frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 12 January 2023
DOI 10.3389/fenvs.2022.1088162

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to
Environmental Economics and
Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 03 November 2022
ACCEPTED 30 December 2022
PUBLISHED 12 January 2023

CITATION
Shi C, Chen L, Yu W and Zhang Z (2023), Will the embedded service in supply chains play a role in lowering manufacturer's carbon emission and maintaining economic growth?
Front. Environ. Sci. 10:1088162.
doi: 10.3389/fenvs.2022.1088162

Will the embedded service in supply chains play a role in lowering manufacturer's carbon emission and maintaining economic growth?

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Introduction: The carbon cap and trade mechanism (CCTM) is forcing companies to reduce carbon emissions. Due to financial and technical constraints, manufacturers responsible for recycling and remanufacturing begin to seek embedded services from energy service companies (ESCOs), marking the emergence of embedded low-carbon service supply chains. The purpose of this paper is to explore the role of embedded low-carbon service in supply chains in lowering manufacturer's carbon emissions and maintaining economic growth.

Methods: In this paper, a decision model for risk-averse closed-loop supply chain for embedded low-carbon service in uncertain markets is built by using the Stackelberg theory and mean-variance (MV) approach. Equilibrium decisions, the manufacturer's expected utility growth, and total carbon emission reduction are obtained. Sensitivity analysis is performed for the main parameters.

Results: The results indicate that only when the manufacturer's risk aversion level and consumers' low-carbon preference are within the range of 0.35–0.9, can the manufacturer bring in embedded low-carbon service by cooperating with an ESCO through revenue-sharing contracts. When there is a higher carbon price, embedded low-carbon service can further increase the manufacturer's expected utility, maintain economic growth and reduce carbon emissions.

Discussion: Embedded low-carbon service in supply chains can play a role in lowering manufacturers' carbon emissions and maintaining economic growth when the manufacturer's risk aversion level, carbon price, and consumers' low-carbon preference are high. Theoretically, this study combines closed-loop supply chains (CLSCs) and embedded low-carbon services, enriching supply chain theories. In addition, the findings provide managerial insights for manufacturers, ESCOs, and governments.

KEYWORDS

embedded low-carbon service supply chain, risk aversion, revenue-sharing contract, carbon cap and trade mechanism, consumers' low-carbon preference

1 Introduction

The growing demand for products has caused significant CO_2 emissions from production, resulting in global warming (Xu et al., 2016; Ahmed and Sarkar, 2018). To curb CO_2 emissions and reverse the trend, governments and institutions with higher environmental awareness have implemented several stringent policies (Cheng et al., 2022). For example, many countries, including China, the EU, the US and Japan, have enacted carbon cap and trade mechanism (CCTM) policies (Toptal and Çetinkaya, 2017; Liu H. et al., 2021). According to the CCTM, there are two main carbon allowances for manufacturers: the government-issued carbon allowances and the additional allowances purchased from the carbon market (Du et al., 2015). In other words, manufacturers can sell their surplus carbon allowances in the carbon market; Or if their carbon allowances are insufficient, they can purchase them from the carbon market to meet the goal.

Meanwhile, consumers' low-carbon preference is becoming increasingly important. For example, their low-carbon preference has increased product demand (Hadi et al., 2021; Qiao et al., 2021), leading to a growing number of manufacturers engaging in emission reduction for higher revenue. Against such a backdrop, manufacturers must implement their emission reduction initiatives to make green upgrades and develop products with high efficiency and low emissions. That is, they have to green and invest heavily in upgrading their equipment. For example, Wuhan Iron and Steel Group invested more than 200 million yuan in emission reduction technology upgrades. For manufacturers with financial difficulties, seeking embedded low-carbon service from an energy service company (ESCO) is a feasible solution. Embedded low-carbon service refers to the model in which the ESCO as a low-carbon service provider is integrated into a manufacturer's operation through investment and business embedding to provide low-carbon service (Liao et al., 2022). For example, Siemens Energy cooperated with the Nigeria LNG plant by investing in and implementing emission reduction operations, and both parties shared the benefits generated from low-carbon activities (Liao et al., 2022). Similarly, Honeywell has provided carbon reduction services to Shenzhen Tsingtao Brewery (Ouyang and Fu, 2020).

Furthermore, remanufacturing can make used products usable again, restoring the value of the old products while saving resources (Jung and Hwang, 2011). Therefore, closed-loop supply chains (CLSCs) that perform the functions of recycling and remanufacturing have become a trend (Mogale et al., 2022). In addition, risk is an inherent characteristic of supply chains (Kusi-Sarpong et al., 2021). When the manufacturer shares the earnings of the supply chain with ESCO, carbon reduction risk is also transferred to ESCO. However, faced with uncertain market demand and CCTM, manufacturers still risk financial losses and not achieving optimal emission reductions (Liao et al., 2022). In addition, selecting the right partners and taking advantage of their resources effectively throughout the supply chain also remain challenging for manufacturers (Cheng et al., 2011). Therefore, ESCOs and manufacturers have different risk aversion levels that may cause troubled coordination within low-carbon service supply chains.

To explore the role of embedded low-carbon service in supply chains in lowering manufacturer's carbon emissions and maintaining economic growth, this paper builds a model of the risk-averse closed-loop supply chain for embedded low-carbon service with the participation of a risk-averse manufacturer that performs recycling and remanufacturing and a risk-averse ESCO that provides low-carbon service. Expected utility and equilibrium decision outcomes of the supply chain led by a manufacturer are discussed, and so are the amount of expected utility growth and total emission reduction for manufacturers choosing embedded low-carbon service. Therefore, the major issues explored in this study are as below: 1) Manufacturers choose embedded low-carbon services to increase emission reduction and expected utility. Can they achieve this purpose through revenue-sharing contracts? If not, under what conditions can they achieve their purposes? 2) How do the manufacturer's and ESCO's risk aversion levels, consumers' low-carbon preference, and the carbon price affect equilibrium decisions and the expected utility of the supply chain?

This study has three main contributions: 1) Based on the Stackelberg game, a decision model of the risk-averse closed-loop supply chain for embedded low-carbon service is constructed. Unlike previous models, it considers the co-existence of embedded low-carbon service and remanufacturing, as well as the factors like the risk aversion level, market uncertainty, carbon price and carbon allowance. Also, the model's operation rules are discussed, which enriches relevant supply chain theories. 2) By comparing and analyzing the differences between the manufacturer's expected utility and total emission reduction before and after the introduction of embedded ESCO, the role of embedded low-carbon service in supply chains in lowering the manufacturer's carbon emissions and maintaining economic growth is explored. 3) By using the mean-variance (MV) approach to describe the risk-averse characteristics, this study can not only solve the problem of de-randomization of embedded low-carbon service in closed-loop supply chains but also analyze the equilibrium decision-making problem in the supply chain through expected utility.

The paper is organized into eight sections. Section 2 will review the relevant literature. Then, the model of the risk-averse closed-loop supply chain for embedded low-carbon service will be introduced in Section 3. In Section 4, relevant game models will be constructed and analyzed. After that, sensitivity analysis and an analysis of the expected utility growth and the total amount of emission reduction will be conducted using numerical simulations in Section 5. Section 6 will analyze the results of the article. Section 7 will present managerial implications and the conclusions and limitations will be presented in Section 8.

2 Literature review

As mentioned above, this study examines the decision-making of a risk-averse ESCO and a risk-averse manufacturer in the closed-loop supply chain for embedded low-carbon service under carbon trading constraints. Therefore, studies on service supply chains, risk aversion and carbon policies are selected for a comprehensive review.

