

Article

Screening Contract Excitation Models Involving Closed-Loop Supply Chains Under Asymmetric Information Games: A Case Study with New Energy Vehicle Power Battery

Xiaodong Zhu and Lingfei Yu *

School of Management Science and Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China; zxd@nuist.edu.cn

* Correspondence: ylf@nuist.edu.cn; Tel.: +86-025-5823-5552

Received: 12 November 2018; Accepted: 31 December 2018; Published: 3 January 2019



Abstract: In closed-loop supply chain systems for power battery remanufacturing, recycling and dismantling tasks will be relegated to third-party recyclers. This has significant disadvantages, inasmuch as the asymmetric exchange of information regarding the level of recycling capacity and effort after signing a contract fiscal risks to the manufacturers. The purpose of this paper is to study the “adverse selection” of recyclers and “moral hazards” hidden in their purported effort levels, based on Information Screening Models in the principal-agent theory. Our information screening model for revenue sharing will be presented, and subsequently verified using numerical simulation to demonstrate the impact of the screening contract on the expected returns of both parties. Our results show that the sharing coefficient of the remanufacturing revenue for low-capability recyclers is distorted downwards, and only truthful reporting can retain profits. High-capacity recyclers will obtain additional information while retaining profit. At the same time, as the proportion of high-capacity recyclers in the market increases, the expected return of the entrusting party increases. One critical area where this will impact the Chinese economy is in the area of new energy vehicles. We investigate a case study of our approach in new energy vehicles, which are being used to reduced CO₂ emissions, but have environmentally hazardous batteries that must be recycled safely and economically.

Keywords: remanufacturing; closed-loop supply chain; asymmetric information; adverse selection; moral hazard

1. Introduction

Traffic-related greenhouse gas (GHG) emissions have increased significantly over the past few years, accounting for more than a quarter of global GHG emissions (Thiel C et al., 2010 [1]). New energy vehicles (EVs) are an important component of the adaptation to a new global energy development trend and the green transformation of the industry. While effectively curbing the geometric growth of greenhouse gases related to road transportation, they also involve national energy security, energy conservation and emission reduction, and technology innovation (Li W et al., 2016 [2]). Since the State Council of the Chinese government issued the “Energy Conservation and New Energy Vehicle Industry Development Plan (2012–2020)” and the “Notice on the Exemption of New Energy Vehicle Purchase Tax” (State Council, 2012; State Council, 2014 [3,4]), as well as other policies to inspire large-scale growth of the new energy vehicle market, assuming a 6–8 year lifetime of the batteries from new energy vehicles, there will be an explosive decommissioning stage from 2018 to 2020, containing large amounts of destructive pollutants and precious metals (for example, Li, Ni, Mn). Power batteries from

new EVs will bring huge economic benefits, but if their safe disposal is not guaranteed, can also cause ecological disasters. Improving the efficiency of resource use and effectively curbing environmental damage has attracted the attention of policy makers and business managers. According to statistics, by 2022, China's recycling market share is expected to exceed 50 billion yuan, and the total number of discarded batteries will exceed 114 GWh (Liu Z et al., 2018 [5]). Recognizing the dual economic and environmental benefits, in late 2018, China's Ministry of Industry and Information Technology's Seventh Ministries and Commissions presented the "Seventh Department's Notice on Pilot Work on Recycling and Utilization of New Energy Vehicles' Power Battery" (State Council, 2018 [6]). It can be foreseen that the recycling of decommissioned power batteries will become a new trend in the development of closed-loop supply chains.

The growing demand for scarce energy resources, an increasing desire to move toward a low-CO₂ economy, and the fact that more than 50% of new energy vehicles in the world (Zeng X et al., 2015 [7]) shows that China's power battery recycling problem is a global issue. However, the management of power battery remanufacturing in China is still in its infancy. The choice of battery disassembly use modes is therefore a key feature of their closed-loop supply chain management (see Figure 1). According to GGII statistics, in 2017, a total of 114,000 tons of lithium batteries were used and dismantled in China, of which disassembly and use accounted for 95%. New energy vehicles include pure electric passenger cars (BEV), plug-in hybrid passenger cars (PHEV), hybrid passenger cars (HEV) and start-stop systems (SS) for micro-hybrid passenger cars. The most popular battery is a ternary lithium variety, with a high-voltage platform and high-current charging, and is expected to dominate the future power battery market (Gaines L. et al., 2014 [8]). By dismantling and using lithium (Li), cobalt (Co), nickel (Ni), manganese (Mn), copper (Cu), aluminum (Al), graphite, separator and other materials extracted from it, it is theoretically possible to achieve an economic benefit of about 42,900 yuan per ton. Taking nickel sulfate as an example, the cost of dismantling and reconstructing a ternary lithium battery is less than 40,000 yuan per ton of nickel, while the cost of directly producing nickel ore is more than 60,000 yuan. The cost of obtaining raw metal materials through resource recycling is much lower than directly obtaining them from primary sources.

Driven by the responsibility extension system of the producer, the battery manufacturer (the principal) authorizes third-party recyclers (the agents) to provide power through supply chain tracing and open communication protocols. Later then, third-party recyclers disassemble batteries and transfer the recaptured raw materials to battery manufacturers, who finally produce new batteries and load them into new energy vehicles, selling it to the market through new energy automobile companies, thus achieving a closed-loop ecology (see Figure 1). In practice, BMW cooperates with third-party recycler BRUNP and battery manufacturing company Ningde Times (CATL) to carry out closed-loop operation of power battery to jointly build BMW Novo 2018 brand 60H, with an overall recycling rate of 98.5%. Incorporating the power battery disassembly and use model into the closed-loop supply chain system has become an effective way to reduce the scarcity of energy and achieve clean production, and to achieve a green supply chain system to cope with market competition (Xu L et al., 2013 [9]).

However, merely incorporating a power battery disassembly use model into a closed-loop supply chain system is not enough to show that it can create high performance. Due to the rapid technological changes in complex industrial systems, as well as new dismantling and use models, China's recycling process has been disappointing in the face of such a huge power battery recycling market (for example, research shows that China's power battery regular recovery rate is less than 2%). In the closed-loop supply chains of decommissioned power batteries, due to the information asymmetry, the actual situation of the agent in the market is complicated, and its real cost coefficient, capability level, and risk preference are difficult to observe (Wei J et al., 2015 [10]). It is, therefore, very important to choose the right agent. Based on the asymmetric game theory, our research proposes the problem of dual information asymmetry, that is, the problem of "reverse selection" caused by information asymmetry before signing (i.e., the inability to observe the real ability information of the agent), and the "moral

hazard” problem caused by the information asymmetry after signing (i.e., the agent secretly hides the actual effort level information after signing the contract.). According to the principal-agent theory, this paper provides a problem-solving idea by designing the screening contract model, which means, the principal provides multiple contracts for the agent to choose, and the agent selects the appropriate contract based on its own capability type and determines the optimal effort level. Therefore, designing a screening contract with incentive effect is of great important for improving the recycling rate of secondary resources and the benefits of both parties (Feng Q et al., 2014 [11]). In this paper, by analyzing the role of agents with different recycling capabilities in the market, the remanufacturers of the closed-loop supply chain of decommissioned power batteries under dual information asymmetry provide a basis for decision-making to address the incentive problem of recyclers.

The rest of the paper is structured as follows: The second part summarizes the relevant theories and empirical literature. Based on the literature review, in the third part, we propose hypotheses and modeling between the dual information asymmetry, principal-agent theory and supply chain operation, and obtain important propositions through model optimization. In the fourth part, we analyze the contractual properties in detail for the designed information screening contract model. The results of numerical simulations are presented in the fifth part. The sixth part summarizes our work (including our theoretical contributions, management implications, and limitations), and finally proposes further directions for future research.

