriate policies, and that this can contribute to promoting the development of the green product market.



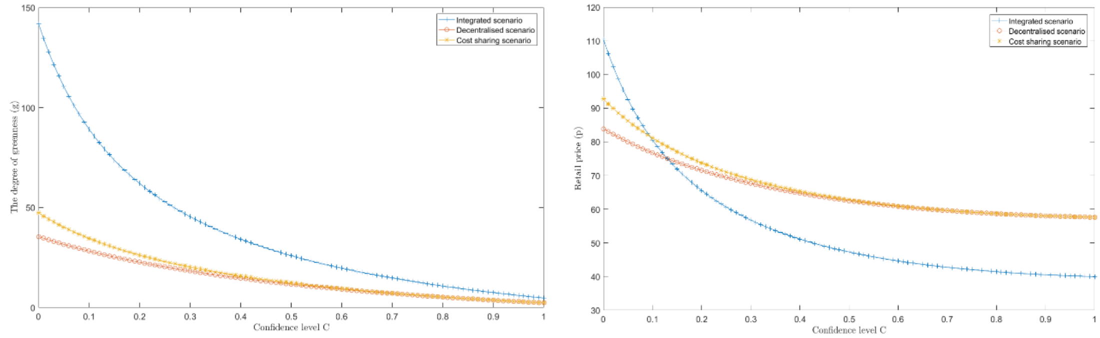
(a) The impact of consumer sensitivity on the degree of greenness of a product

(b) The impact of consumer sensitivity on the cost-sharing rate

Fig 9. The impact of consumer sensitivity on the degree of greenness of a product and the cost-sharing rate.

5.2. Analysis of results with C<1

In this section, we focus on the impacts of the confidence level on the degree of greenness, retail price, profits of supply chain members and cost sharing rate, respectively.



(a) The impacts of confidence level on the degree of greenness of a product

(b) The impacts of confidence level on retail price

Fig 10. The impacts of confidence level on the degree of greenness and retail price.

Fig. 10 illustrates that the degree of greenness of a product and the retail price decrease with respect to the confidence level. The degree of greenness under the integrated scenario is greater than under the cost sharing scenario, and is also greater than under the decentralised scenario. This is because investment in a green product will decrease as the risk increases, which will lead to a lower degree of greenness. However, the impact of the confidence level on the retail price follow a different trend. It was found that the retail price is still highest in the integrated scenario, when the confidence level is relatively low. As the confidence level increases, the value of the retail price decreases significantly and the rankings quickly drop. This is caused by the rapid decline in greenness of a product. Compared with the integrated scenario, the degree of greenness of a product under the decentralised scenario and the cost sharing scenario decrease more gently as the confidence level increases.

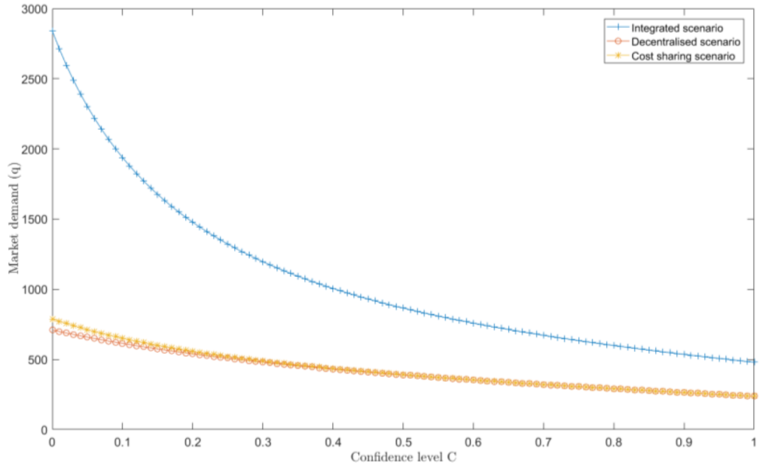


Fig 11. The impacts of the confidence level on market demand.

Fig. 11 shows that the impacts of the confidence level on market demand follows a similar trend to that observed for the greenness of a product. This may indicate that improving the greenness of a product has a positive effect on expanding the market share when other factors remain unchanged. Fig. 12 desplays the impacts of the confidence level on profits under different scenarios. It can be seen that the confidence level significantly affects the profits of the supply chain. Moreover, the confidence level has the greatest influence on the profits under the integrated scenario, but less influence under the decentralised scenario and the cost sharing scenario. The results shown in Fig. 12 are mainly due to the trends described above in relation to greenness and market demand.