2.1 Service supply chains

Service is becoming increasingly important in global economies, making the concept of the service supply chain (SSC) conspicuous in current operations management (Cheng et al., 2011). According to Peng et al. (2009), research on the SSC could be divided into two directions: 1) SSC as related service activities in traditional supply chains; 2) SSC as an innovation that applies traditional supply chain theories to the service sector. Similarly, Wang et al. (2015) discussed the definitions of the SSC and classified it into service-only supply chains (SOSC) and product service supply chains (PSSC). In SOSC, no physical products are offered. For instance, Ren et al. (2022) studied the quality and pricing issues in IT service supply chains. And Farsi

TABLE 1 Comparison of related literature studies.

Authors	Type of supply chain		Demand pattern		Coordinated contract		Risk	CCTM	Consumer preferences
	Low-carbon services	Closed-loop	Certain	Uncertain	Revenuesharing	Costsharing			
Qian and Guo (2014)	√		√		√		√		
Shang et al. (2015)	√		√		√		√		
Wang and He (2018)	√			√			√		√
Goli et al. (2019)				√			√		
Zhang et al. (2020)	√		√		√				
He et al. (2020)	√		√			√			√
Ouyang and Fu (2020)	√		√		√				√
Gupta and Ivanov (2020)				√			√		
Xia et al. (2020)			√			√			√
Qu et al. (2021)		√	√		√			√	
Liu et al. (2021)			√			√		√	√
Kalantari et al. (2022)		√		√			√	√	
Zhu et al. (2022)				√		√	√		√
Liao et al. (2022)	√		√		√				√
Zang et al. (2022)				√		√	√		
Das et al. (2022)		√		√			√		
Mao et al. (2022)	√		√		√		√	√	
This paper	√	√		√	√		√	√	√

et al. (2020) explored supply chains that offer customized services such as customer maintenance and facility management. By contrast, in PSSC, service coexists with physical products. For instance, Jia et al. (2019) and Niu et al. (2022) analyzed logistics service supply chains that provide logistics and distribution services for products. And Liao et al. (2022) explored low-carbon service supply chains that reduce product carbon emissions.

Scholars have also studied the issue of contract design for low-carbon service supply chains. In examining the cost-sharing decision in low-carbon service supply chains, He et al. (2020) integrated the variable of corporate social responsibility into the research. They not only examined an ESCO but also a service integrator of low-carbon advertising. Shang et al. (2015) argued that issues in the benefits distribution of energy efficiency in embedded low-carbon service programs were a barrier to the rapid development of contracting. Qian and Guo (2014) also studied the design of revenue-sharing contracts between ESCOs and manufacturers and analyzed what revenue-sharing contracts were optimal. In addition, Ouyang and Ju (2017) examined how manufacturers differed in their choice of ESCO partnership models. Ding et al. (2017; 2018) analyzed the behavior of outsourced emission reduction services for coal-fired power plants. Ouyang and Fu (2020) explored how consumers' low-carbon preference impacted the manufacturer's choice of ESCOs. Zhang et al. (2020) examined the effect of the revenue-sharing rate on the quality of ESCO's service. Mao et al. (2022) examined the effect of financing risk in the embedded low-carbon service supply chain. Liao et al. (2022) analyzed an embedded low-carbon service supply chain containing a manufacturer and an ESCO in a certain market context. They explored the issue of contract design with varying ESCO emission reduction efficiency under the information asymmetry between manufacturers and ESCOs.

2.2 Risk aversion

Risk aversion is a strategy used by an enterprise to voluntarily discontinue from or alter the risk of loss of an action to avert potential risks associated with the action. Thus, in the low-carbon service supply chain, the risk aversion level may cause ESCOs and manufacturers to renounce or terminate the implementation of the supply chain. Das et al. (2022) established a two-stage risk-averse closed-loop supply chain. They noted that a risk-averse approach that incorporated the effects of stochastic outcome variability would provide a more robust performance compared to a risk-neutral approach. Qu and Yang (2015) explored the relationship between risk aversion level and social trust in supply chains. Liu et al. (2018) stated that the risk

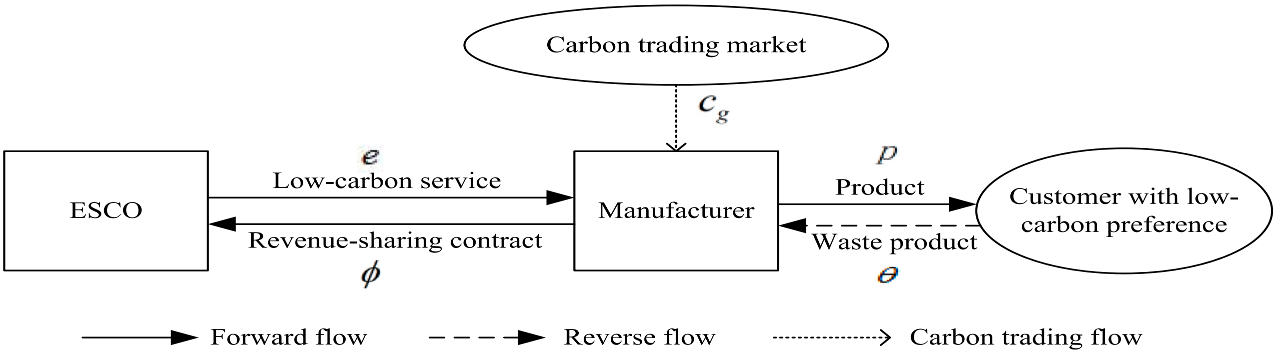

FIGURE 1
The model of the closed-loop supply chain for embedded low-carbon service.

aversion level could impact channel optimization in supply chains. They also explored the effect of supply chain disruption risks on the channels. Luo et al. (2018) studied repurchase agreements in the supply chain considering the risk aversion level. Gupta and Ivanov (2020) examined the role of the risk aversion level on supply chain decisions in the sharing economy. Zhu et al. (2022) studied green investment solutions in a rice supply chain containing risk-averse growers and risk-neutral suppliers.

Many studies have adopted the MV approach regarding the measurement of risk aversion levels. For instance, Choi (2011) used the MV approach for a two-channel risk-averse supply chain and showed that radio frequency identification could add to the profitability of the supply chain. Using the MV approach, Gan et al. (2011) analyzed multiple risk aversion scenarios and proposed corresponding optimal solutions. Shen et al. (2013) explored suppliers' risk-averse pricing strategies for price reduction in textile and apparel supply chains. Li et al. (2013) examined the supply chain containing a supplier and multiple retailers and analyzed how returns were made within the supply chain when they were all risk-averse. Wang and He (2018) examined the contractual design issue in a low-carbon service supply chain comprised of a supplier, a manufacturer and a low-carbon service provider. Furthermore, they analyzed the effect of risk aversion levels of the manufacturer and supplier on the contract. Goli et al. (2019) used the MV approach to determine the risk level of the product portfolio. Adopting an MV research framework, Wen and Siqin (2020) explored how risk aversion levels and the uncertainty of product quality might influence optimal decisions on sharing economy platforms. Zang et al. (2022) examined the sharing of external costs between risk-averse suppliers and manufacturers in two-stage supply chains with different power structures. They found that under the MV framework, the supplier and manufacturer who were more risk-averse earned less.