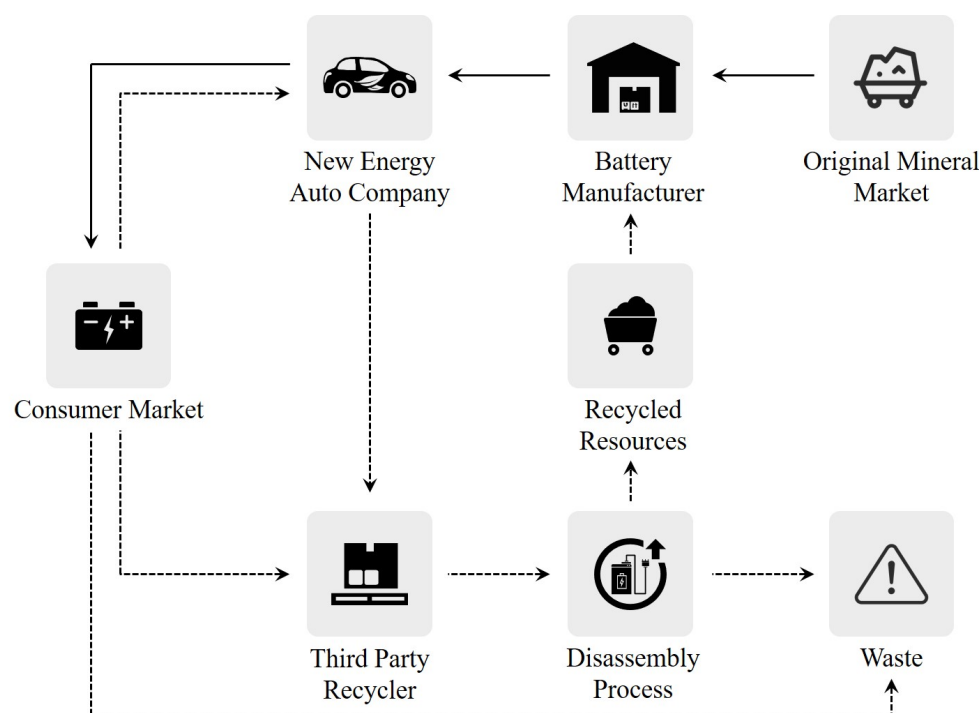


Figure 1. New energy vehicle power battery closed-loop supply chain system.

2. Literature Review

In response to climate change, the energy crisis, and increased global competition, it is inevitable that the new energy vehicle industry will choose a closed-loop supply chain (CLSC) operation (Kannan Govindan K et al., 2015 [12]). At this time, the strategy to recover hazardous waste such as power batteries and resource recycling is under intense scrutiny in industry and academia. However, the regular recovery rate of China’s power battery is less than 2%, with a conversion rate of renewable resources less than 30% (Tian X et al., 2014 [13]), which is far below the world average. It is therefore important to motivate supply chain companies to improve the level of recycling efforts while improving the ability to recycle and dismantle devices.

This paper deals with interdisciplinary research using closed-loop supply chains (CLSC) and game theory (GT). Closed-loop supply chains include reverse and forward supply chains, and are referred to as “value creation” systems (Christopher M, 2016 [14]). In the study of information and knowledge flow in the supply chain, Hult G.T.M et al. (2004 [15]) devised a model linking knowledge development to cycle time in strategic supply chains, research show that substantial variance in cycle time could be explained by knowledge development; Hult G.T.M. et al. (2006 [16]) proposed that the strategy-knowledge fit is associated with supply chain performance, and research show that only if the relative emphasis on various knowledge elements matches strategy that capitalizing on knowledge can create superior performance in supply chains; Tseng, S.M. (2009 [17]) through five primary activities illustrated how supply chain member companies enhance enterprise competitiveness by apply the internal knowledge chain to transform supply chain knowledge; Tseng, S.M. (2014 [18]) explores the impact of knowledge management capabilities (KMC) and supplier relationship management (SRM) on corporate performance through questionnaire and statistical analysis methods. The results show that KMC has a positive impact on corporate performance; Cerchione, R., et al. (2016 [19]) believes that the supply chain as a complex system, the management of the processes of adoption, the transfer and application of knowledge are necessary responses to the new challenges posed to the SC by globalization and sustainability issues. In the study of the realization of the sales value of closed-loop supply chain products, Zhu X et al. (2017 [20]) investigated the difference in recycling costs between distributors and online recyclers in the Stackelberg model and explored the impact of recycling competition on remanufacturing. Hong X et al. (2017 [21]) established a closed-loop supply chain referred to as “The Nobel Model,” to study two different technology licenses and explore the impact of technology licensing on remanufacturing. Cheng J et al. (2017 [22]) designed an environmental responsibility transfer model for original equipment manufacturers (OEMs) and retailers to supply businesses. The chain benefits are optimal. Jena S K et al. (2014 [23]) developed three cases of non-cooperation, channel cooperation and global cooperation, to study the cooperation and competition of duopoly manufacturers in closed-loop supply chains. Yoo S H et al. (2016 [24]) constructed a three-tier supply chain consisting of original manufacturers (OEMs), remanufacturers (REMs), and distributors, considered various possible supply chain process combinations, introduced different supply chain structures of various species, and compared the performances of the five models. However, in the above related literature, the remanufacturing system focused more on the sales of the forward supply chain to realize the product value context. This paper will focus on the recycling contract in the reverse supply chain while considering the realization of sales value.

From the perspective of game theory (GT), this paper mainly deals with two aspects of closed-loop supply chain management, and considers the problem as an incomplete information game governing the risk management of the principal agent and the optimal design of their contracts. For principle agents, risk sharing and technological advancement are two of the driving forces of the supply chain principal-agent model (Giannakis M et al., 2015 [25]). Technology outsourcing can bring significant benefits, while generating uncertainty risks. Aqlan F et al. (2015 [26]) proposed a risk assessment model that was also used in areas such as transfer payments and principal-agents. The works of Mancini L et al. (2018 [27]) and Helbig C et al. (2018 [28]) used quantitative theory to analyze the reverse supply chain. The design of the agency incentive contract considered the value of the renovation as well as the technical risk. This paper considers the agent’s dismantling ability risk and contract risk preference. It has also been demonstrated that the use of a revenue-sharing contract in the supply chain can motivate clients to achieve optimal profits for principle agents in cases of asymmetric information exchange (De Giovanni P, 2017 [29]). In the complex system recycling outsourcing model, the joint technology model can internalize external interests, effectively solving the problem of “moral hazards” and improving the benefits of cooperative innovation (Yan B et al., 2017 [30]).

However, in addition to studying the “moral hazards” caused by a “single” information asymmetry, one major concern is how to design a recycling contract for power battery companies to make optimal choices among many agents that do not disclose accurate information. The problem

of “reverse selection” is also a major challenge for supply chain systems (Gümüş M et al., 2012 [31]). Scholars have gradually made new explorations in the context of dual information asymmetry. For instance, Crama P et al. (2013 [32]) constructed a technology research and development contract for risk-averse biological research and development, and risk-neutral pharmaceutical companies under information asymmetry, including payment contracts for prepayment, mileage payment, and copyright payment. Another example is Mangla S K (2015 [33]), who established a supplier’s optimal return strategy model in the face of ambiguous market demands in cases where the retailer’s grasp of market price provided a unilateral information asymmetry, which encouraged retailers to release optimal order quantities to improve overall supply chain performance. Kerkkamp R B O et al. (2018 [34]) considered how the manufacturer designs the outsourcing screening contract to encourage the contractor to perform optimally in the product development process, under the double asymmetry of the contractor’s capability and cost level information. In this paper, in the research of power battery disassembly system outsourcing, the identification contract is used to solve the problem of information asymmetry.

Although scholars have designed revenue sharing contracts in an environment that examines product development risks and agent efforts, the use of a mixed principal-agent mechanism creates two problems, i.e., the inability to observe the agent’s true information, and the incentives to the agent. Using principal-agent theory, this paper studies cases where only some of the recovered power batteries can be remanufactured, and the recycling and dismantling abilities of the agent (the recycler) are unknown to the client (the battery manufacturer). This creates a situation with dual information asymmetry. By analyzing the relationship between the proportion of agents of different capability types in the market and the expected profit of the supply chain system, the manufacturers of the closed-loop supply chain of power battery remanufacturing provide decision support for the incentive problem of recyclers.

3. Problem Description and Model Hypothesis

3.1. Problem Description

This paper considers a single-stage closed-loop supply chain system consisting of a battery manufacturing company, a new energy vehicle company, and a third-party recycler. As shown in Figure 1, the battery manufacturer (the principal) is responsible for the manufacture of the power battery, and the third-party recycler (the agent) is entrusted by the principle, and is responsible for the recycling and dismantling of the used power battery to obtain remanufactured raw materials. In our model, p_t is the maximum recycling price paid by the battery manufacturer to the third-party recycler, p_m is the maximum recycling price paid by the recycler to the new energy vehicle company, and p_n is the product sales price. In our model, battery manufacturers and new energy auto companies are risk-neutral and completely rational, whereas third-party recyclers are risk-averse, and battery manufacturers dominate the Stackelberg game.

3.2. Basic Assumptions and Parameters

(1) Assuming that there is no difference in quality and performance between the remanufactured battery and the new battery, the new battery unit remanufacturing cost is c_r (recycling raw material cost), and $f(v) = v^r$ indicates the battery remanufacturing rate, where v represents the efficiency of lithium-ion battery disassembly, r represents the coefficient of influence of lithium-ion battery disassembly efficiency on remanufacturing rate, r satisfies $\partial f(v)/\partial v > 0$, $\partial^2 f(v)/\partial v^2 < 0$, and $r \in [0, 1]$.

