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RESEARCH ARTICLE

Manufacturing resource outsourcing and matching: service mode selection and equilibrium evolution

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ABSTRACT

Manufacturing resource outsourcing platforms facilitate the meeting and matching of manufacturing service seekers and providers. The platform's service mode, the willingness of seekers to match, and providers' carbon emission reduction (CER) directly affect entities' decisions. Therefore, this paper employs an evolutionary game approach to analyse the manufacturing resource matching (MRM) between the providers and seekers and a sequential game model to analyse the pricing and CER strategies between the platform and providers. First, this study reveals that the service mode does not influence the evolutionary path and stability of MRM. However, matching in the cooperative mode becomes easier due to higher resource quantities. Second, we find that the cooperative mode can enhance the system's profits, and an appropriate revenue-sharing ratio is crucial for the platform and providers. Third, the analysis indicates that while the cooperative model can generate higher profits, it may also result in increased total carbon emissions.

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Manufacturing outsourcing; manufacturing resource matching; carbon emission reduction; service mode selection; evolutionary game

1. Introduction

Enterprises use manufacturing outsourcing as a critical means to maintain their core competitiveness (Allon & Babich, 2020; Cullen & Farronato, 2021). For example, Hewlett-Packard and Apple outsource part of their manufacturing process to contracted providers so they can focus on building up their key strengths, such as marketing and design, to bring higher profit (Hubs, 2023; Young, 2023).

Manufacturing outsourcing platforms, including cloud platforms, have become essential for entities to seek manufacturing outsourcing partners, providing matching services to providers and seekers (Cullen & Farronato, 2021). For example, Tao Factory provides an opportunity for costume designers to connect with garment plants (Tao Factory, 2021). The costume designer can outsource the manufacturing process to the garment plants *via* Tao Factory, and the platform provides the necessary services for the entities to match each other and build a trustworthy business relationship. With this successful business mode, Tao Factory has become one of the largest outsourcing platforms in China. Independent and cooperative modes are two common service modes of the outsourcing platform. Due to the providers' large production capacity, a buyer's market is often formed. Consequently, the platform and providers reach a revenue-sharing cooperation agreement to facilitate efficient matching with seekers. Some platforms, like Amazon Mechanical Turk and Hubs (Hubs, 2023; Mechanical Turk, 2023), use the independent mode, which collects a corresponding service fee from the provider according to the transaction volume, and the seeker can use the platform-related services for free. In contrast, using the cooperative mode, the platform and providers share the costs and benefits of resource manufacturing and manufacturing resource matching (MRM); this mode is used in Crowdsupply and GrabCAD (Crowd Supply, 2023; GrabCAD, 2023).

In addition to the opportunities brought by manufacturing outsourcing, the industry faces new challenges. With the growing concern about environmental pollution, most nations have adopted certain carbon emission reduction (CER) policies to control carbon emissions. Under such regulations, manufacturers must upgrade their production techniques to maintain an environmentally friendly production process. For example, Foxconn incorporated green intelligence into the company's development strategy and carried out 1587 CER projects (Foxconn, 2023). Samsung Electronics reduces carbon emissions in production by developing environmentally friendly materials and implementing new technologies (Samsung Electronics, 2023).

Various studies have been conducted to investigate how to forge successful manufacturing outsourcing

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matches under the CER regulation. Considering a low-carbon policy, Ma et al. (2023a) explore capacity matching in a duopoly market and analyse the production and profit strategies for both the supply and demand sides. Lin et al. (2021) consider the matching problem on a service-sharing platform and use mixed-integer linear programming to compute the optimal matching strategy under different rules. Wang et al. (2020a) investigate how information asymmetry impacts resource matching. They assume the participants are loss-averse and explore the evolutionary equilibrium in the resource matching. Considering different CER strategies, Liu et al. (2021) investigate two-sided matching and coordination for finite groups of providers and seekers. Although researchers have studied the resource matching problem and discussed the equilibrium strategies from different perspectives, few scholars have gone on to discuss how mode selection affects the production and emission quantity decision and equilibrium evolution.