2.3 Carbon policies

Many scholars have researched carbon policies concerning low-carbon emissions in supply chains. Jin et al. (2014) examined the three most common carbon policies: carbon taxes, strict carbon caps and the CCTM. And their research implications for companies include redesigning the supply chains and selecting different transport modes (truck, rail or water). Toptal et al. (2014) evaluated the role of multiple carbon policies on the optimal supply chain decision. Wang et al. (2017) analyzed the relationship between supply chain decisions and carbon tax policies. Tirkolaee et al. (2020) explored the optimization of supply chain operations by considering factors, such as carbon emissions and customer satisfaction. Xia et al. (2020) explored the effect of consumers' low-carbon preference on the carbon emissions of supply chains. Golpîra and Javanmardan (2022) focused on optimizing CLSCs in the context of carbon emissions in their research. Another theme in the current literature is carbon trading. Considering the uncertainty of recycling quality,

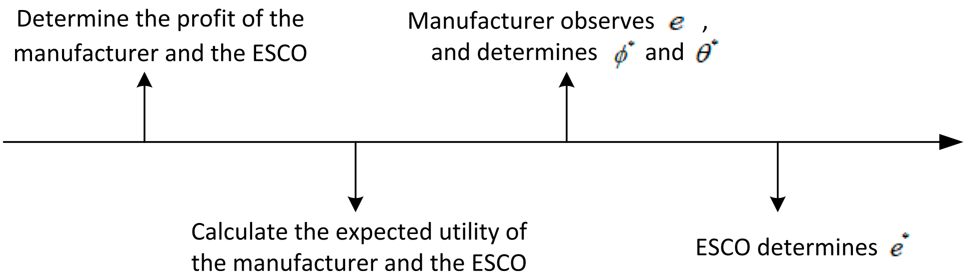

FIGURE 2
The methodological framework.

Zhao et al. (2021) investigated the optimal production decision for CLSC in a carbon market. Wei et al. (2021) evaluated the role of carbon trading in renewable energy investment and marketing activities based on an electricity supply chain. Entezaminia et al. (2021) discussed the joint production and carbon trading policies in supply chain systems under trading supervision. Yang et al. (2021) investigated the non-compliant behaviors of CLSC companies in carbon trading. They found that violation penalties, remanufacturing rates, and carbon emissions can affect all members' decisions in the CLSC network. Kalantari et al. (2022) explored the effect of policies such as carbon trading and carbon tax on closed-loop supply chains in the scenario of inflation. Using the remanufacturing of spring pallets as an example, Haolan et al. (2022) analyzed the effect of carbon price fluctuations on CLSC under demand uncertainty.

Some scholars have examined the effect of the CCTM on supply chains using the Stackelberg game. The Stackelberg game is a simple game where both leaders and followers make decisions to maximize their respective profits (Meng et al., 2021). Adopting the Stackelberg approach, Du et al. (2015) examined the influence of the CCTM on CLSC. Du et al. (2016) addressed the issue of the manufacturer's joint multi-product pricing when consumers have low-carbon preference. More specifically, they found conditions under which enterprises can maximize their profit in low-carbon production. With consumers' low-carbon preference and social preference considered, Xia et al. (2018) examined the influence of carbon reduction and CCTM policies on the supply chain led by the manufacturer. Liu M. et al. (2021) developed a Stackelberg model to explore the best scenario for joint manufacturer and retailer emission reduction under the CCTM. And Qu et al. (2021) adopted the Stackelberg approach to analyze how to optimize the supply chain for emission reduction under the CCTM. In addition, Gong and Zhou (2013) analyzed a model to provide enterprises with optimal emissions trading, technology choices and production strategies under the CCTM. Xu et al. (2017) studied supply chains built upon the CCTM, pointing out that carbon price can significantly affect the optimal decision of supply chains. Drawing on the optimized consensus model and the basic allocation scheme from the closed-loop supply chain trading system that considered income and equity, Xu et al. (2021) proposed a theoretical innovation in their research and designed a flexible cap and trade scheme.

In conclusion, the following research gaps can be identified: 1) Studies related to traditional low-carbon service supply chains focus more on the bargaining power of manufacturers and ESCOs. There lack studies on closed-loop supply chains for embedded low-carbon service in an uncertain market, considering factors like supply chain risks, carbon price, carbon allowances, and product recycling. 2) Studies on closed-loop supply chains for recycling and remanufacturing that use the MV approach to measure supply chain risks and incorporate ESCOs are scarce. 3) Few studies consider the role of the CCTM in the decision-making of the closed-loop supply chain for embedded low-carbon service. Therefore, considering demand uncertainty and the risk aversion level of ESCOs and manufacturers, this paper will build a Stackelberg model of a risk-averse closed-loop supply chain for embedded low-carbon service to explore how embedded low-carbon service in supply chains lowers manufacturer's carbon emission and maintains economic growth. A comparison of the relevant literature reviewed is shown in Table 1.

3 Model description and parameters

3.1 Model description

To explore the role of embedded low-carbon service in supply chains in lowering manufacturer's carbon emissions and maintaining economic growth, this paper examines a closed-loop supply chain for embedded low-carbon service that includes a manufacturer who is responsible for recycling, production and remanufacturing and an ESCO who provides low-carbon service (shown in Figure 1). And both of them have different risk aversion levels facing market demand uncertainty, consumers' low-carbon preference and the CCTM. Aligned with Liao et al. (2022), the ESCO (t) is not only responsible for emission reduction investments but also offers low-carbon service to the manufacturer (m), who is responsible for recycling, production and remanufacturing. And the two parties share the earnings obtained from low-carbon products.

This paper will build a Stackelberg model and construct the expected utility function using the MV approach. The reason for adopting the MV approach is that it can portray the risk aversion level of supply chain participants, which is a risk analysis method widely used in supply chain studies (Zhu et al., 2022). Meanwhile, the market demand in this paper is uncertain and follows a normal distribution. The manufacturer and ESCO will make equilibrium decisions between high returns and low risks.

The Stackelberg approach model is a game between leaders and followers. Since it considers the status and information asymmetries that exist between the participants, which is close to reality, it is widely used in pricing and decision-making in the supply chain (Yang et al., 2021). In the Stackelberg game, the leader has a significant advantage in predicting followers' reactions and

TABLE 2 Relevant variables and parameters.

	Definition
Decision variables	
π_i	Profit of node companies in supply chain, $i = t, m$
$E(U_i(\pi_i))$	Expected utility of node companies in supply chain, $i = t, m$
ϕ	Revenue-sharing rate for the manufacturer and ESCO
θ	Recycling rate of used products
e	Unit carbon emission reduction of ESCO
Parameters	
k_i	Risk aversion level, $i = t, m$, $0 \le k_i \le 1$
q	Output of low-carbon products
p	Selling price per unit of low-carbon product
a	Basic market size
σ	Variance
δ	Consumers' low-carbon preference
Δ	Marginal cost savings from remanufacturing, $\Delta = c_m - c_r$
e_0	Initial carbon emissions of new and remanufactured products
λ	Carbon emission reduction level of ESCO, $\lambda = e/e_0$
m	Unit carbon emission reduction cost of ESCO
G	Carbon allowances allocated by the government
c_g	Unit carbon price
b	Purchasing price of used products
h	Difficulty level of recycling
μ	Difficulty level of emission reduction

making decisions to maximize profits (Meng et al., 2021). In this paper, the game's leader is the manufacturer, and the ESCO is the follower. Therefore, the sequence of decision-making is as below: firstly, the manufacturer proposes the revenue-sharing and recycling rates to the ESCO. Then the ESCO decides on the sum of carbon reduction in light of revenue maximization. The methodological framework is shown in Figure 2.