(2) The amount of recovery can be expressed by the function $Q = r_i e_{ij} + \theta + \xi$, where r_i indicates the real dismantling use level of the recycler, and e_{ij} indicates the recycler recovery effort. The label i represents the real information of the third party recycler, j represents the information reported by the third party recycler to the battery manufacturer, and $i, j \in \{H, L\}$, H, L. The values r_H and r_L represent high and low capacity levels, respectively, with $r_H > r_L$. Battery manufacturers can

observe the proportion of high-capacity recyclers in the market at δ , and low-capacity recyclers at $1 - \delta$. The variable θ indicates the amount of recycling when the recovery effort level is zero, ξ indicates a market random factor, and $\xi \sim N(0, \sigma^2)$.

(3) The recovery effort cost is expressed as $\mu = ke_{ji}^2/2$, and is a marginal increment function ($\mu' > 0$), where $k(k > 0)$ is defined as a recovery effort cost factor.

(4) The level of third-party recycling efforts is private information, and battery manufacturing companies cannot observe and present asymmetric differences. The battery manufacturer gives its linear reward $E(T_j)$, $E(T_j) = T_j + f(v)\beta_jQ$, $j \in \{H, L\}$ based on the recycling yield of the third-party recycler. Here, T_j indicates that the third-party recycler reports a fixed remuneration for the disassembly use level of r_j , and β_j indicates that the recycler reports the disassembly use level for r_j . The number of products is divided into proportions (i.e., the battery manufacturer provides a revenue to the third-party recycler based on the number of remanufactured products), and $f(v)Q$ indicates effective recycling.

In the following, the variable subscripts “M”, “R” and “T” respectively represent power battery manufacturers, new energy vehicle companies, and third-party recyclers. The superscript “*” indicates the optimal decision, and E indicates the expected utility. Decision variables and model parameters are shown in Table 1.

Table 1. Decision variables and model parameters.

Decision Variables	
T_j	The manufacturer pays the recycler a fixed payment
β_j	Proportion of revenue sharing between manufacturers and recyclers
Model Parameter	
p_t	Manufacturer gives recycler maximum recycling price
p_m	Recyclers pay the largest recycling price for auto companies, $p_t > p_m$
p_n	Power battery sales price
c_r	Dismantling raw material cost after use
Q	Recycling function, $Q = r_i e_{ij} + \theta + \xi$
r_i	Recycler’s real disassembly use level
e_{ij}	Recycler recovery effort level, i indicates the real information of the recycler, and j indicates the information reported by the recycler to the manufacturer
θ	Recovery amount when recovery effort is 0
ξ	Market random factor
μ	Recycler recycling effort costs, $\mu = e_{ji}^2/2$
δ	Proportion of high recycling and recycling capacity recyclers in the market, $\delta \in [0, 1]$
$f(v)$	Battery remanufacturing rate, $f(v) = v^r \in [0, 1]$

4. Closed-Loop Supply-Chain Decision Making and Model Analysis

4.1. Profit Function Construction

The power battery manufacturer is the entrusting party in the closed-loop supply chain system, and entrusts third-party recyclers to recycle used power storage batteries in the commercial market and to carry out dismantling and use processes to extract available elements as remanufactured raw materials. When a battery manufacturer signs a contract with a recycler that has a disassembly capacity of r_i , the battery manufacturer expects the profit to be:

$$\Pi_{M_i} = (e_{ij}r_i + \theta + \xi) [f(v)(p_n - c_r) - f(v)\beta_j - p_t] - T_j \quad (1)$$

Since the battery manufacturer is risk-neutral, its expected profit is equal to its expected utility, and the battery manufacturer expects the utility to be:

$$E(\Pi_{M_i}) = (e_{ij}r_i + \theta) [f(v)(p_n - c_r) - f(v)\beta_j - p_t] - T_j \quad (2)$$

The third-party recycler is based on a risk aversion feature, and its utility function uses the negative exponential function $U_R(\Pi_T) = -e^{\rho \Pi_T}$, where ρ is the degree of risk aversion, and $\rho \in \{\rho > 0, \rho = 0, \rho < 0\}$, indicating cases of being risk adverse, risk neutral, and risk tolerant, respectively. When the real dismantling ability is r_i and the reporting ability to the client is r_j , the third-party recycler expects the profit to be:

$$\Pi_{T_{ij}} = (e_{ij}r_i + \theta + \xi) [f(v)\beta_j - p_m + p_t] - \frac{1}{2}ke_{ij}^2 + T_j \quad (3)$$

According to the deterministic equivalent income method, the solution yields the expected utility of the recycler $E(\Pi_T)$:

$$E(\Pi_{T_{ij}}) = (e_{ij}r_i + \theta) [f(v)\beta_j - p_m + p_t] - \frac{1}{2}ke_{ij}^2 - \frac{1}{2}\rho\sigma^2 [f(v)\beta_j]^2 + T_j \quad (4)$$

4.2. Incentive Mechanism Design

4.2.1. Information Screening Contract Model

In the practice of closed-loop operation of the new energy vehicle power battery industry, since the power battery recycling and disassembly process has market licensing, complex process requirements, and intellectual property protection of power batteries, in the process of remanufacturing power batteries, companies usually first consider recycling and dismantling outsourcing, and find suitable agents through bidding. Under the principal-agent framework, the information asymmetry of the closed-loop supply chain of the power battery includes the “reverse selection problem” hidden by the recycling capacity of the recycler before an agreement is made, and the “moral hazard problem” of the recycler’s retention of their efforts after an agreement is made. The timing of supply chain decision-making is shown in Table 2. Before the agreement, the recycler’s ability to recycle and disassemble is its private information, which cannot be observed by the battery manufacturer. At this time, the information asymmetry is reflected in the typical “reverse selection” problem. After the agreement is made, the recycling business chooses the optimal level of effort according to the principle of maximizing its own revenue. At this time, the information asymmetry is reflected in the typical “moral hazard” problem. It is therefore crucial in supply-chain systems to design incentives to induce third-party recyclers to report their true recycling and dismantling capabilities and improve their efforts after agreements have been made.

Table 2. Time series of closed-loop supply chain information screening contract.

Stage One	
i	Recyclers are aware of their own dismantling capabilities e_{ij}
ii	Remanufacturers offer a compensation contract $\{(T_j, \beta_j)\}$
iii	Recyclers choose the appropriate contract based on their own dismantling ability $\{(T_j, \beta_j)\}$
Stage Two	
iv	The manufacturer pays the recycler a certain amount of fixed compensation T_j
v	Recyclers choose the best effort based on maximizing their own earnings e_{ij}
Stage Three	
vi	The manufacturer uses the raw materials to remanufacture and sell according to the returned dismantling
vii	Manufacturers give recyclers revenue share sharing based on sales performance β_j

The information screening contract established in this paper will provide corresponding contracts for recyclers of different capability types. The contract will induce recyclers to improve their efforts while having the characteristics of “self-selection” to achieve the goal of information screening. The contract process essentially involves the Stackelberg game model, as follows. First, we consider the “reverse selection” problem, where the recycler conceals its true recycling and dismantling ability before

signing. The principal first designs the contract $\{(T_j, \beta_j)\}$, for recyclers with a reporting capability of r_j , the recycler signs a contract based on its true ability type r_i , presenting a “self-selected” feature. Second, we consider the recycler’s efforts after an agreement as a “moral hazard” problem of retaining the response. After the agreement is made, the recycler chooses its own recycling effort level of e_{ij} to maximize the benefits. Finally, the battery manufacturer remanufactures and sells the purchased remanufactured raw materials. The number of products sold has given the recycler a certain revenue share, denoted by β_j . The sequence of the recycling channel decision is shown in Table 2.

When the power battery manufacturer (the entrusting party) faces the recycler (the agent) with different types of recycling and dismantling capabilities in the market, in order to enable the agent to truthfully report its true dismantling use level r_i , the entrusting party must satisfy the agent’s Participation Constraint (IR). At the same time, to induce the agent to adopt the optimal recovery effort level, the Principal Information Screening Contract must satisfy the agent’s incentive compatibility constraint (IC), that is, the recycler expects profit maximization. The client provides different types of contracts $\{(T_H, \beta_H), (T_L, \beta_L)\}$, enabling high-capacity recyclers and low-capacity recyclers to choose the type of contract, allowing them to avoid untruthful reporting. This achieves the goal of information screening of recycling capability and proposed efforts.