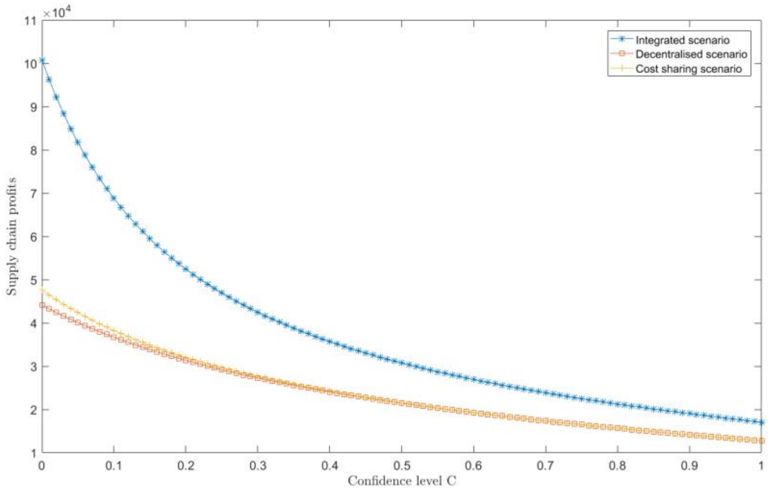


Fig 12. The impacts of confidence level on profits under different scenarios.

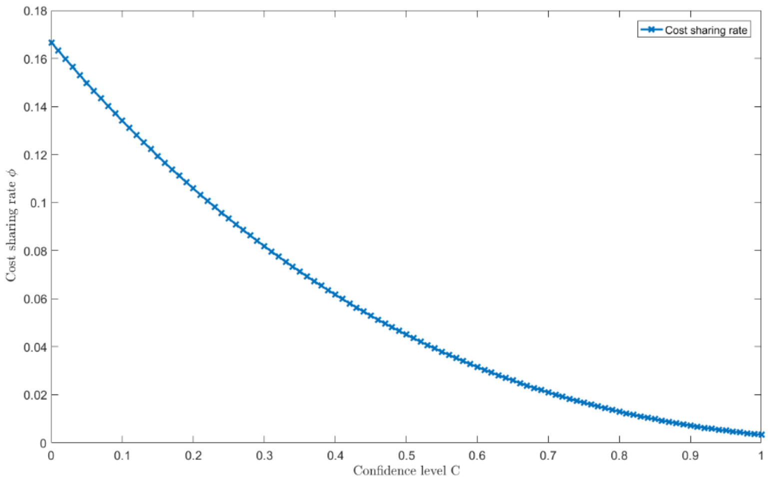


Fig 13. The impacts of confidence level on the cost sharing rate.

Fig. 13 illustrates the effects of the confidence level on the cost sharing rate. It can be seen that the confidence level significantly affects the cost sharing rate. When the risk rises, the retailer will lower the cost sharing rate to reduce the potential risks. A lower cost-sharing ratio would cause the manufacturer to invest less in green products, which would be detrimental to the promotion of green products and the development of a low-carbon economy. In this case, increasing consumer sensitivity to green products may help to mitigate the decline in the cost-sharing rate.

6. Discussion and Conclusions

As consumers become increasingly aware of environmental issues, they show a greater WTP for green products (Ghosh and Shah, 2015; Ishaswini and Datta, 2011). Thus, green market competition has become an active research area within the field of operations research. Moreover, the rapid development of green products has had the effect of attracting researchers to study strategic issues involving green products. In light of this, it is meaningful to investigate the impact of consumers' WTP for green products, investment in green technology, and green cost-sharing between supply chain participants. Motivated by these factors, we first explored consumers' WTP for green products and then investigated its impact on cost-sharing contracts and decision making by green supply chain participants. Two different cases were considered: one with a cost-sharing contract, and one without a cost-sharing contract.

