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Game-Theoretic Optimisation of Resource Sharing and Carbon Reduction Synergies in Closed-Loop Supply Chains

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Abstract. Closed loop supply chains play an important role in the green transformation of manufacturing because they connect production, sales, recovery, and remanufacturing. However, independent investment in recovery capacity and low carbon technologies may lead to duplicated resource input. It may also intensify conflicts over cost sharing and benefit allocation among supply chain members. A decision scenario is developed for a consumer electronics closed loop supply chain with a manufacturer, a retailer, a third party recycler, and a resource sharing platform. Public data from 2020 to 2024 are used to calibrate basic parameters, while simulated parameters are generated through Latin Hypercube Sampling. Based on these inputs, a Stackelberg Nash hybrid game model is constructed to compare three scenarios: no sharing, resource sharing, and resource sharing with carbon cost. The results show that resource sharing improves total supply chain profit and recovery rate. Carbon cost further strengthens carbon reduction investment and remanufacturing utilisation. Carbon price sensitivity results indicate that a moderate carbon cost expands the synergy gain of resource sharing, while an excessively high carbon price compresses the profit space. The findings suggest that resource sharing is not only a cost reduction mechanism. It can also form a coordinated emission reduction pathway through recovery efficiency, remanufacturing substitution, and low carbon investment. This provides a computational basis for platform governance and low carbon coordination in closed loop supply chains.

Keywords: closed-loop supply chain, game theory, resource sharing, carbon reduction, computational optimisation

1. Introduction

Global manufacturing is shifting from linear production toward circular utilisation, making closed-loop supply chains important for linking production, sales, recovery, and remanufacturing. Although recovered products retain substantial value, recovery networks, low-carbon investment, and idle-resource allocation increase costs and create tension between profitability and emission reduction. Existing studies show that pricing, recovery channels, subsidies, member power structures, carbon policies, and green consumer preferences all influence supply-chain outcomes [1, 2].

This study examines strategic interactions among a manufacturer, retailer, third-party recycler, and resource-sharing platform using a Stackelberg-Nash hybrid game. Python-based numerical

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optimisation compares three scenarios: no sharing, resource sharing, and resource sharing under carbon-cost constraints. Profit, recovery rate, carbon emissions, and sharing synergy are evaluated within a unified framework.

2. Literature review

2.1. Closed-loop supply chain decisions

Closed-loop supply chain decisions integrate forward sales and reverse recovery into a circular system of production, collection, and remanufacturing. Manufacturers focus on wholesale pricing, remanufacturing savings, and carbon investment; retailers on pricing, demand, and green marketing; and third-party recyclers on recovery incentives and service levels. Different leadership and recovery-channel structures significantly affect profit distribution, recovery motivation, and system efficiency [3].

With recovery and remanufacturing targets, performance also depends on recovery rate, carbon emissions, and social welfare [4]. Introducing a resource-sharing platform further changes member cost structures through shared equipment, recovery capacity, and low-carbon investment, extending coordination from channels to platform-based resource allocation.

2.2. Game-theoretic optimisation

Game-theoretic optimisation is suitable for closed-loop supply chains because members pursue different objectives in pricing, recovery, shared investment, and carbon reduction. Stackelberg games capture hierarchical decisions, such as manufacturers moving first, while Nash games represent simultaneous choices including retail price, recovery effort, and platform fees. Existing low-carbon and dual-channel models show that technology level, power structure, channel competition, cost sharing, and dynamic pricing jointly affect economic and environmental performance [5, 6].

Building on this, the resource-sharing platform is modeled as an independent participant whose service fee and capacity constraints influence the manufacturer, retailer, and recycler. This better reflects the operating logic of platform-based supply chains.

2.3. Carbon reduction synergies

Carbon reduction in closed-loop supply chains involves production, recovery, and platform activities, including both low-carbon technology investment and resource savings from remanufacturing. Under carbon taxes or cap-and-trade policies, manufacturers must coordinate production, abatement investment, and inventory, while retailers adjust ordering and sales strategies [7]. ESG and carbon-trading mechanisms further introduce dynamic interactions among recovery investment, abatement effort, goodwill, and profitability [8, 9].

Resource sharing therefore reduces not only equipment idleness and recovery costs but also improves remanufacturing utilisation and carbon-investment efficiency. The interaction between shared capacity and carbon-cost constraints creates measurable synergy within the closed-loop supply chain.

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3. Experimental methods

3.1. System boundary and data setting

The experimental object is set as a closed loop supply chain for consumer electronics from 2020 to 2024. The system includes one manufacturer, one retailer, one third party recycler, and one resource sharing platform. Public data are used to calibrate basic market parameters and environmental parameters. The data include product sales scale, industry average recovery rate, carbon trading price, unit electricity emission factor, remanufacturing cost difference, corporate low carbon investment level, and electronic waste recovery volume. The data sources include consumer goods retail and industrial production data from the National Bureau of Statistics of China, national carbon market operation information from the Ministry of Ecology and Environment, the IEA electricity emission factor database, ESG reports of listed firms, electronic waste recycling industry reports, and public WEEE statistics. Game decision parameters that are difficult to obtain directly from public sources are generated through fixed interval simulation. The sharing service fee is set at 3 to 8 yuan per unit. The shared resource utilisation rate is set at 0.10 to 0.80. The carbon reduction effort cost coefficient is set at 20 to 80. The recovery incentive coefficient is set at 0.02 to 0.10. The consumer green preference coefficient is set at 0.15 to 0.45. The remanufacturing cost saving rate is set at 0.18 to 0.35. Latin Hypercube Sampling is used in Python to generate 3000 parameter combinations. Each parameter combination is then entered into the following Stackelberg Nash game model for equilibrium solving.