The contract can be obtained by solving the following mode:

$$\max_{T_L, \beta_L, T_H, \beta_H} E(\Pi_M) = \delta [(e_{HH}r_H + \theta) (f(v) (p_n - c_r) - f(v)\beta_H - p_t) - T_H] + (1 - \delta) [(e_{LL}r_L + \theta) (f(v) (p_n - c_r) - f(v)\beta_L - p_t) - T_L] \quad (5)$$

$$s.t = \begin{cases} \max_{e_{HH}} E(\Pi_{T_H r_H}) \geq \max_{e_{HL}} E(\Pi_{T_H r_L}) & (6) \\ \max_{e_{LL}} E(\Pi_{T_L r_L}) \geq \max_{e_{LH}} E(\Pi_{T_L r_H}) & (7) \\ E(\Pi_{T_H r_H}) \geq \pi & (8) \\ E(\Pi_{T_L r_L}) \geq \pi & (9) \end{cases}$$

Among them:

$$\max_{e_{HH}} E(\Pi_{T_H r_H}) = (e_{HH}r_H + \theta) [f(v)\beta_H - p_m + p_t] - \frac{1}{2}ke_{HH}^2 - \frac{1}{2}\rho\sigma^2 (f(v)\beta_H)^2 + T_H \quad (10)$$

$$\max_{e_{HL}} E(\Pi_{T_H r_L}) = (e_{HL}r_H + \theta) [f(v)\beta_L - p_m + p_t] - \frac{1}{2}ke_{HL}^2 - \frac{1}{2}\rho\sigma^2 (f(v)\beta_L)^2 + T_L \quad (11)$$

$$\max_{e_{LL}} E(\Pi_{T_L r_L}) = (e_{LL}r_L + \theta) [f(v)\beta_L - p_m + p_t] - \frac{1}{2}ke_{LL}^2 - \frac{1}{2}\rho\sigma^2 (f(v)\beta_L)^2 + T_L \quad (12)$$

$$\max_{e_{LH}} E(\Pi_{T_L r_H}) = (e_{LH}r_L + \theta) [f(v)\beta_H - p_m + p_t] - \frac{1}{2}ke_{LH}^2 - \frac{1}{2}\rho\sigma^2 (f(v)\beta_H)^2 + T_H \quad (13)$$

In the formula, constraints (6) and (7) are the incentive compatibility constraints (IC), and Formula (6) indicates that the high dismantling use ability recycler faithfully chooses the contract (T_H, β_H) . At the given level of concealment, Formula (7) indicates that recyclers with low disassembly capability truthfully selects the contract (T_L, β_L) whose profit is greater than or equal to the level at which the ability is disguised. Formulae (8) and (9) represent the participation constraint (IR), where π retains the profit for the agent, indicating that the recycler accepts the contract on the condition that its guaranteed equivalent income is greater than or equal to π .

4.2.2. The Solution of the Information Screening Contract Model

In the case of asymmetric information, the recyclers of different capabilities determine the optimal effort level of the second stage (see Table 1) according to the “self-selection” information screening contract to achieve the goal of maximizing their own interests.

The best-effort level for the recycler with real recovery and dismantling abilities of r_H and r_L is:

$$e_{HH}^* = \frac{r_H [f(v)\beta_H - p_m + p_t]}{k} \quad (14)$$

$$e_{LL}^* = \frac{r_L [f(v)\beta_L - p_m + p_t]}{k} \quad (15)$$

The true recovery and dismantling ability is r_H , the recycler selection contract is (T_L, β_L) , with ability type r_L , real recovery and dismantling ability r_L , and false reporting likelihood r_H . When the recycler chooses the contract (T_H, β_H) , in order to maximize its own interests, the optimal level of effort made at that time is:

$$e_{HL}^* = \frac{r_H [f(v)\beta_L - p_m + p_t]}{k} \quad (16)$$

$$e_{LH}^* = \frac{r_L [f(v)\beta_H - p_m + p_t]}{k} \quad (17)$$

Proposition 1. Under the conditions of double information asymmetry, the optimal contract (T_L, β_L) , (T_H, β_H) is:

$$\beta_H^* = \frac{r_H^2 [f(v)(p_n - c_r) - p_t]}{f(v)(r_H^2 + k\rho\sigma^2)} \quad (18)$$

$$\beta_L^* = \frac{r_L^2 [(1-\delta)(f(v)(p_n - c_r) - p_t) + \delta(p_t - p_m)] - \delta r_H^2 (p_t - p_m)}{f(v)(\delta r_H^2 + (1-\delta)k\rho\sigma^2 + (1-2\delta)r_L^2)} \quad (19)$$

$$T_L^* = -\frac{r_L^2 [f(v)\beta_L^* - p_m + p_t]^2}{2k} + \frac{1}{2}\rho\sigma^2 f(v)^2 \beta_L^{2*} + \theta(-f(v)\beta_L^* + p_m - p_t) + \pi \quad (20)$$

$$T_H^* = \frac{f(v)(\beta_H^* - \beta_L^*) [f(v)(\beta_H^* + \beta_L^*)(k\rho\sigma^2 - r_H^2) + 2r_H^2 p_m - 2r_H^2 p_t - 2\theta k] + 2kT_L^*}{2k} \quad (21)$$

Proof. We solve the first-order partial derivative of Equations (10)–(13), which is 0, and obtain Equations (14)–(17).

$$\frac{\partial E(\Pi_{T_H r_H})}{\partial e_{HH}^*} = r_H [f(v)\beta_H - p_m + p_t] - ke_{HH} = 0 \quad (22)$$

$$\frac{\partial E(\Pi_{T_L r_L})}{\partial e_{LL}^*} = r_L [f(v)\beta_L - p_m + p_t] - ke_{LL} = 0 \quad (23)$$

$$\frac{\partial E(\Pi_{T_H r_L})}{\partial e_{HL}^*} = r_H [f(v)\beta_L - p_m + p_t] - ke_{HL} = 0 \quad (24)$$

$$\frac{\partial E(\Pi_{T_L r_H})}{\partial e_{LH}^*} = r_L [f(v)\beta_H - p_m + p_t] - ke_{LH} = 0 \quad (25)$$

Substituting the Formulae (14)–(17) into Equation (5) and solving the available Proposition 1 with the second-level planning method, the proof is completed. \square

Proposition 2. The high-capacity agent will obtain more profit. If the low recycling ability of the agent is greater than the retained utility, the high recycling ability of the agent must be greater than the retained utility.

Proof. Substituting Equations (14)–(17) into Equations (6) and (9) and solving it, we obtain:

$$E(\Pi_{T_{H^r_L}}) = (f(v)\beta_L - p_m + p_t) \left[\theta + \frac{r_H^2 (f(v)\beta_L - p_m + p_t)}{k} \right] - \frac{r_H^2 (f(v)\beta_L - p_m + p_t)^2}{2k} - \frac{1}{2} \rho \sigma^2 f(v)^2 \beta_L^2 + T_L \quad (26)$$

$$E(\Pi_{T_{L^r_L}}) = (f(v_L)\beta_L - p_m + p_t) \left[\theta + \frac{r_L^2 (f(v)\beta_L - p_m + p_t)}{k} \right] - \frac{r_L^2 (f(v)\beta_L - p_m + p_t)^2}{2k} - \frac{1}{2} \rho \sigma^2 f(v)^2 \beta_L^2 + T_L \quad (27)$$

Due to:

$$E(\Pi_{T_{H^r_L}}) - E(\Pi_{T_{L^r_L}}) = \frac{(r_H^2 - r_L^2) [f(v_L)\beta_L - p_m + p_t]^2}{2k} > 0 \quad (28)$$

Therefore:

$$E(\Pi_{T_{H^r_L}}) > E(\Pi_{T_{L^r_L}}) \quad (29)$$

Which is:

$$E(\Pi_{T_{H^r_H}}) > E(\Pi_{T_{H^r_L}}) > E(\Pi_{T_{L^r_L}}) \geq \pi \quad (30)$$

□

Proposition 3. Under the information screening contract model, the recycler will report the recycling and dismantling capability information truthfully. In order to maximize its own profits, the entrusting party will expect the agent with low recovery and dismantling abilities to retain profits. The agent with high recovery and dismantling ability will obtain additional information rent while retaining profit. If the low-capacity agent falsely reports the capability information, the obtained revenue will be less than the retained profit.