This study produced some interesting and important findings. First, we found that consumer willingness to pay a higher premium for green products, counterintuitively, does not make the supply chain greener, and nor does it improve the quality of the environment. This explains why governments expend a great deal of effort on increasing consumer WTP for green products, but often do not achieve the expected outcomes. The finding also challenges the conventional argument that greater environmental awareness is beneficial for the green economy and the environment (Zhang et al., 2015). This may be due to a lack of focus on the transmission mechanism between consumers' WTP for green products and supply chain decisions. Therefore, predictions about the positive effect of consumer WTP on the development of the green supply chain appear to be over-optimistic. However, consumer willingness to pay more for green products and retailers sharing the costs of greening products can work in tandem to encourage manufacturers to increase their level of green investment. This study links consumers' WTP with the demand for green products and has shown that understanding this relationship can help to make the supply chain members more perceptive about changes in consumer preferences. If consumers prefer greener products and are willing to pay more for them, the manufacturer will rapidly increase their investment in green technology, which will incur higher costs. Consequently, the retailer will share the rapidly rising costs via a negotiated cost-sharing contract. However, the retailer will also be quick to anticipate that the manufacturer will invest more in the future, and hence the former will immediately make a cost-sharing adjustment and negotiate with the manufacturer to reduce the cost-sharing rate. Faced with rising costs, the manufacturer will eventually decelerate the pace of their investment in green products.

This finding is closely linked to green consumption, and could also provide a useful reference for supply chain participants and the government to explore incentivising mechanisms with which to increase the premium that consumers are willing to pay for green products and consumer sensitivity to greenness. To resolve this contradiction, retailers and manufacturers need to cooperate more closely. For example, in response to the 'Huawei Sustainability Report 2013', Huawei implemented a complete new green supply chain management system. Meanwhile, JD, China's second largest retailer in 2019, launched 'the Running Chicken', an innovative poverty alleviation project designed to integrate new supply chains in rural areas. The company also developed a green supply chain known as the 'Qingliu Plan'. Dell's business success owes much to its rapid response supply chain. The firm closely integrated upstream and downstream members and established an entire new mode of business operation built around customers and suppliers. Dell shares information with suppliers through an Enterprise Resource Planning (ERP) system to facilitate a highly flexible supply chain, which allows it to make dynamic adjustments to the production plans and fulfil the aim of achieving ‘virtual integration’. These findings can provide theoretical references and practical guidance for small and medium-sized enterprises in particular. In addition, this paper provides a theoretical reference for the integration of the green supply chain.

Second, although this study agrees with the findings of some previous research that retailers are willing to bear part of the greening costs together with manufacturers, the optimal cost-sharing rate produced by the modelling in this study is lower than the value claimed in previous research (e.g., Ghosh and Shah, 2015). This is perhaps due to the fact that our research took more practical considerations into account, most notably the effect of consumers’ WTP for green products on the participants’ decision-making process. This allows consumers’ preference for green products to be quickly and easily captured by manufacturers, who then respond by increasing their investment in green products. This increase in investment will incur higher costs, which will be partly borne by retailers under the terms of the cost-sharing contract. Thus, the retailer will negotiate with the manufacturers to reduce their share. In addition, unlike in the previous studies carried out by Liu (2012) and Zhang (2014) that optimise strategies by considering consumers’ environmental awareness, this study takes consumer WTP a premium for green products into account. By doing so, the supply chain participants can obtain a higher market share and produce more profits. In addition, we found that retailers are willing to lower the cost sharing rate to reduce the potential risks as the confidence level increases. As would be expected, when the risk increases, this is likely to lower the degree of greenness of a product, the retail price and the profits of supply chain members.

The main contribution of this work lies in exploring heterogeneous consumers’ WTP for green products and its effects on enabling optimal decisions to be made within a green supply chain under a cost-sharing contract and conditions of uncertainty. The findings can be used to help the manufacturer to make cost-sharing adjustments and negotiate with the retailer to bear a higher cost-sharing rate within the green product market, and thus contribute to creating a low carbon economy in the field of green supply chain management. First, this study is one of the first to shed light on the transmission mechanism that operates between consumer demand for green products and supply chain members’ (e.g., retailers and manufacturers) decisions under conditions of uncertainty by taking consumers’ WTP for green products into account. In recent years, due to increasing levels of awareness and education, concern for the environment and advertising campaigns, consumers have become increasingly willing to pay more for green products (Goldstein et al., 2008; Kaman, 2008; Sheehan et al., 2012; Zhang and Wu, 2012). If consumers’ WTP for green products is not taken into account in relation to decision-making within the green supply chain, it will make it much more difficult for retailers to respond to consumer preferences and understand or predict the behaviour of other members of the green supply chain. Our study focused on this aspect because of its relevance to current market trends.