3.2. Game model and optimisation

Based on the public calibrated parameters and simulated decision parameters obtained in 3.1, a Stackelberg Nash hybrid game model is constructed. The manufacturer acts as the leader. The retailer and the recycler respond to the manufacturer, while the resource sharing platform participates in pricing [10]. Market demand is affected by the retail price, carbon reduction investment, and green marketing effort. The demand function is shown in formula (1).

$$D=a-bp+\theta e+\eta g \tag{1}$$

In formula (1), D denotes market demand, a denotes basic market potential, b denotes the price sensitivity coefficient, p denotes the retail price, eee denotes carbon reduction investment, g denotes green marketing effort, θ denotes the demand response coefficient of carbon reduction investment, and η denotes the demand response coefficient of green marketing effort.

The recovery quantity is determined by market demand, recovery incentive, and shared resource utilisation. The recovery function is shown in formula (2).

$$Q_r=(\tau_0+\lambda r+\mu s)D \tag{2}$$

In formula (2), Q denotes the recovery quantity, τ_0 denotes the initial recovery rate, r denotes the recovery incentive, s denotes the shared resource utilisation rate, λ denotes the effect of recovery incentive on recovery rate, and μ denotes the effect of shared resource utilisation on recovery rate.

Carbon emissions are calculated from new production emissions, remanufacturing emissions, and carbon reduction investment. The carbon emission function is shown in formula (3).

$$E=e_n(D-Q_r)+e_rQ_r-\phi e \tag{3}$$

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In formula (3), E denotes total carbon emissions, e_n denotes the emission factor of new production, e_r denotes the emission factor of remanufacturing, and ϕ denotes the carbon reduction efficiency coefficient. $(D-Q_r)$ represents the quantity produced through new production, while Q_r represents the quantity supplied through remanufacturing.

The total profit of the closed loop supply chain includes sales revenue, production cost, remanufacturing cost, recovery incentive, sharing cost, carbon reduction cost, green marketing cost, and carbon cost [11]. The integrated profit function is shown in formula (4).

$$\Pi=pD-c_n(D-Q_r)-c_rQ_r-rQ_r-f_ssD-\frac{k_ce^2}{2}-\frac{k_gg^2}{2}-p_cE \tag{4}$$

In formula (4), Π denotes the total profit of the closed loop supply chain, c_n denotes the unit cost of new production, c_r denotes the unit cost of remanufacturing, f_s denotes the resource sharing service fee, k_e denotes the carbon reduction cost coefficient, k_g denotes the green marketing cost coefficient, and p_c denotes the carbon trading price.

3.3. Scenario simulation and metrics

Scenario simulation uses the equilibrium solutions from Section 3.2 within the parameter ranges defined in Section 3.1. Three scenarios are compared: a no-sharing baseline, resource sharing through platform-provided recovery, warehousing, and low-carbon resources, and resource sharing under carbon-cost constraints. In the third scenario, carbon trading prices are introduced into the manufacturer's profit function.

Evaluation covers total and member profits, recovery rate, unit carbon emissions, carbon-reduction investment, shared-resource utilisation, and synergy gains. Economic, circular, and low-carbon performance are assessed jointly, while sensitivity analysis examines carbon price, service fee, consumer green preference, and remanufacturing cost savings to test equilibrium stability.

4. Results

4.1. Equilibrium performance

Based on public data from 2020 to 2024 and 3,000 LHS parameter combinations, Table 1 compares three equilibrium scenarios. Under no sharing, total profit is 21.46 million yuan and the recovery rate is 27.8%, indicating limited independent recovery capacity. Resource sharing increases profit to 23.18 million yuan, an 8.0% gain, while recovery rises to 33.6% and shared-resource utilisation reaches 61.2%.

With carbon costs, total profit slightly declines to 22.94 million yuan, but recovery increases to 36.4% and resource utilisation to 68.5%. This indicates that carbon constraints reduce short-term profit while encouraging greater carbon-reduction investment and remanufacturing. The manufacturer gains most from sharing, while recycler and platform profits continue to improve under carbon constraints.