Proof. According to Proposition 2, the participation constraint (IC) Formula (8) can be omitted. Under the condition of asymmetric information, the principal must only consider the participation constraint of the agent that meets the low recovery and dismantling ability in the contract design. The agent with high recovery and dismantling abilities is involved in the constraint and is satisfied at the same time. Introducing the Lagrangian multipliers A, B, M to solve the Kuhn-Tucker optimal condition, we obtain:

$$L(T_H, T_L, \beta_H, \beta_L, A, B, M) = \Pi_M + A(\Pi_{T_{H^r_H}} - \Pi_{T_{H^r_L}}) + B(\Pi_{T_{L^r_L}} - \Pi_{T_{L^r_H}}) + M(\Pi_{T_{L^r_L}} - \pi) \quad (31)$$

$$\frac{\partial L}{\partial T_H} = A - B - \delta \quad (32)$$

$$\frac{\partial L}{\partial T_L} = -A + B + \delta + M - 1 \quad (33)$$

Solution: $A = B + \delta, M = 1$, i.e., Equation (9) takes the equal sign:

$$E(\Pi_{T_{L^r_L}}) = \pi \quad (34)$$

This indicates that the entrusting party allows the agent with low recovery and dismantling abilities to retain the utility to meet the participation constraint. At this time, the IC does not generate incentives.

Those agents that have high recovery and dismantling abilities report truthfully that their ability information is the same as those who misrepresent their low abilities, which is expressed as the sum of

retained profit and information rent. Those with low recovery and dismantling abilities report that their ability information profit is less than the retained profit, i.e.:

$$E(\Pi_{T_{H^H}}) = E(\Pi_{T_{H^L}}) = \pi + \frac{(r_H^2 - r_L^2) [f(v)\beta_L - p_m + p_t]^2}{2k} \quad (35)$$

$$E(\Pi_{T_{L^H}}) = \pi - \frac{(r_H^2 - r_L^2) [f(v)\beta_L - p_m + p_t]^2}{2k} \quad (36)$$

Therefore, independent of the agent's motivations, the real-type contract can be selected to obtain the optimal profit, so the information screening contract has the characteristics of "self-selection". Proposition 3 is proved. \square

Proposition 4. *With the increase in the proportion of recyclers with high capacity in the market, the increase in information rent will be reduced, that is, such agents expect their profit to decrease. At this time, the commissioner signs such an agent, who will obtain more benefits.*

Proof. Substituting Equations (14) and (15) into Equation (5):

Under the dual information asymmetry, when the battery manufacturer agrees to a contract with a recycler that has high recovery and dismantling capacity, the battery manufacturer expects the profit to be:

$$E(\Pi_{Mr_H}) = - \frac{[f(v)(c_r + \beta_H^* - p_n) + p_t] [r_H^2 (f(v)\beta_H^* - p_m + p_t) + \theta k]}{k} - T_H^* \quad (37)$$

When a battery manufacturer agrees to a contract with a recycler that has low recycling capacity, the battery manufacturer expects the profit to be:

$$E(\Pi_{Mr_L}) = - \frac{[f(v)(c_r + \beta_L^* - p_n) + p_t] [\theta k + r_L^2 (f(v)\beta_L^* - p_m + p_t)]}{k} - T_L^* \quad (38)$$

We solve the first-order partial derivatives of δ for Equations (37) and (38), respectively:

$$\begin{aligned} \frac{\partial E(\Pi_{Mr_H})}{\partial \delta} &= \frac{(1 - \delta) (r_H^2 - r_L^2)^2 [r_L^2 (f(v)c_r + p_m - f(v)p_n) + k\rho\sigma^2 (p_m - p_t)]^2}{k (-\delta r_H^2 + (\delta - 1)k\rho\sigma^2 + (2\delta - 1)r_L^2)^2} > 0 \\ \frac{\partial E(\Pi_{Mr_L})}{\partial \delta} &= \frac{\partial E(\Pi_{Mr_L})}{\partial \beta_L^*} \times \frac{\partial \beta_L^*}{\partial \delta} \\ &= - \frac{f(v) [r_L^2 (f(v)(c_r + 2\beta_L - p_n) - p_m + 2p_t) + \theta k]}{k} \times \frac{\partial \beta_L^*}{\partial \delta} < 0 \end{aligned} \quad (39)$$

Between them:

$$\frac{\partial \beta_L^*}{\partial \delta} = \frac{(r_H^2 - r_L^2) [r_L^2 (f(v)c_r + p_m - f(v)p_n) + k\rho\sigma^2 (p_m - p_t)]}{f(v) [\delta r_H^2 + (\delta - 1)(-k)\rho\sigma^2 + (1 - 2\delta)r_L^2]^2} > 0 \quad (40)$$

That is, Π_{Mr_H} is an increasing function of δ , indicating that the battery manufacturer has agreed to a contract with a recycler that has high recovery and dismantling capacity, thus a high capacity ratio δ exists in the market, hence is positively correlated and Proposition 4 is proved. \square

5. Analysis of Contract Characteristics

Characteristic 1. *High recovery and dismantling capacity. The recycler is willing to pay for a higher level of effort, and the high recovery and dismantling ability of the agent's efforts is higher than the low recovery and dismantling ability. At this time, if the entrusting party increases the revenue sharing ratio, it will positively motivate the agent's recycling efforts.*

Proof. Solving the first-order partial derivatives of Formulae (14) and (15) with regard to recycling and dismantling ability and revenue sharing ratio:

$$\frac{\partial e_{HH}^*}{\partial r_H} = \frac{f(v)\beta_L - p_m + p_t}{k} > 0, \frac{\partial e_{LL}^*}{\partial r_L} = \frac{f(v)\beta_H - p_m + p_t}{k} > 0 \quad (41)$$

$$\frac{\partial e_{LL}^*}{\partial \beta_H} = \frac{f(v)r_H}{k}, \frac{\partial e_{LL}^*}{\partial \beta_L} = \frac{f(v)r_L}{k} \quad (42)$$

$$\frac{\partial e_{HH}^*}{\partial r_H} - \frac{\partial e_{LL}^*}{\partial r_L} = \frac{f(v)(\beta_H - \beta_L)}{k} > 0, \frac{\partial e_{HH}^*}{\partial r_H} > \frac{\partial e_{LL}^*}{\partial r_L} \quad (43)$$

□

Characteristic 2. The revenue sharing ratio β_j is positively correlated with the recycling effort level e_{ij} , with market uncertainty σ^2 , risk aversion degree ρ , and effort cost factor k , which shows a negative correlation.

Proof. This can be obtained from Equations (18) and (19):

$$\frac{\partial \beta_H^*}{\partial r_H} = \frac{2k\rho\sigma^2r_H[f(v)p_n - f(v)c_r - p_t]}{f(v)(r_H^2 + k\rho\sigma^2)^2} > 0, \frac{\partial \beta_H^*}{\partial k} = -\frac{\rho\sigma^2r_H^2[f(v)p_n - f(v)c_r - p_t]}{f(v)(r_H^2 + k\rho\sigma^2)^2} < 0 \quad (44)$$

$$\frac{\partial \beta_H^*}{\partial \rho} = -\frac{k\sigma^2r_H^2[f(v)p_n - f(v)c_r - p_t]}{f(v)(r_H^2 + k\rho\sigma^2)^2} < 0, \frac{\partial \beta_H^*}{\partial \sigma^2} = -\frac{k\rho r_H^2[f(v)p_n - f(v)c_r - p_t]}{f(v)(r_H^2 + k\rho\sigma^2)^2} < 0 \quad (45)$$

$$\frac{\partial \beta_L^*}{\partial r_L} > 0, \frac{\partial \beta_L^*}{\partial k} < 0, \frac{\partial \beta_L^*}{\partial \rho} < 0, \frac{\partial \beta_L^*}{\partial \sigma^2} < 0 \quad (46)$$

This also shows that with the increase of market uncertainty σ^2 , degree of risk avoidance ρ , and effort cost coefficient k , the agent is willing to accept the risk reduction. □

Characteristic 3. With the increase in the market's proportion δ of high recovery and dismantling capacity recyclers, with dismantling ability r_H , the ratio of recyclers with low recovery and dismantling ability revenue sharing is reduced by β_L^* . That is, the greater the difference between r_H and r_L , the smaller the value of β_L^* . The low recycling ability of the agent is not affected by the high capacity side, reflecting the high-end distortion in economics. At this point, the information screening contract triggered the market encroachment effect, and the income share of the agent with low capacity was distorted downward.