3.2 Model variables and parameters

To construct the profit functions for the manufacturer and ESCO, this paper assumes that the model of the closed-loop supply chain for embedded low-carbon service satisfies the following conditions.

1) Both participants in the closed-loop supply chain for embedded low-carbon service are risk-averse. Their risk characteristics are measured by the MV function (Wei and Choi, 2010). The expected utility function is written as $E(U_i(\pi_i)) = E(\pi_i) - k_i\sqrt{Var(\pi_i)}$.
2) As consumers prefer low-carbon products, the low-carbon feature becomes an essential factor influencing market demand. And the market demand X is random (Zhu et al., 2022), $X = q + \varepsilon$, here, $q = a + \delta e$, $\varepsilon \in N(0, \sigma^2)$.
3) It costs a manufacturer c_m to produce a low-carbon product from fresh raw materials; c_r to remanufacture using recycled materials; $c_r < c_m$. The remanufactured low-carbon product is of the same quality and sells at the same price as the new product (Liu, 2019).
4) The fixed emission reduction cost of an ESCO is written as $\mu\lambda^2/2$ (Qu et al., 2021). The manufacturer's total fixed cost of recycling is written as $h\theta^2/2$ (Liu, 2019).

Other relevant variables and parameters are described in Table 2.

4 Model construction and analysis

4.1 Model construction

The sequence of the game in the closed-loop supply chain for embedded low-carbon service is as follows: First, the manufacturer proposes to the ESCO ϕ as well as θ, and then the ESCO makes a decision based on the principle of revenue e maximization. At this point, according to the model variables and parameters given in Section 3.2, the ESCO's profit is expressed as follows:

$$\pi_t^e = (1-\phi)pX - meq - \frac{1}{2}\mu\lambda^2 \tag{1}$$

In Equation 1, the first term indicates the earnings allocated to the ESCO from the manufacturer's sales of low-carbon products; the second term indicates the ESCO's emission reduction cost; the third term is the fixed cost of the ESCO's investment in emission reduction technology.

The manufacturer's profit is expressed below:

$$\pi_m^{\phi,\theta} = \phi pX - c_g\left((e_0 - e)q - G\right) - c_m q + (\Delta - b)\theta q - \frac{1}{2}h\theta^2 \tag{2}$$

In Equation 2, the first term indicates the earnings allocated to the manufacturer from its sales of low-carbon products; the second term is the benefit or cost of the manufacturer's carbon allowance; the third term refers to the production cost; the fourth term means the cost savings from remanufacturing; the fifth term indicates the total fixed investment cost of recycling.

According to the MV approach, the expected utility functions of the ESCO and the manufacturer are written as below:

$$\begin{aligned} E(U_t(\pi_t^e)) &= E(\pi_t^e) - k_t\sqrt{D(\pi_t^e)} \\ &= \left[(1-\phi)p - me\right](a+\delta e) - k_t(1-\phi)p\sigma - \frac{\mu e^2}{2e_0^2} \end{aligned} \tag{3}$$

$$\begin{aligned} E\left(U_m\left(\pi_m^{\phi,\theta}\right)\right) &= \phi p(a+\delta e) - k_m\phi p\sigma \\ &\quad - \left[c_g(e_0 - e) + c_m - (\Delta - b)\theta\right](a+\delta e) + c_g G - \frac{1}{2}h\theta^2 \end{aligned} \tag{4}$$

The equations are solved using inverse operations. Lemma 1 is the result of the equilibrium decision (details in Appendix A).

Lemma 1. The recycling rate, revenue-sharing rate and unit carbon emission reduction for the equilibrium decision are as follows:

$$\theta^* = \frac{(b-\Delta)\left(\mu(a+\sigma k_m) + \delta e_0^2\left(am + p\delta - \delta c_m - c_g(a+\delta e_0) + 2m\sigma k_m\right)\right)}{A} \tag{5}$$

$$\begin{aligned} \phi^* = {} & (\delta^2 e_0^4(2hp\delta c_g - (am+p\delta)(2hm - \delta(b-\Delta)^2) + 2hm(2m\sigma k_m - \delta c_m)) + \delta\mu e_0^2(a(\delta(b-\Delta)^2 - \\ & 3hm) + h(ac_g - \delta c_m + 4m\sigma k_m) - hp\delta) - h\delta^2\mu c_g e_0^3 - 2hm\delta^3 c_g e_0^5 + h\mu^2(\sigma k_m - a))\big/ Ap\delta^2 e_0^2 \end{aligned} \tag{6}$$

$$e^* = \frac{ah\mu + \delta e_0^2(a(3hm - \delta(b-\Delta)^2) + h\delta c_m + hc_g(\delta e_0 - a) - hp\delta) - h\sigma(\mu + 2m\delta e_0^2)k_m}{\delta A} \tag{7}$$

where $A = -2h\mu + \delta e_0^2(-4hm + \delta(b-\Delta)^2 + 2hc_g)$. Substitute θ^*, ϕ^* and e^* into $E(U_t(\pi_t^e))$ and $E(U_m(\pi_m^{\phi,\theta}))$, then the expected utility of the ESCO and the manufacturer can be obtained.

4.2 Analysis of model properties

4.2.1 The impact of embedded low-carbon service on the manufacturer

To analyze and compare the changes in the expected utility of manufacturers after introducing embedded ESCOs, a scenario without ESCO involvement needs to be considered. Under this scenario, we assume $e = 0$, $\phi = 1$, then $q = a$. Then, the manufacturer's expected utility is as below:

$$E\left(U_m\left(\pi_m^{\theta}\right)\right) = pa - k_m p\sigma - \left[c_g e_0 + c_m - (\Delta - b)\theta\right]a + c_g G - \frac{1}{2}h\theta^2 \tag{8}$$

Given the manufacturer's target of maximizing benefits and the fixed recycling rate of used products, Lemma 2 can be obtained (details in Appendix B).

Lemma 2. The manufacturer's maximum expected utility without introducing an ESCO is as follows:

$$E\left(U_m\left(\pi_m^{\theta}\right)\right)^* = ap + \frac{a^2(b-\Delta)^2}{2h} + c_g(G - ae_0) - ac_m - p\sigma k_m \tag{9}$$

$E_0{}^*$ is assumed to be the amount of expected utility growth after the manufacturer introduces an embedded ESCO, then $E_0{}^* = E(U_m(\pi_m^{\phi,\theta}))^* - E(U_m(\pi_m^{\theta}))^*$.

An analytical derivation of E_0* concerning relevant influencing factors leads to Proposition 1.

Proposition 1. As the manufacturer's risk aversion level and consumers' low-carbon preference increase, its expected utility growth is a convex function. And the manufacturer's expected utility growth is positively associated with the carbon price, independent of the risk aversion level of the ESCO.

Proposition 1 suggests that as factors such as the manufacturer's risk aversion level increase, the quantity of growth in the manufacturer's expected utility falls and then rises. During the falling process, the growth may become negative (see the simulation results in Section 5.2). In other words, although cooperating with an ESCO can achieve the goal of carbon emission reduction, it is at the expense of the manufacturer's expected utility. Therefore, when considering whether to partner with an embedded ESCO, manufacturers must consider the factors of consumers' low-carbon preference, their risk aversion levels and the carbon price.

4.2.2 Analysis of factors influencing balanced decision making

Proposition 2. The recycling rate of used products and unit carbon emission reduction are positively associated with the carbon price, consumers' low-carbon preference and the manufacturer's risk aversion level. They are independent of the ESCO's risk aversion level. The opposite conclusion can be reached for the revenue-sharing rate.