Second, this study complements research on the traditional demand function by linking consumer WTP for green products to the demand for green products, in order to gain a more realistic and accurate understanding of the market and thus implement practices designed to improve the management of the green supply chain. This work is among the first to incorporate heterogeneous consumers' WTP into the demand for green products, and thus provides a key theoretical foundation for green supply chain decision-making and a means of achieving the optimal cost-sharing rate in the coordination of the green supply chain. If attention is not paid to consumers' WTP for green products in regard to decision-making within the green supply chain, retailers will find it hard to respond appropriately or understand the behaviour of other members of the green supply chain. Capturing this aspect could help supply chain members to quickly catch onto changes in consumer preferences and implement green supply chain practices in a timely manner.

Future research could focus on the main factors affecting consumers' WTP for green products based on empirical analysis of different types of products and consumer utility functions, so as to gain a more accurate picture of the impact of consumers' WTP for green products on the decision-making of supply chain members and on the environment. In addition, further research could also build on the findings of this study to explore the idea that consumers and supply chain players may make irrational decisions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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Appendix

Integrated channel scenario:

Proof of Theorem 1. In an integrated channel, we solve the supply chain's profit function:

$$\max_{p,g} \Pi_{SCI} = (p-c)\frac{\Theta^{-1}(1-C)\left[\bar{\theta}-p+\Psi^{-1}(1-C)g\right]}{\bar{\theta}}-\beta g^2$$

The first order conditions

$$\frac{\partial \Pi_{SCI}}{\partial p}=\frac{\Theta^{-1}(1-C)\left[\bar{\theta}-p+\Psi^{-1}(1-C)g\right]-\Theta^{-1}(1-C)(p-c)}{\bar{\theta}}$$

and

$$\frac{\partial \Pi_{SCI}}{\partial g}=\frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)(p-c)}{\bar{\theta}}$$

The Hessian $H=\begin{vmatrix}\frac{-2\Theta^{-1}(1-C)}{\bar{\theta}} & \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{\bar{\theta}}\\ \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{\bar{\theta}} & -2\beta\end{vmatrix}$,

H is negative definite for $4\beta\bar{\theta} > \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2$

By solving the first order conditions, we get

$$p_I = \frac{2\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

$$g_I = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)(\bar{\theta}-c)}{4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

□

Proof of Proposition 1

$$\frac{\partial g_I}{\partial \bar{\theta}} = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)\left[4\beta c - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2}$$

$$\frac{\partial p_I}{\partial \bar{\theta}} = \frac{1}{2} + \frac{\Psi^{-1}(1-C)}{2}\frac{\partial g}{\partial \bar{\theta}}$$

$$\frac{\partial q_I}{\partial \bar{\theta}} = \frac{2\Theta^{-1}(1-C)\beta\left[4\beta c - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2}$$

$$\frac{\partial \Pi_{SCI}}{\partial \bar{\theta}} = 2\beta\Theta^{-1}(1-C)(\bar{\theta}-c)$$

If $4\beta c > \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2$, $\frac{\partial g_I}{\partial \bar{\theta}} > 0, \frac{\partial p_I}{\partial \bar{\theta}} > 0, \frac{\partial q_I}{\partial \bar{\theta}} > 0, \frac{\partial \Pi_{SCI}}{\partial \bar{\theta}} > 0.$ □

Decentralised scenario:

Proof of Theorem 2

We first solve the retailer's profit function:

$$\max_p \Pi_{RD} = (p-w)\frac{\Theta^{-1}(1-C)\left[\bar{\theta} - p + \Psi^{-1}(1-C)g\right]}{\bar{\theta}} - \phi\beta g^2$$

The first order condition

$$\frac{\partial \Pi_{RD}}{\partial p} = \frac{\Theta^{-1}(1-C)\left[\bar{\theta} - p + \Psi^{-1}(1-C)g\right] - \Theta^{-1}(1-C)(p-w)}{\bar{\theta}}$$

The second order condition

$$\frac{\partial^2 \Pi_{RD}}{\partial p^2} = \frac{-2\Theta^{-1}(1-C)}{\bar{\theta}} < 0$$

Thus the retailer's profit function is strictly concave in p.