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Table 1. Equilibrium performance comparison under three scenarios

Scenario	Total profit million yuan	Manufacturer profit million yuan	Retailer profit million yuan	Recycler and platform profit million yuan	Recovery rate %	Shared resource utilisation rate %
No sharing baseline scenario	21.46	11.82	7.11	2.53	27.8	0.0
Resource sharing scenario	23.18	12.53	7.42	3.23	33.6	61.2
Resource sharing with carbon cost scenario	22.94	12.18	7.28	3.48	36.4	68.5

4.2. Carbon synergy outcomes

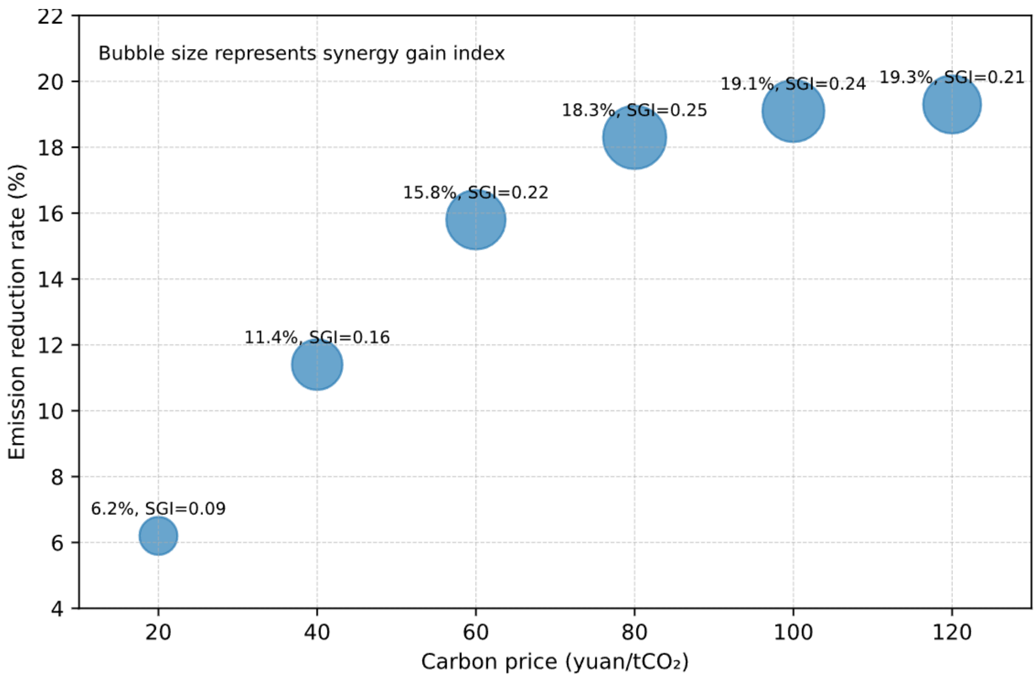

Figure 1. Carbon price, emission reduction, and synergy gain

Carbon synergy outcomes are tested through carbon price sensitivity simulation. The carbon price interval is set from 20 to 120 yuan per ton, based on the fluctuation range of public carbon market prices and calibrated literature parameters. As shown in Figure 1, when the carbon price increases from 20 yuan per ton to 80 yuan per ton, the unit product emission reduction rate rises from 6.2% to 18.3%. The synergy gain index increases from 0.09 to 0.25. This indicates that a moderate carbon cost strengthens the emission reduction incentive of shared resources. It also encourages the manufacturer to use shared low carbon equipment and remanufacturing inputs. When the carbon price further increases to 100 yuan per ton and 120 yuan per ton, the emission reduction rate only rises slightly to 19.1% and 19.3%. The synergy gain index decreases to 0.24 and 0.21. This shows that an excessively high carbon cost weakens the space for profit improvement, leading to a marginal decline in synergy gains. The bubble size represents the synergy gain index. Larger bubbles are concentrated in the range of 60 to 100 yuan per ton, which suggests that resource

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sharing and carbon cost constraints have an optimal matching interval. A higher carbon price does not always produce stronger synergy.

5. Discussion

In the resource sharing scenario, total profit and recovery rate increase at the same time. This indicates that platform based resource allocation can reduce fragmented recovery capacity and duplicated investment in closed loop supply chains. After carbon cost is introduced, total profit decreases slightly, while recovery rate, shared resource utilisation, and carbon reduction performance continue to improve. This shows that carbon constraints encourage the manufacturer to allocate more resources to remanufacturing and low carbon investment. When the carbon price becomes too high, the synergy gain declines. Policy pressure therefore needs to match the profit space of firms. Platform service fees, green preference, and remanufacturing cost savings jointly influence equilibrium outcomes. The resource sharing mechanism requires reasonable pricing and benefit allocation to maintain members' participation willingness.

6. Conclusion

A synergy optimisation framework for resource sharing and carbon reduction is developed for a consumer electronics closed loop supply chain. The framework uses a Stackelberg Nash game and Python based numerical simulation to examine equilibrium differences across three scenarios. The results show that resource sharing improves recovery efficiency and supply chain profit, while carbon cost strengthens low carbon investment and remanufacturing substitution. The analysis demonstrates that the sharing platform can serve as an important mechanism linking economic performance and environmental performance. The proposed framework offers a reproducible modelling path for platform governance, carbon cost transmission, and member coordination in closed loop supply chains.

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