Proposition 3. The expected utility of an ESCO is positively associated with the manufacturer's risk aversion level, consumers' low-carbon preference and the carbon price. The expected utility of an ESCO is positively correlated with its risk aversion level when manufacturers have a lower risk aversion level. And an opposite conclusion can be made when manufacturers have a higher risk aversion level.

Proposition 4. The manufacturer's expected utility positively correlates with the carbon price. However, it is negatively correlated with its risk aversion level and is unrelated to the ESCO's risk aversion level.

Propositions 2–4 show the role of the carbon price, risk aversion level, and consumers' low-carbon preference on the recycling rate of used products, revenue-sharing rate, unit carbon emission reduction and expected utility of the manufacturer and the ESCO. It could be argued that different influencing factors have different mechanisms for controlling the equilibrium solutions of the participants in the closed-loop supply chain for embedded low-carbon service. Therefore, manufacturers and ESCOs need to exchange and communicate promptly and weigh up the benefits and losses when making decisions.

4.2.3 Analysis of factors influencing the total emission reduction

To explore the factors influencing the total amount of emission reduction, it is essential to obtain the total emission reduction eq, which is $(a + \delta e^*)e^*$. And Proposition 5 can be derived by taking partial derivatives of the total emission reduction.

Proposition 5. The total emission reduction of the closed-loop supply chain for embedded low-carbon service is positively associated with the carbon price, manufacturer's risk aversion level and consumers' low-carbon preference. But the risk aversion level of ESCOs does not affect the total amount of emission reduction.

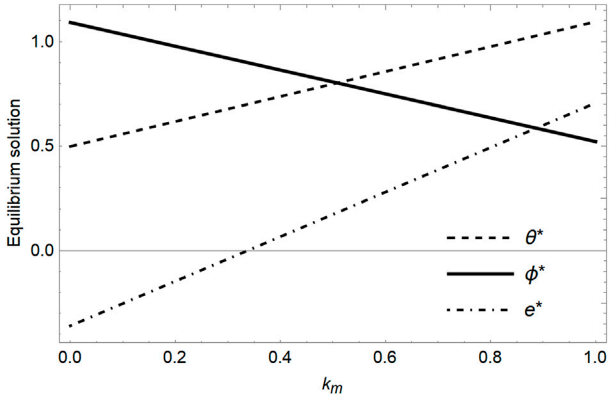

FIGURE 3
The impact of k_m on equilibrium solutions.

Proposition 5 suggests that the carbon price, the manufacturer's risk aversion level and consumers' low-carbon preference can all raise total emission reductions. However, when they are at a low level, further analysis is needed to determine whether the closed-loop supply chain for embedded low-carbon service model might impinge on the total amount of emission reduction (see the simulation results in Section 5.3).

5 Numerical analysis

This paper uses numerical simulation for the sensitivity analysis of k_t, k_m, δ and c_g. It also explores their impact on the manufacturer's expected utility growth and the total amount of emission reduction. Drawing on parameter settings from relevant literature (Li et al., 2017; Qu et al., 2021; Zhu et al., 2022), this study assumes: $a = 1$, $\delta = 0.8$, $e_0 = 1$, $m = 4$, $G = 3$, $c_g = 9.1$, $c_m = 30$, $\Delta = 10$, $p = 50$, $b = 3$, $h = 10$, $\mu = 15$, $\sigma = 1$, $k_t = 0.8$, $k_m = 0.8$.

5.1 Sensitivity analysis

Firstly, the impact of k_t and k_m on the recycling rate of used products, revenue-sharing rate and unit carbon reduction is analyzed. The equilibrium solution shows that the ESCO's risk aversion level k_t has no effect on the three equilibrium decisions, and the impact of the manufacturer's risk aversion level k_m is shown in Figure 3.

Based on Figure 3, as manufacturers become increasingly risk-averse, the recycling rate of used products and unit carbon reduction rise, but the revenue-sharing rate declines. Furthermore, when $k_m > 0.9$, the recycling rate of used products exceeds 1; when $k_m < 0.35$, the unit carbon reduction is below 0; when $k_m < 0.05$, the revenue-sharing rate exceeds 1 that it does not satisfy the equilibrium constraint. When $0.35 < k_m < 0.9$, the revenue-sharing rate and the recycling rate of used products are between 0 and 1, and the carbon emission reduction is less than the initial carbon emission but greater than 0, satisfying the equilibrium constraint. Therefore, only when the manufacturers' risk aversion level is between 0.35 and 0.9 can they choose to form supply chains for embedded low-carbon services by entering into revenue-sharing contracts with ESCOs.

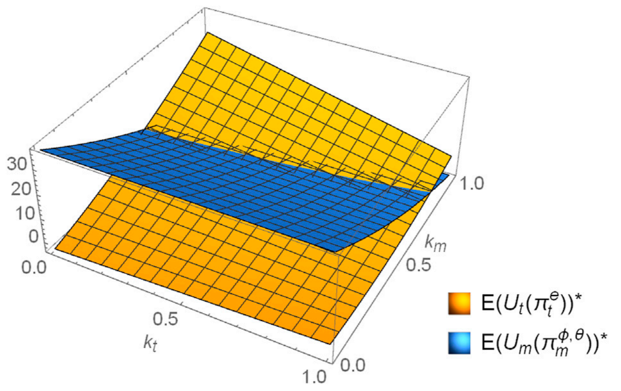

FIGURE 4
The impact of k_t and k_m on the expected utility of the manufacturer and the ESCO.

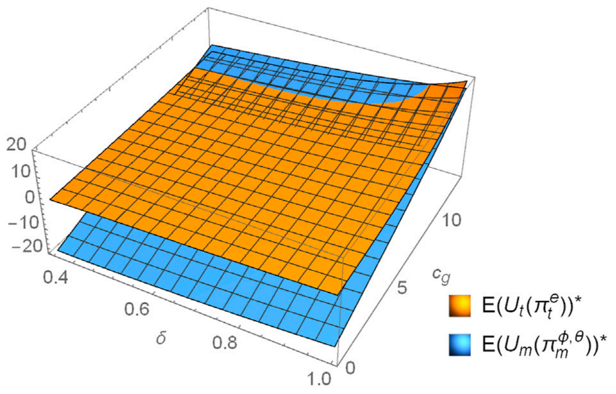

FIGURE 6
The impact of δ and c_g on the expected utility of the manufacturer and the ESCO.

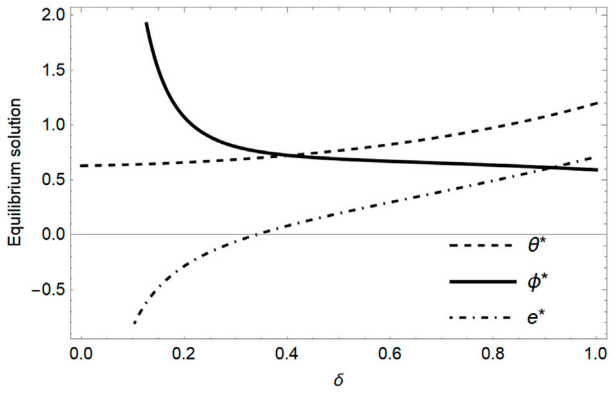

FIGURE 5
The impact of δ on equilibrium solutions.