Proof.

$$\frac{\partial \beta_H^*}{\partial r_L} = 0 \quad (47)$$

$$\frac{\partial \beta_L^*}{\partial r_H} = \frac{2(\delta - 1)\delta r_H[k\rho\sigma^2(p_t - p_m) - r_L^2(f(v)c_r + p_m - f(v)p_n)]}{f(v)(\delta r_H^2 + (\delta - 1)(-k)\rho\sigma^2 + (1 - 2\delta)r_L^2)^2} < 0 \quad (48)$$

When the recycler is risk neutral, i.e., $\rho \rightarrow 0$:

$$\beta_H - \beta_L^* = \frac{\delta(r_H^2 - r_L^2)[f(v)(p_n - c_r) - p_m]}{f(v)(\delta r_H^2 + (1 - 2\delta)r_L^2)} > 0 \quad (49)$$

□

Characteristic 4. Revenue sharing ratio. The premise that the contract is effective is contingent on the fact that the recycler has risk-taking ability. That is, when $\rho \rightarrow \infty$, $\beta_H^* = 0$, $\beta_L^* = 0$. In the case of risk aversion, the degree of ρ is negatively correlated with the revenue sharing ratio of β_H^* , and β_L^* , indicating that the degree of risk aversion will gradually offset the incentive effect of the revenue sharing contract.

Characteristic 5. There is a threshold of $\{\chi_1, \chi_2\} \in [0, 1]$ in the information screening contract, when the proportion of recyclers with high recycling and capacity is $\delta > \chi_1$. The agent's contract for high recovery and dismantling ability is thus more profitable. When $\delta > \chi_2$, agreements with agents that have low recycling capability will be unprofitable. This is because when the proportion of recyclers with high recovery and dismantling capacity in the agent market is small, the rational entrusting party will give higher information rent, and at the same time, the probability of signing a recycler with low recovery and dismantling capacity is higher. When the proportion of recyclers with medium or high capacity exceeds χ_2 , the commissioning party can eliminate the low recycling ability by distorting the low-end information screening contract.

6. Numerical Simulation

This paper designs the information of the battery manufacturers in the closed-loop supply chain to identify contract incentive mechanisms. According to recyclers with different capacities, the entrusting party implements different incentive policies. The following is a numerical simulation of the above model in combination with the actual supply chain operation. Let the relevant parameters be denoted as $r_L = 2, r_H = 5, k = 2, \rho = 3, \sigma = 3, f(v) = 0.75, p_t = 1.75, c_r = 3, p_n = 8, p_m = 0.75$. The market share of recyclers with high capacity is $\delta \in (0, 1)$, which is common market information.

1. We investigate the relationship between revenue sharing β_j , and contract decision parameters in the incentive mechanism, as shown in Figure 2. Under the dual asymmetry of the efforts and capabilities of third-party recyclers, those with low capacity will be divided into revenue sharing only when the remanufacturing rate meets certain conditions. In these cases, the revenue sharing is divided into β and the remanufacturing rate of $f(v)$ is positively correlated. From Equations (18) and (19), given the increase in the proportion of recyclers in the market with high recovery and dismantling ability (δ), the proportion of high-capacity income sharing remains unchanged, while low. The proportion of revenue sharing of abilities is declining, and its market competitiveness is becoming increasingly insufficient. This reflects the phenomenon of “high end lack of distortion” in economics, and its nature is further evidenced.

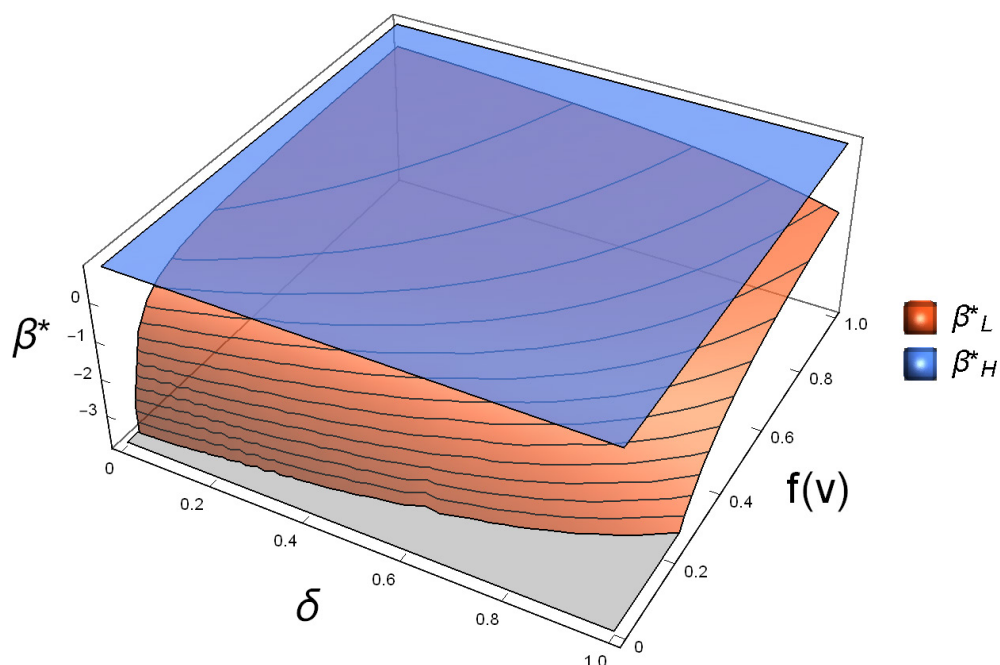


Figure 2. The change in the agent's revenue sharing ratio β_j with $\delta, f(v)$.

2. We examine the relationship between the fixed compensation T_j and the contract decision parameters in the incentive mechanism, as shown in Figure 3. First, with the increase in the remanufacturing rate of $f(v)$, the degree of differentiation in the fixed returns of the recyclers of

various capacities in the market is intensified, when the remanufacturing rate of $f(v)$ and the ratio of the market players to δ reaches the threshold function. At the time, the fixed rewards of each type of capability are reversed. Secondly, Formulae (20) and (21) are obtained. With the increase of the proportion of the high-recyclability and dismantling ability in the market, the increase in the proportion of δ causes a downward trend, indicating that the competition pressure of recyclers will increase, the fixed compensation of recyclers with high recovery and dismantling capacity will decrease, and the fixed payment of recyclers with low recovery and dismantling capacity will increase. This means that the contractor will hire higher recovery and dismantling ability at a higher cost, with fixed remuneration.

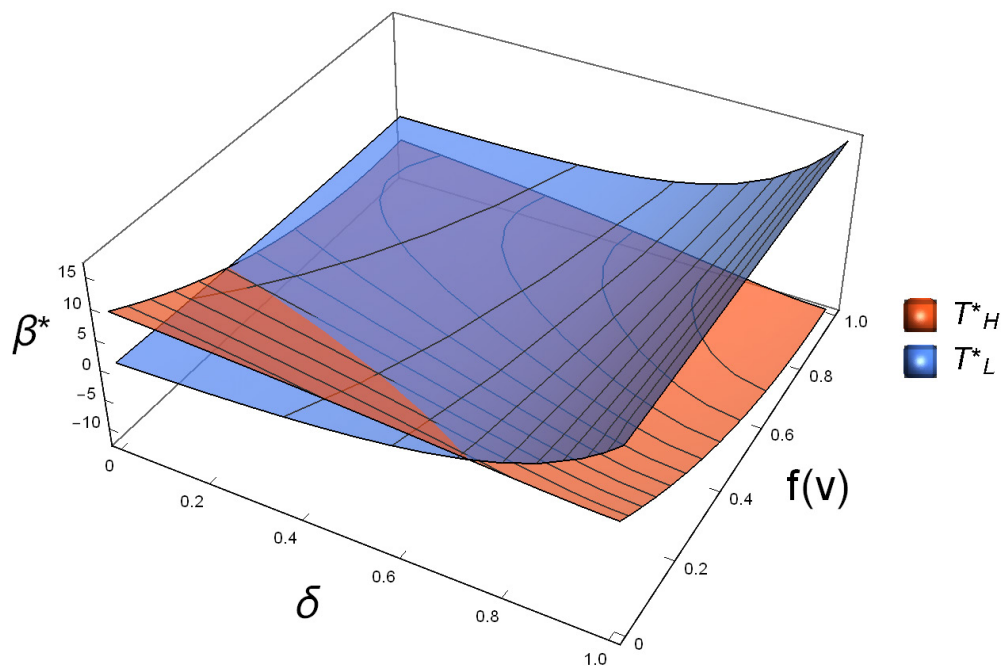


Figure 3. Fixed remuneration of T_j with $\delta, f(v)$.

3. We investigate the relationship between the proportion of δ in the market and the expected profit of various types of recyclers, $\Pi_{T_{ij}}$, from (35) and (36), as shown in Table 3. According to the increase of the proportion of δ in the market of recyclers with high recovery and dismantling abilities, the recyclers of all capacity types expect a downward trend in profits. Among them, high-capacity recyclers will receive a certain amount of information rent while obtaining retained profits. Moreover, the high-capacity agent who truthfully reports the capability information and the high-capacity agent who falsely reports the capability information expect the same profit. At this time, the high capacity agent has no warning of untruthfulness, while the low capacity agent can obtain the retained profit only in the situation of truthful reporting of their capability. Otherwise, their profit will be lower than the retained profit. This reflecting the information of distinguishing the characteristics of “self-selection.”