The optimal price is

$$p = \frac{\bar{\theta} + \Psi^{-1}(1-C)g + w}{2}$$

We then solve the manufacturer's profit function

$$\max_{\mathrm{w},w} \Pi_{MD} = (\mathrm{w}-c)\frac{\Theta^{-1}(1-C)\left[\bar{\theta} - p + \Psi^{-1}(1-C)g\right]}{\bar{\theta}} - \beta g^2$$

The first order condition:

$$\frac{\partial \Pi_{MD}}{\partial w} = \frac{\Theta^{-1}(1-C)\left[\bar{\theta} - w + \Psi^{-1}(1-C)g\right] - \Theta^{-1}(1-C)(\mathrm{w}-c)}{2\bar{\theta}}$$

$$\frac{\partial \Pi_{MD}}{\partial g} = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)(w-c)}{2\bar{\theta}} - 2\beta g$$

The Hessian H is:

$$H = \begin{vmatrix} \frac{\partial^2 \Pi_{MD}}{\partial w^2} & \frac{\partial^2 \Pi_{MD}}{\partial w \partial g} \\ \frac{\partial^2 \Pi_{MD}}{\partial g \partial w} & \frac{\partial^2 \Pi_{MD}}{\partial g^2} \end{vmatrix} = \begin{vmatrix} \frac{-\Theta^{-1}(1-C)}{\bar{\theta}} & \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{2\bar{\theta}} \\ \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{2\bar{\theta}} & -2\beta \end{vmatrix}$$

H is negative definite for $8\beta\bar{\theta}^2 > \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2$

Thus the manufacturer's profit function is jointly concave in w and g. We then get the following:

$$w(g) = \frac{\bar{\theta} + \Psi^{-1}(1-C)g + c}{2}$$

$$g(w) = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)(w-c)}{4\beta\bar{\theta}}$$

By substituting the value of w and g for the value of p, we get:

$$g_D = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)(\bar{\theta}-c)}{8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

$$w_D = \frac{4\beta\bar{\theta}(\bar{\theta}+c) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 c}{8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

$$p_D = \frac{2\beta\bar{\theta}(3\bar{\theta}+c) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 c}{8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

In order to make sure w_D is positive, $8\beta c > \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2$ should be satisfied. □

Proof of Proposition 2

$$\frac{\partial g_D}{\partial \bar{\theta}} = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)\left[8\beta c - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2} > 0$$

$$\frac{\partial p_D}{\partial \bar{\theta}} = \frac{12\beta\bar{\theta}\left[4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right] + 6\beta c\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{\left[8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2} > 0$$

$$\frac{\partial w_D}{\partial \bar{\theta}} = \frac{8\beta\bar{\theta}\left[4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right] + 4\beta\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{\left[8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2} > 0$$

$$\frac{\partial q_D}{\partial \bar{\theta}} = \frac{2\beta\Theta^{-1}(1-C)\left[8\beta c - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2} > 0$$

$$\frac{\partial \Pi_{MD}}{\partial \bar{\theta}} = \frac{2\beta(\bar{\theta}-c)\Theta^{-1}(1-C)[4\beta(\bar{\theta}+c) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]}{\left[8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^2} > 0$$

$$\frac{\partial \Pi_{SC}}{\partial \bar{\theta}} = \frac{\partial \Pi_{MD}}{\partial \bar{\theta}} + \frac{\partial \Pi_{RD}}{\partial \bar{\theta}} > 0$$

$$\frac{\partial \Pi_{RD}}{\partial \bar{\theta}} = \frac{2\beta(\bar{\theta}-c)\Theta^{-1}(1-C)}{\left[8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]^3}[8\beta^2\bar{\theta}^2$$

$$+24\beta^2 c\bar{\theta} - \beta(\bar{\theta}-c)\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 - 4\beta\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2] > 0$$

□

Integrated Scenario VS. Decentralised Scenario

Proof of Proposition 3:

$$p_D - p_I = -\frac{2\beta\bar{\theta}(\bar{\theta}-c)\left[4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right] + 6\beta\bar{\theta}(\bar{\theta}-c)\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{\left[4\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]\left[8\beta\bar{\theta} - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]} < 0$$

$$g_D - g_I = \frac{-4\beta\bar{\theta}(\bar{\theta}-c)\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{\left[4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]\left[8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]} < 0$$

$$q_D - q_I = \frac{-8\beta^2\bar{\theta}(\bar{\theta}-c)\Theta^{-1}(1-C)}{\left[4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]\left[8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]} < 0$$