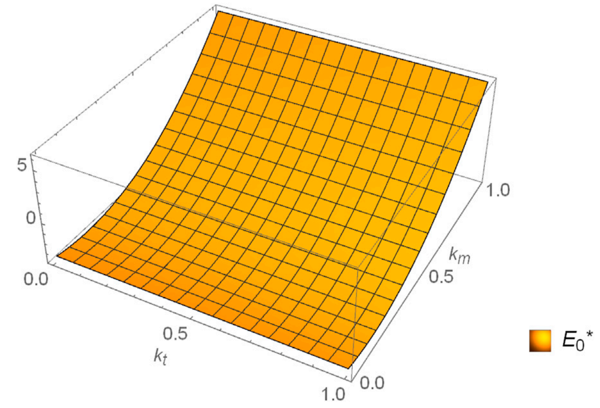

FIGURE 7
The impact of k_m on the amount of growth in the manufacturer's expected utility.

Secondly, the impact of k_t and k_m on the expected utility of the manufacturer and the ESCO is studied and the results are shown in Figure 4.

According to Figure 4, the manufacturer's expected utility drops as its risk aversion level rises; when ESCO's risk aversion level changes, it remains unchanged. When $k_m > 0.16$, the ESCO's expected utility diminishes as its risk aversion level ascends. When $k_m < 0.16$, the ESCO's expected utility rises as its risk aversion level increases. This advises that the manufacturer's risk aversion level affects the expected utility of the manufacturer and the ESCO, as well as the ESCO's risk aversion level. A higher expected utility can be achieved for both parties when the manufacturer has a high risk aversion level and the ESCO has a low risk aversion level.

In addition, the impact of δ on the recycling rate of used products, revenue-sharing rate and unit carbon reduction is studied, and the results are shown in Figure 5.

Based on Figure 5, as consumers' low-carbon preference goes up, the recycling rate of used products and unit carbon reduction increase, but the revenue-sharing rate goes down. However, when $\delta > 0.9$, the recycling rate of used products exceeds 1; when $\delta < 0.35$, the unit carbon reduction is below 0, and the revenue-sharing rate exceeds 1 meaning the equilibrium constraint is not satisfied. Hence, consumers' low-carbon preference is a vital influencing factor in the manufacturer's emission reduction. When consumers' low-carbon preference is high, manufacturers will be more likely to consider emission reduction and seek cooperation with ESCOs for low-carbon service.

Then, the impact of δ and c_g on the expected utility of the manufacturer and the ESCO is analyzed. Based on Figure 5, the range of δ is from 0.35 to 1, and the results are shown in Figure 6.

According to Figure 6, the expected utility of both the manufacturer and the ESCO grows when consumers' low-carbon preference and the carbon price rise, suggesting that higher consumers' low-carbon preference and a higher carbon price prompt manufacturers to reduce their carbon emissions. Meanwhile, when $c_g > 10$ and $\delta < 0.9$, the manufacturer's expected utility is greater than that of the ESCO, with both parties' expected utility at a relatively high level.

5.2 Analysis of factors influencing the manufacturer's expected utility growth

The ESCO's risk aversion level k_t does not affect the manufacturer's expected utility before and after introducing an embedded ESCO. Thus, it does not cause a change in the value of

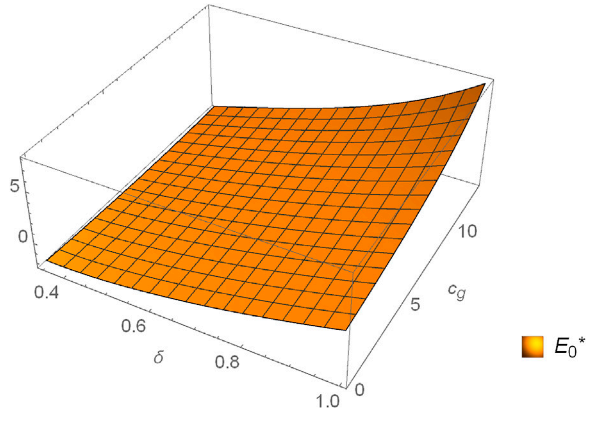

FIGURE 8
The impact of δ and c_g on the amount of manufacturer's expected utility growth.

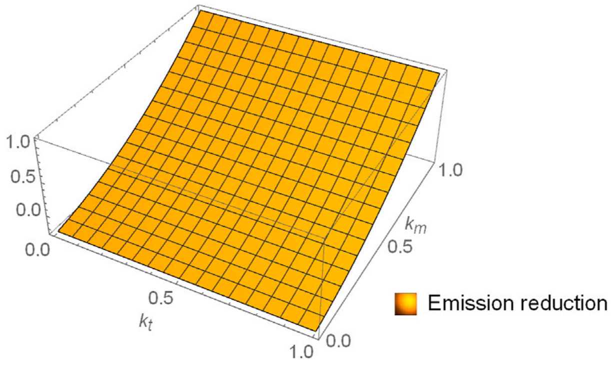

FIGURE 9
The impact of k_t and k_m on the total amount of emission reduction.

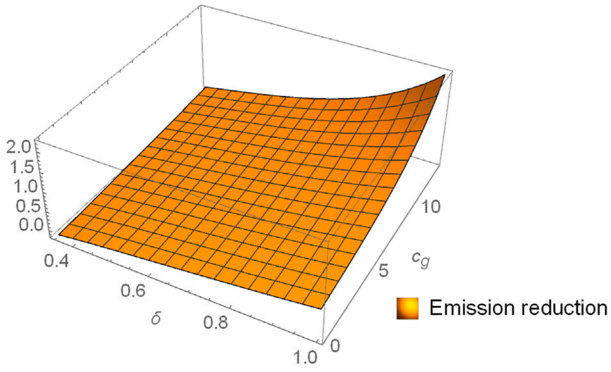

FIGURE 10
The impact of δ and c_g on the total amount of emission reduction.

the manufacturer's expected utility growth E_0*. Further reasoning of the relationship between the manufacturer's risk aversion level k_m and E_0* is shown in Figure 7.

According to Figure 7, when the manufacturer's risk aversion level rises, its expected utility growth decreases and then increases, and it becomes negative when $k_m < 0.65$, $E_0* < 0$. In other words, only when the manufacturer has a greater risk aversion level that the introduction of an embedded ESCO can improve the manufacturer's expected utility and reduce carbon emissions.

After that, the impact of δ and c_g on the manufacturer's expected utility growth is analyzed, with δ ranging from 0.35 to 1. The results are presented in Figure 8.

Based on Figure 8, the manufacturer's expected utility growth is positively associated with consumers' low-carbon preference. To be more specific, when $\delta < 0.48$, the expected utility growth falls and then rises as the carbon price declines. When $\delta > 0.48$, the expected utility growth rises as the carbon price rises. The reason is that market demand rises with consumers' low-carbon preference and carbon emission reduction. And consumers' low-carbon preference certainly affects the amount of carbon emission reduction. When consumers' low-carbon preference is lower, the rise in market demand is moderate. However, given that the product price remains the same after the introduction of ESCOs, and manufacturers need to share part of the profit with ESCOs, so when $\delta < 0.55$ or $\delta < 0.7$, $c_g < 4$, the manufacturer's expected utility growth may be less than 0 and sees negative growth. This indicates that consumers' low-carbon preference plays a decisive role in the manufacturer's expected utility growth. Manufacturers can cooperate with ESCOs for low-carbon emission reduction only when consumers' low-carbon preference and the carbon price are high so that they can retain their profits.

5.3 Analysis of factors influencing the total emission reduction

The results obtained from the analysis of the impact of k_t and k_m on the total amount of emission reduction of the closed-loop supply chain for embedded low-carbon service are shown in Figure 9.