Table 3. Recycler expects profit Π_{Tij} with $\delta, f(v)$ changes.

$f(v)$	δ	False Ability Information		Report Truthfully	
		Π_{LH}	Π_{HL}	Π_{LL}	Π_{HH}
0.75	0.4	11.6304	17.4115	13.0714	17.4115
	0.6	11.4081	15.855	13.0714	15.855
	0.8	11.1622	14.1341	13.0714	14.1341
	1	11.0002	13.0714	13.0714	13.0714
0.95	0.4	11.8589	18.9624	14.0714	18.9624
	0.6	11.6088	17.2115	14.0714	17.2115
	0.8	11.3322	15.2758	14.0714	15.2758
	1	11.1524	14.0714	14.0714	14.0714

4. We examine the relationship between the expected profit of the battery manufacturer Π_M and the contract decision parameters in the incentive mechanism, as shown in Figure 4. From Formula (5), with the increase in the proportion of δ in the market with high recovery and dismantling abilities, those who enter contracts with agents that have high capacity will obtain more benefits. Among them, when the proportion of agents with high recovery and dismantling abilities in the market is $\delta < 0.181$, the battery agent tends to agree to contracts with low recovery and dismantling ability, and the profit obtained in this case is higher than contractual agreements with agents that have high recovery and dismantling ability. When $\delta > 0.841$, signing a low-capacity person will make the client unprofitable, and the power battery manufacturer will only choose to sign a high-recycling capacity recycler. Characteristic 5 is proved.

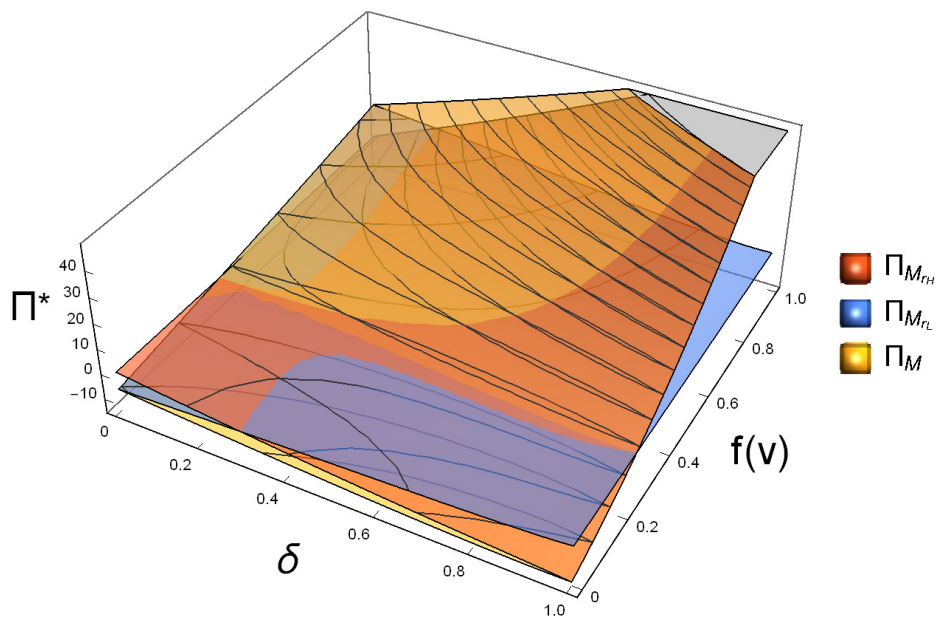


Figure 4. The entrusted party expects the profit of Π_M to change with $\delta, f(v)$.

7. Conclusions and Future Development Direction

7.1. Research Results

In order to exert scarce energy pressure and cope with climate change, China is striving to stimulate the development of battery technologies, and accelerate the deployment of new energy vehicle markets. Information asymmetry in the closed-loop supply chain system of used batteries will have an impact on the expected utility of the supply chain. This paper assumes that the dismantling ability of the agent in the market is a discrete variable. From the standpoint of the battery manufacturer,

a closed-loop supply-chain system consisting of a battery manufacturer, a new energy automobile company, and a recycler is constructed. Based on principal-agent theory, we have explored how to design a contract that inspires recyclers to disclose their true recycling and dismantling abilities, and improve the level of effort after agreeing to a contract. The established information screening contract enables the recycler to obtain a fixed remuneration while also achieving their remanufacturing goals. According to the nature of the information screening contract, our study has confirmed the following facts.

Firstly, high-capacity agents should choose high-risk contracts. The commission of information rent is not related to the proportion of dismantling ability in the market and the level of dismantling ability of low-capacity agents. Those with low ability should choose low-risk contracts, and the commission of information rent will follow. In the market, the proportion of agents with high dismantling ability decreases, and the greater the degree of capability, the less information rent is added. In addition, with the increase of market uncertainty and the cost of labor, the risk aversion of recyclers increases, and information screening reduces incentives for recyclers.

Secondly, in the information screening contract model of this article, recyclers will report their true information truthfully regardless of their capacity. Battery manufacturers can therefore effectively identify the dismantling abilities of the recycler, presenting the characteristics of “self-selection” and reducing the “self-selection” features. The risk of “reverse selection”, and those with high ability, will choose high-risk contracts, while those with low ability will try to avoid risks.

Thirdly, in the closed-loop supply-chain system with disassembly and use at its core, the revenue of the battery manufacturing enterprise is closely related to the pre-estimated value of the ratio of the agent’s capability type in the market, and the signing of agent with high dismantling ability will increase the entrusting party’s income. This will also reduce the moral hazard, that is, the stronger the ability of the agent, the greater the recovery effort after agreeing to the contract, and the greater the profit of the client.

7.2. Theoretical Contribution

Our theoretical analysis and models of decision making contribute two major findings. First of all, this study compensates for the shortcomings of the research on recycling and remanufacturing in the closed-loop operation of China’s new energy vehicle power battery low-carbon industry through mathematical models. Although the new energy vehicle industry is recognized as one of the key drivers to reduce pollutant emissions, previous studies have not fully addressed the re-integration of the material flow during the closed-loop life cycle of the battery. Second of all, based on principal-agent theory, we comprehensively investigated the dual information asymmetry conditions, namely “reverse selection” and “moral hazards”, and studied the game relationship between the principal and the agent in the closed-loop supply chain system of battery remanufacturing. We sought the optimal balance of earnings. Our research shows that the setting of the parameters in the information screening contract is closely related to the pre-estimated value of the principal’s ratio of the agent’s dismantling ability in the market. The design-information screening contract can induce the recycler to disclose their true capability and stimulate the recycling. The company gives their best effort. This may contribute to the game model literature on information asymmetry.

7.3. Management Significance

Our results have important practical significance for the management practice of China’s new energy vehicle battery remanufacturing industry. Firstly, the model results show that battery manufacturers can deploy the information screening contract to deal with the “reverse selection” problem before agreeing to contracts and the “moral hazard” problem after agreeing to contracts, which means that the agent can only obtain the best profit if it can report their capability truthfully. Secondly, the offsetting effect of risk aversion on revenue sharing is divided into incentive utilities. In the face of high dismantling ability and low risk avoidance, the entrusting party should give

the agent a higher degree of remanufacturing risk and encourage it to make the most profit. Excellent efforts to achieve stable operation of the remanufacturing process result in the acquisition of optimal information rent. In practice, the high-risk cooperation model between the Ningde era (CATL) and the Bangpu Group (BRUMP) effectively achieved a win-win cooperation and created an advantage in the joint response to the turbulent battery remanufacturing market.

Thirdly, considering the fact that the increase in the proportion of high-capacity parties in the market will make the ability of low-capacity agents to be distorted downwards, when the number of low-capacity enterprises in the market exceeds the threshold of χ , the dismantling project will be recycled. Agents with low capacity levels will make the entrusting party unprofitable or even affixed. Therefore, the entrusting party can choose to open the recycling and dismantling line by itself or eliminate the low-capacity enterprises by distorting the low-end screening contract. At the same time, it will encourage low-level enterprises. This will also increase innovation investments to cope with rapid technological changes in the dismantling and use models.