□

Proof of Proposition 4:

$$\Pi_{SCD} - \Pi_{SCI} = \frac{\beta(\bar{\theta}-c)^2\Theta^{-1}(1-C)\left[-32\beta^2\bar{\theta}-4\beta\bar{\theta}^2\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{\left[4\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]\left[8\beta\bar{\theta}-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]} < 0$$

□

Cost sharing contract scenario

Proof of Theorem 3

We first solve the retailer's profit function

$$\max_{p} \Pi_R^c = (p-w)\frac{\Theta^{-1}(1-C)\left[\bar{\theta}-p+\Psi^{-1}(1-C)g\right]}{\bar{\theta}} - \phi\beta g^2$$

The first order condition

$$\frac{\partial \Pi_R^c}{\partial p} = \frac{\Theta^{-1}(1-C)\left[\bar{\theta}-p+\Psi^{-1}(1-C)g\right]-\Theta^{-1}(1-C)(p-w)}{\bar{\theta}}$$

The second order condition

$$\frac{\partial^2 \Pi_R^c}{\partial p^2} = \frac{-2\left[\Theta^{-1}(1-C)\right]^2}{\bar{\theta}} < 0$$

Thus Π_R^c is concave with p, and the optimal price is:

$$p = \frac{\bar{\theta}+w+\Psi^{-1}(1-C)g}{2}$$

We then solve the profit function of the manufacturer:

$$\max_{g,w} \Pi_M^c = (w-c)\frac{\Theta^{-1}(1-C)\left[\bar{\theta}-p+\Psi^{-1}(1-C)g\right]}{\bar{\theta}} - c(1-\phi)\beta g^2$$

The first order condition

$$\frac{\partial \Pi_M^c}{\partial w} = \frac{\Theta^{-1}(1-C)\left[\bar{\theta}-w+\Psi^{-1}(1-C)g\right]-\Theta^{-1}(1-C)(w-c)}{2\bar{\theta}}$$

$$\frac{\partial \Pi_M^c}{\partial g} = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)(w-c)}{2\bar{\theta}} - 2(1-\phi)\beta g$$

The Hessian H is:

$$H = \begin{vmatrix} \frac{-\Theta^{-1}(1-C)}{\bar{\theta}} & \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{2\bar{\theta}} \\ \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{2\bar{\theta}} & -2(1-\phi)\beta \end{vmatrix}$$

H is negative definite for $8\beta\bar{\theta}(1-\phi) > \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2$

The optimal values of g_D^c, w_D^c, p_D^c are:

$$g_D^c = \frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)(\bar{\theta}-c)}{8\beta\bar{\theta}(1-\phi) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

$$w_D^c = \frac{4\beta\bar{\theta}(1-\phi)(\bar{\theta}+c) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 c}{8\beta\bar{\theta}(1-\phi) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2},$$

$$p_D^c = \frac{2\beta\bar{\theta}(1-\phi)(3\bar{\theta}+c) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 c}{8\beta\bar{\theta}(1-\phi) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

Finally, we solve the retailer's optimal cost-sharing parameter ϕ by plugging g_D^c, w_D^c and p_D^c into the retailer's profit function:

$$\max_{\phi} \Pi_R^c(\phi) = \frac{\beta\Theta^{-1}(1-C)(\bar{\theta}-c)^2[4\beta\bar{\theta}(1-\phi)^2 - \phi\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]}{[8\beta\bar{\theta}(1-\phi) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}$$

The first order condition:

$$\frac{\partial \Pi_R^c}{\partial \phi} = \frac{4\beta(\bar{\theta}-c)^2\left[\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^4 - 16\beta\bar{\theta}\phi\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{[8\beta\bar{\theta}(1-\phi) - \Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^3}$$

The second order condition:

$$\frac{\partial^2 \Pi_R^c}{\partial \phi^2} < 0$$

Thus the optimal value of ϕ is:

$$\phi^* = \frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta\bar{\theta}}$$

As $8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2>0$, so $\phi<\dfrac{1}{3}$