Based on Figure 9, the ESCO's risk aversion level doesn't affect the total amount of emission reduction. However, when the manufacturer's risk aversion level rises, the total emission reduction increases. When $k_m < 0.35$, the total emission reduction is less than 0, indicating that introducing an embedded ESCO does not serve the purpose of low-carbon emission reduction. Therefore, the embedded ESCO should not be introduced for low-carbon emission reduction when the manufacturer has a lower risk aversion level.

The results of the impact of δ and c_g on the total amount of emission reduction of the closed-loop supply chain for embedded low-carbon service are shown in Figure 10.

According to Figure 10, the total emission reduction rises with the carbon price and consumers' low-carbon preference. When $\delta < 0.5$, $c_g < 6$, the total emission reduction is below 0. When $\delta > 0.8$, $c_g > 8$, the total emission reduction will increase rapidly, indicating that total emission reduction is greatly influenced by the carbon price and consumers' low-carbon preference. However, when consumers' low-carbon preference is small, embedded low-carbon service may result in negative growth in total emissions reduction.

6 Discussion

Carbon dioxide emitted through production contributes to climate warming (Xu et al., 2016; Ahmed and Sarkar, 2018). And the CCTM, a robust economic policy, has been implemented by many countries to prompt manufacturing companies to reduce carbon emissions (Yang et al., 2021). Existing studies note that many manufacturers outsource low-carbon projects to ESCOs and the cooperation mechanisms between the two have raised much attention from academia (He et al., 2020; Zhang et al., 2020). Using the MV approach and considering the scenarios for the manufacturers' recycling and remanufacturing, the paper has built and investigated a Stackelberg model of the risk-averse closed-loop supply chain for embedded low-carbon service under demand uncertainty. It explores the effect of various factors, such as risk aversion levels of the manufacturer and ESCO, the carbon price and consumers' low-carbon preference, on low-carbon service supply chains. And the role of embedded low-carbon service in supply chains in lowering manufacturer's carbon emissions and maintaining economic growth is analyzed.

Through sensitivity analysis, the results of the effect of risk aversion level, carbon price and consumers' low-carbon preference on the embedded low-carbon service supply chain are verified. According to the results, to let embedded low-carbon service supply chain operate, certain conditions should be met: the manufacturer's risk aversion level and consumers' low-carbon preference should be within 0.35–0.9, a higher level. Meanwhile, as the carbon price, the manufacturer's risk aversion level and consumers' low-carbon preference rise, the recycling rate of used products and the unit carbon emission reduction increase but the revenue-sharing rate decreases. Second, the manufacturer's expected utility becomes lower when its risk aversion level goes higher. However, when the ESCO's expected utility is less than 0, its expected utility would increase with its risk aversion level, suggesting that higher consumers' low-carbon preference and carbon price will lead to the manufacturer's higher willingness to abate carbon emissions and develop an embedded low-carbon service supply chain. With a greater carbon price and consumers' low-carbon preference, the expected utility of the manufacturer and the ESCO becomes higher, meaning that greater expected utility can be obtained from low-carbon service supply chains. Thus, the manufacturer and ESCO need to focus on consumers' low-carbon preference and carbon price, as well as developing and enhancing emission reduction technologies.

The above results can be supported and verified by the existing studies. Firstly, as consumers' low-carbon preference goes higher, the ESCO enhances its development and investment in emission reduction technology to expand market demand, which is evidenced in the study by Qu et al. (2021). At this point, the manufacturer's revenue grows and it voluntarily lowers the revenue-sharing rate and concedes part of the benefits to the ESCO to continue reducing emissions. Meanwhile, the manufacturer's revenue grows, making its investment enthusiasm go up, which in turn improves the recycling rate of used products. Secondly, when the carbon allowances cannot satisfy the manufacturer's needs, the rise in the carbon price will elevate the manufacturer's costs, as shown by Xu et al. (2017). At this point, the manufacturer is more willing to encourage the ESCO to invest more and enhance its unit carbon emission reduction. But to do so, the manufacturer needs to reduce the revenue-sharing rate and let the ESCO enjoy more benefits. The rise in the unit carbon emission reduction will lead to higher market demand, benefits and the recycling rate of used products for the manufacturer. Thirdly, the higher the manufacturer's risk aversion level, the greater the risk it avoids. And the manufacturer will encourage the ESCO to invest more to obtain greater benefits (Zhu et al., 2022). To achieve this, again, the manufacturer needs to reduce its revenue-sharing rate and allows the ESCO to take a larger share of the revenue. When the ESCO acquires a larger share, it will be more enthusiastic about investing and increasing the unit carbon emission reduction, increasing market demand, bringing more benefits to the manufacturer and raising the recycling rate of used products. Finally, according to Zhu et al. (2022) and Zang et al. (2022), though the manufacturer's risk aversion level can help it avoid risks and reduce potential losses, it might limit its expected utility.

In addition, to explore the way in which embedded low-carbon service in supply chains lowers manufacturer's carbon emissions and maintains economic growth, this paper compares and analyzes the changes in the manufacturer's expected utility and the total quantity of emission reduction before and after the introduction of embedded ESCOs. It is found that the rise in the manufacturer's risk aversion level will lead to a decrease and then an increase in both its expected utility growth and the total amount of emission reduction. When consumers' low-carbon preference is high, as the carbon price and consumers' low-carbon preference grow, the manufacturer's expected utility growth and total carbon emission reduction rise. This is because when the manufacturer's risk aversion level, the carbon price and consumers' low-carbon preference increase, the unit carbon emission reduction and market demand rise, leading to growth in total emission reduction. Consumers' low-carbon preference and the carbon price have significant effects on market demand: when they increase, the manufacturer's expected utility growth increases. In addition, the manufacturer's risk aversion level has a more significant effect on the revenue-sharing rate: when the manufacturer's risk aversion level is low, its expected utility growth decreases. This indicates that when the carbon price, the manufacturer's risk aversion level and consumers' low-carbon preference are high, entering into a revenue-sharing contract with an ESCO can be more rewarding to the manufacturer in terms of expected utility and emission reduction. At this point, the manufacturer has no barriers to investment and returns, so it is more likely to choose embedded low-carbon service for carbon emission reduction, which is conducive to investment in carbon emission reduction and technological advancement. This will further increase unit carbon emission reduction, market demand and environmental pollution reduction. Given that manufacturing is the main economic sector and the basis of economic growth (Tirkolaee et al., 2022), technological progress and investment will bring economic growth (Iqbal et al., 2022), and environmental pollution will harm economic growth (Murshed, 2022), so it is reasonable to state that embedded service in supply chains can maintain economic growth.

7 Managerial implications

The research has the following managerial implications.

1) Manufacturers with insufficient financial capacity and technical skills in carbon emission reduction may choose to enter into revenue-sharing contracts with professional ESCOs to form an embedded low-carbon service supply chain. However, the manufacturer's risk aversion level and consumers' low-carbon preference may affect the conclusion of revenue-sharing contracts. To be more specific, when their risk aversion level,

carbon price and consumers' low-carbon preference are high, manufacturers may choose to introduce embedded low-carbon service to reduce carbon emissions.