7.4. Limitations and Directions of Future Research

There are a few limitations of this study. Firstly, since it is difficult to observe the types of recycler capabilities in the market from a continuous perspective, we have adopted discrete variables in the construction of information screening contract models, i.e., high capability (H) and low capability (L). However, discrete variables may mask relationships that are important to objective performance. Future research can establish a continuous and discrete parameter model for the key processes of the closed-loop supply chains. Secondly, this paper considers only two-stage remanufacturing and sales phases, and further analyzes the multi-stage remanufacturing supply chain game of the closed loop supply chain of power storage. Thirdly, the closed-loop supply chain in the model consists of battery manufacturers, third-party recyclers, and new energy auto companies. However, the new energy auto industry is highly cooperative and competitive, and in future research, we can consider manufacturing with a closed-loop supply chain system in which competitors and multi-recyclers participate in competition. Finally, based on published policies, the new energy vehicle power battery remanufacturing industry needs to examine the multi-faceted factors. This paper focus on incentive mechanism from the perspective of supply chain member companies, future research can further study the influence of policy factors from the perspective of policy makers.

Author Contributions: Conceptualization, X.Z. and L.Y.; Resources, X.Z.; Methodology, L.Y.; Software, L.Y.; Formal analysis, L.Y.; Validation, L.Y.; Visualization, L.Y.; Project Administration, L.Y.

Funding: This research was funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions, Top-notch Academic, Programs Project of Jiangsu Higher Education Institutions, Grant Number PPZY2015A072; the Practice Innovation Training Program of College Students in Jiangsu Province, Grant Number 201810300025Z.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Thiel, C.; Perujo, A.; Mercier, A. Cost and CO₂ aspects of future vehicle options in Europe under new energy policy scenarios. *Energy Policy* **2010**, *38*, 7142–7151. [CrossRef]
2. Li, W.; Long, R.; Chen, H. Consumers' evaluation of national new energy vehicle policy in China: An analysis based on a four paradigm model. *Energy Policy* **2016**, *99*, 33–41. [CrossRef]
3. Notice of the State Council on Printing and Distributing the Development Plan for Energy-Saving and New Energy Vehicle Industry (2012–2020). Available online: http://www.gov.cn/zwgg/2012-07/09/content_2179032.htm (accessed on 28 June 2012).
4. Announcement on Exemption of New Energy Vehicle Purchase Tax. Available online: <http://www.chinatax.gov.cn/n810341/n810755/c1150779/content.html> (accessed on 1 August 2014).
5. Liu, Z.; Hao, H.; Cheng, X.; Zhao, F. Critical issues of energy efficient and new energy vehicles development in China. *Energy Policy* **2018**, *115*, 92–97. [CrossRef]

6. Available online: http://www.gov.cn/xinwen/2018-07/26/content_5309433.htm (accessed on 23 July 2018).
7. Zeng, X.; Li, J.; Liu, L. Solving spent lithium-ion battery problems in China: Opportunities and challenges. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1759–1767. [[CrossRef](#)]
8. Gaines, L. The future of automotive lithium-ion battery recycling: Charting a sustainable course. *Sustain. Mater. Technol.* **2014**, *1*, 2–7. [[CrossRef](#)]
9. Xu, L.; Mathiyazhagan, K.; Govindan, K.; Haq, A.N.; Ramachandran, N.V.; Ashokkumar, A. Multiple comparative studies of green supply chain management: Pressures analysis. *Res. Conserv. Recycl.* **2013**, *78*, 26–35. [[CrossRef](#)]
10. Wei, J.; Govindan, K.; Li, Y.; Zhao, J. Pricing and collecting decisions in a closed-loop supply chain with symmetric and asymmetric information. *Comput. Oper. Res.* **2015**, *54*, 257–265. [[CrossRef](#)]
11. Feng, Q.; Lai, G.; Lu, L.X. Dynamic bargaining in a supply chain with asymmetric demand information. *Manag. Sci.* **2014**, *61*, 301–315. [[CrossRef](#)]
12. Govindan, K.; Soleimani, H.; Kannan, D. Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *Eur. J. Oper. Res.* **2015**, *240*, 603–626. [[CrossRef](#)]
13. Tian, X.; Gong, Y.; Wu, Y.; Agyeiwaa, A.; Zuo, T. Management of used lead acid battery in China: Secondary lead industry progress, policies and problems. *Resour. Conserv. Recycl.* **2014**, *93*, 75–84. [[CrossRef](#)]
14. Christopher, M. *Logistics & Supply Chain Management*; Pearson: London, UK, 2016.
15. Hult, G.T.M.; Ketchen, D.J.; Slater, S.F. Information processing, knowledge development, and strategic supply chain performance. *Acad. Manag. J.* **2004**, *47*, 241–253.
16. Hult, G.T.M.; Ketchen, D.J.; Cavusgil, T.; Calantone, R.J. Knowledge as a strategic resource in supply chains. *J. Oper. Manag.* **2006**, *24*, 458–475. [[CrossRef](#)]
17. Tseng, S.M. A study on customer, supplier, and competitor knowledge using the knowledge chain model. *Int. J. Inf. Manag.* **2009**, *29*, 488–496. [[CrossRef](#)]
18. Tseng, S.M. The impact of knowledge management capabilities and supplier relationship management on corporate performance. *Int. J. Prod. Econ.* **2014**, *154*, 39–47. [[CrossRef](#)]
19. Cerchione, R.; Esposito, E. A systematic review of supply chain knowledge management research: State of the art and research opportunities. *Int. J. Prod. Econ.* **2016**, *182*, 276–292. [[CrossRef](#)]
20. Zhu, X.; Wu, B.; Wang, Z. The Pricing Strategy and Coordination Mechanism of Closed-Loop Supply Chain under the Difference of Double Channel Recycling Cost. *China Manag. Sci.* **2017**, *25*, 188–196.
21. Hong, X.; Govindan, K.; Xu, L.; Du, P. Quantity and collection decisions in a closed-loop supply chain with technology licensing. *Eur. J. Oper. Res.* **2017**, *256*, 820–829. [[CrossRef](#)]
22. Cheng, J.; Li, B.; Gong, B.; Cheng, M.; Xu, L. The optimal power structure of environmental protection responsibilities transfer in remanufacturing supply chain. *J. Clean. Prod.* **2017**, *153*, 558–569. [[CrossRef](#)]
23. Jena, S.K.; Sarmah, S.P. Price competition and co-operation in a duopoly closed-loop supply chain. *Int. J. Prod. Econ.* **2014**, *156*, 346–360. [[CrossRef](#)]
24. Yoo, S.H.; Kim, B.C. Joint pricing of new and refurbished items: A comparison of closed-loop supply chain models. *Int. J. Prod. Econ.* **2016**, *182*, 132–143. [[CrossRef](#)]
25. Giannakis, M.; Papadopoulos, T. Supply chain sustainability: A risk management approach. *Int. J. Prod. Econ.* **2016**, *171*, 455–470. [[CrossRef](#)]
26. Aqlan, F.; Lam, S.S. A fuzzy-based integrated framework for supply chain risk assessment. *Int. J. Prod. Econ.* **2015**, *161*, 54–63. [[CrossRef](#)]
27. Mancini, L.; Benini, L.; Sala, S. Characterization of raw materials based on supply risk indicators for Europe. *Int. J. Life Cycle Assess.* **2018**, *23*, 726–738. [[CrossRef](#)]
28. Helbig, C.; Bradshaw, A.M.; Wietschel, L.; Thorenz, A.; Tuma, A. Supply risks associated with lithium-ion battery materials. *J. Clean. Prod.* **2018**, *172*, 274–286. [[CrossRef](#)]
29. De Giovanni, P. Closed-loop supply chain coordination through incentives with asymmetric information. *Ann. Oper. Res.* **2017**, *253*, 133–167. [[CrossRef](#)]
30. Yan, B.; Chen, Z.; Kang, H. Coordination model of quality risk control of the aquatic supply chain based on principal-agent theory. *Supply Chain Manag.* **2017**, *22*, 393–410. [[CrossRef](#)]
31. Gümüş, M.; Ray, S.; Gurnani, H. Supply-side story: Risks, guarantees, competition, and information asymmetry. *Manag. Sci.* **2012**, *58*, 1694–1714. [[CrossRef](#)]
32. Crama, P.; Reyck, B.D.; Degraeve, Z. Milestone payments or royalties? Contract design for R&D licensing. *Oper. Res.* **2008**, *56*, 1539–1552.

33. Mangla, S.K.; Kumar, P.; Barua, M.K. Risk analysis in green supply chain using fuzzy AHP approach: A case study. *Resour. Conserv. Recycl.* **2015**, *104*, 375–390. [[CrossRef](#)]
34. Kerkkamp, R.B.O.; van den Heuvel, W.; Wagelmans, A.P.M. Two-echelon supply chain coordination under information asymmetry with multiple types. *Omega* **2018**, *76*, 137–159. [[CrossRef](#)]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).