The optimal profit functions of the manufacturer, retailer and supply chain are:

$$\Pi_{MD}^{c}=\frac{\beta\Theta^{-1}(1-C)(1-\phi)(\bar{\theta}-c)^2}{8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}$$

$$\Pi_{RD}^{c}=\frac{\beta\Theta^{-1}(1-C)(\bar{\theta}-c)^2[4\beta\bar{\theta}(1-\phi)^2-\phi\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}$$

$$\Pi_{SCD}^{c}=\frac{\beta\Theta^{-1}(1-C)(\bar{\theta}-c)^2[12\beta\bar{\theta}(1-\phi)^2-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}$$

□

Proof of Proposition 5:

$$\frac{\partial g_D^c}{\partial\bar{\theta}}=\frac{\Theta^{-1}(1-C)\Psi^{-1}(1-C)[8\beta(1-\phi)c-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}>0$$

$$\frac{\partial p_D^c}{\partial\bar{\theta}}=\frac{12\beta\bar{\theta}(1-\phi)[4\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]+6\beta c(1-\phi)\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}>0$$

$$\frac{\partial w_D^c}{\partial\bar{\theta}}=\frac{8\beta\bar{\theta}[4\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]+4\beta c(1-\phi)\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}>0$$

$$\frac{\partial q_D^c}{\partial\bar{\theta}}=\frac{2\beta\Theta^{-1}(1-C)(1-\phi)[8\beta c(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}>0$$

$$\frac{\partial\Pi_{MD}^c}{\partial\bar{\theta}}=\frac{2\beta\Theta^{-1}(1-C)(1-\phi)(\bar{\theta}-c)[4\beta(1-\phi)(\bar{\theta}+c)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2}>0$$

$$\frac{\partial\Pi_{RD}^c}{\partial\bar{\theta}}>0 \text{ for } \bar{\theta}>c$$

$$\frac{\partial\Pi_{SCD}^c}{\partial\bar{\theta}}=\frac{\partial\Pi_{MD}^c}{\partial\bar{\theta}}+\frac{\partial\Pi_{MD}^c}{\partial\bar{\theta}}>0$$

□

Proof of Proposition 6:

$$\frac{\partial\phi}{\partial\beta}=-\frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta^2\bar{\theta}}<0$$

$$\frac{\partial \phi}{\partial \Psi^{-1}(1-C)} = \frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{8\beta\bar{\theta}} > 0$$

$$\frac{\partial \phi}{\partial \bar{\theta}} = -\frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta\bar{\theta}^2} < 0$$

□

Proof of Proposition 7:

$$\frac{\partial g_D^c}{\partial \phi} = \frac{8\beta\bar{\theta}(\bar{\theta}-c)\Theta^{-1}(1-C)\Psi^{-1}(1-C)}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^2} > 0,\ g_D^c > g_D$$

$$\frac{\partial w_D^c}{\partial \phi} = \frac{4\beta\bar{\theta}(\bar{\theta}+c)+8\beta\bar{\theta}w_D^c}{8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2} > 0$$

$$\frac{\partial p_D^c}{\partial \phi} = \frac{\bar{\theta}}{2} + \frac{\Psi^{-1}(1-C)}{2}\frac{\partial g_D^c}{\partial \phi} + \frac{1}{2}\frac{\partial w_D^c}{\partial \phi} > 0$$

□

Proof of Proposition 8:

$$\frac{\partial \Pi_{MD}^c}{\partial \phi} = \frac{\beta(\bar{\theta}-c)\left(\Theta^{-1}(1-C)\right)^2\left(\Psi^{-1}(1-C)\right)^2}{8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2} > 0$$

$$\frac{\partial \Pi_{RD}^c}{\partial \phi} = \frac{4\beta(\bar{\theta}-c)^2\left[\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^4 - 16\beta\bar{\theta}\phi\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2\right]}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^3} > 0$$

$$\text{for}\ \phi = \frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta\bar{\theta}}$$

$$\frac{\partial \Pi_{SCD}^c}{\partial \phi} = \frac{\alpha\beta(\bar{\theta}-c)^2\left(\Theta^{-1}(1-C)\right)^2\left(\Psi^{-1}(1-C)\right)^2\left[\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2 - 8\beta\bar{\theta}\phi\right]}{[8\beta\bar{\theta}(1-\phi)-\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2]^3} > 0$$

$$\text{for}\ \phi = \frac{\Theta^{-1}(1-C)\left(\Psi^{-1}(1-C)\right)^2}{16\beta\bar{\theta}}$$

□