2) ESCOs face the risk of possible losses in the embedded low-carbon service supply chain as they are required to bear the upfront investment in emission reduction. Therefore, they need to improve their risk aversion level and cooperate with manufacturers that can increase their revenue. In addition, they can curtail their investment by appropriately reducing their revenue-sharing rate based on their risk aversion level to improve the sustainability of embedded low-carbon service.
3) The government needs to promote the establishment and implementation of the CCTM and reasonably regulate the carbon price. Meanwhile, since embedded low-carbon service can lower the burden of carbon reduction for manufacturers, the government should encourage financial institutions to provide low-carbon financing services for ESCOs to help them perform embedded low-carbon services. In addition, the government must strengthen environmental education and policy support, actively guide consumers to make low-carbon consumption, and raise consumers' low-carbon awareness.

8 Conclusion

Under the CCTM policy, manufacturers face significant challenges in reducing carbon emissions. But most manufacturers cannot achieve carbon reduction goals independently due to limited financial and technical strength. Instead, they cooperate with ESCOs and embed them into production and operation to construct a closed-loop supply chain for embedded low-carbon service. However, regarding risks such as demand uncertainty within and outside the supply chain, whether embedded low-carbon service in supply chains can lower manufacturer's carbon emission and maintain economic growth remain questionable. This study develops a risk-averse closed-loop supply chain model for embedded low-carbon service under demand uncertainty to investigate the mentioned issue. And the results are listed below.

1) The manufacturer's expected utility growth after introducing an embedded ESCO is mainly influenced by its risk aversion level, consumers' low-carbon preference and the carbon price. When they are high, introducing an embedded ESCO could increase the manufacturer's expected utility and maintain economic growth.
2) High carbon price and consumers' low-carbon preference are forcing manufacturers to reduce carbon emissions, stimulating ESCOs to increase their total emission reduction. Meanwhile, the manufacturer's risk aversion level significantly impacts the total quantity of emission reduction. When the level is low, the manufacturer's embedding of an ESCO cannot meet the carbon emission reduction goal. Therefore, only when the manufacturer has a higher risk aversion level should it introduce an embedded ESCO to increase expected utility and reduce carbon emissions.
3) As the manufacturer's risk aversion level increases, the manufacturer's expected utility and revenue-sharing rate decrease, and the ESCO's expected utility, recycling rate and carbon emission reduction increase. By contrast, the increase in the ESCO's risk aversion level only concerns its expected utility but does not affect other equilibrium decision results. Therefore, it is essential to pay attention to risk management. Only when the manufacturer has a higher risk aversion level can it enter into a revenue-sharing contract with an ESCO to form an embedded low-carbon service supply chain.

Some limitations of this study should also be mentioned. For example, the paper only considers the scenario where market demand is normally distributed. Second, the effect of the recycling quality of used products on the closed-loop supply chain for embedded low-carbon service is not examined. In addition, the situation where manufacturers face multiple competing ESCOs is not considered, which can be a research direction for future studies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CS and LC contributed to the conception and design of the study. WY performed the formal analysis. ZZ organized the database and validated it. CS performed the model design and wrote sections of the manuscript. LC performed the analysis, simulation and discussion of the model and completed the first draft of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

Funding

The authors acknowledge with the National Social Science Fund of China (No. 20BGL017).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Appendix A: The proof process of Lemma 1

The ESCO determines the amount of carbon emission reduction of both new and remanufactured products, $\frac{\partial E(U_t(\pi_t^e))}{\partial e} = -ma + \delta(-2em + p - p\phi) - \frac{e\mu}{e_0^2}$, $\frac{\partial^2 E(U_t(\pi_t^e))}{\partial e^2} = -2m\delta - \frac{\mu}{e_0^2} < 0$, the ESCO's expected utility is a concave function with carbon emission reduction e, proving there is an optimal value in $E(U_t(\pi_t^e))$.

The reaction function for unit carbon reduction is $e = \frac{((1-\phi)p\delta - ma)e_0^2}{\mu + 2m\delta e_0^2}$, therefore, $q = a + \delta e = \frac{a\mu + \delta(am + (1-\phi)p\delta)e_0^2}{\mu + 2m\delta e_0^2}$.

Substitute the reaction functions of e and q into the manufacturer's expected utility function.

$$E\left(U_m\left(\pi_m^{\phi,\theta}\right)\right) = \left(\Delta\theta - b\theta + p\phi - c_m - \frac{c_g e_0 (\mu + e_0(am + p\delta(\phi - 1) + 2m\delta e_0))}{\mu + 2m\delta e_0^2}\right)$$
$$\frac{a\mu + \delta(am + p\delta(1-\phi))e_0^2}{\mu + 2m\delta e_0^2} + c_g G - p\sigma\phi k_m - \frac{1}{2}h\theta^2$$

Its Heisei matrix H is as follows.

$$H = \begin{bmatrix} \frac{\partial^2 E\left(U_m\left(\pi_m^{\phi,\theta}\right)\right)}{\partial \phi^2} & \frac{\partial^2 E\left(U_m\left(\pi_m^{\phi,\theta}\right)\right)}{\partial \phi \partial \theta} \\ \frac{\partial^2 E\left(U_m\left(\pi_m^{\phi,\theta}\right)\right)}{\partial \theta \partial \phi} & \frac{\partial^2 E\left(U_m\left(\pi_m^{\phi,\theta}\right)\right)}{\partial \theta^2} \end{bmatrix}$$
$$= \begin{bmatrix} \frac{2p^2\delta^2 e_0^2\left(\delta c_g e_0^2 - 2m\delta e_0^2 - \mu\right)}{\left(\mu + 2m\delta e_0^2\right)^2} & \frac{p\delta^2 e_0^2 (b - \Delta)}{\mu + 2m\delta e_0^2} \\ \frac{p\delta^2 e_0^2 (b - \Delta)}{\mu + 2m\delta e_0^2} & -h \end{bmatrix}$$

When $m > \frac{c_g}{2} - \frac{\mu}{2\delta e_0^2}$, $H_{11} = \frac{2p^2\delta^2 e_0^2(\delta c_g e_0^2 - 2m\delta e_0^2 - \mu)}{(\mu + 2m\delta e_0^2)^2} < 0$, and $|H| = \frac{2hp^2\delta^2 e_0^2(\mu + 2m\delta e_0^2 - \delta c_g e_0^2) - p^2\delta^4 e_0^4 (b-\Delta)^2}{(\mu + 2m\delta e_0^2)^2} > 0$. Then it can be determined that H is negative definite. The manufacturer can maximize its profit by choosing the optimal revenue-sharing rate in its decision-making.

From the systems of equations $\frac{\partial E(U_m(\pi_m^{\phi,\theta}))}{\partial \theta} = 0$ and $\frac{\partial E(U_m(\pi_m^{\phi,\theta}))}{\partial \phi} = 0$, the equilibrium results of the model can be obtained.

Appendix B: The proof process of Lemma 2

The manufacturer determines the recycling rate of used products, $\frac{\partial E(U_m(\pi_m^{\theta}))}{\partial \theta} = -a(b - \Delta) - h\theta$, $\frac{\partial^2 E(U_m(\pi_m^{\theta}))}{\partial \theta^2} = -h < 0$, the manufacturer's expected utility is a concave function with the recycling rate of used products, indicating the existence of a best value in $E(U_m(\pi_m^{\theta}))$. The manufacturer can maximize its utility by choosing the optimal recycling rate in its decision-making. By solving the function $\frac{\partial E(U_m(\pi_m^{\theta}))}{\partial \theta} = 0$, the equilibrium decision for the recycling rate of used products is obtained as $\theta* = \frac{a(\Delta - b)}{h}$. Substituting the optimal function (formula) into (formula) gives the manufacturer's maximum expected utility without introducing an ESCO.