To fill these research gaps, this study explores MRM and manufacturing decisions in the independent and cooperative modes, addressing the following questions:

1. What is the impact of various factors on the evolution of MRM, such as unregulated behaviours and waiting time?
2. What are the effects of mode selection on the MRM evolution and success rate?
3. How do different service modes affect the production quantities, CER, and entities' profits?

Our study makes the following contributions to the literature. Firstly, considering the long-term variation and evolution of the MRM, we formulate an evolutionary game model to analyse the evolution path and equilibrium stability. Our analysis shows that the entities have the same stability strategies in the independent and cooperative modes, but they have a higher probability of a successful match in cooperative mode. Secondly, contrary to the research focus on a single service mode, we consider and analyse both the independent and cooperative modes. The results show that the mode selection does not impact the MRM evolution paths and stability but does influence the production and emission quantity decisions and optimal profits. Finally, we consider the economic and environmental impact of CER. We find that the cooperative mode brings higher profits but is accompanied by higher total carbon emissions in certain circumstances.

2. Literature review

This study draws upon three literature streams, namely, MRM, evolutionary games, and CER.

2.1. Research on MRM

The rapid development of outsourcing platforms in the past few years has significantly improved MRM efficiency. Scholars have investigated various aspects of MRM, such as matching profits, matching speed, and platform types (Du & Lei, 2022; Halaburda et al., 2018).

In the MRM process, cost reduction and profit maximisation are research focuses. Chen et al. (2019) consider resource matching and profit maximisation in a complex dynamic environment. Argoneto and Renna (2016) propose a capability-sharing framework in cloud manufacturing to reduce resource mismatching. Moghaddam and Nof (2014) optimise service matching according to customers' needs and enterprises' abilities. Qin et al. (2020) investigate the enterprises' profits with insufficient capacity through capacity-sharing strategies and revenue-sharing contracts. Meanwhile, matching speed and satisfaction are other focuses (Wang et al., 2020a). Lu and Xu (2017) achieve adaptive resource matching using multiple evaluation criteria and a knowledge-based service composition mechanism. Luo et al. (2020) propose a model-based system engineering framework to provide technical solutions for rapid matching.

The abovementioned literature primarily focuses on enterprise profitability and the matching speed in a competitive market environment. Few studies consider the choice between independent and cooperative modes, the two primary modes for offering matching services in the supply chain domain. To address this gap, this study explores MRM and mode selection in cooperative and independent service environments.

2.2. Applications of evolutionary games

Evolutionary games can be traced back to their application in the field of biological evolution and heredity. Since the introduction of the "Evolutionary Stability Strategy" by Smith (1982) in the late twentieth century, evolutionary game theory has been employed in multiple research fields (Friedman, 1991).

Evolutionary game theory, with its long-term interaction and dynamic equilibrium features, is suitable for exploring strategic interaction and behavioural evolution among individuals (Phelps et al., 2010; Smith & Swierzbinski, 2007). Liu et al. (2022) explore cooperation trends under the influence of partners' data-sharing decisions and technology authorisation of logistics platforms. They suggest that the key to enhanced data sharing between the matching platform and suppliers is to charge reasonable agency fees and sale prices. Ma et al. (2023b) investigate the impact of carbon emission constraints and the sharing of low-carbon capacity on the stability of the system, finding that the system's upper limit of stability can be effectively enhanced by the implementation of control measures. Xia et al. (2023) find that public opinion can effectively prompt automobile companies to voluntarily recall, and active government regulation during this period can promote the healthy development of automobile companies. Tan et al. (2023) study the evolutionary relationship between farmers' choice to forge information and blockchain platform information traceability and find that information traceability technology can not completely solve the risk of information forgery. According to Shen et al. (2021), weak government supervision significantly contributes to unethical behaviours among platform enterprises. Therefore, enhancing government supervision and fostering consumer engagement in supervision can mitigate unethical behaviours.

The abovementioned articles have studied the enterprises' development trend under different backgrounds, but the literature research on MRM under different service modes is still limited. By utilising the framework of evolutionary game theory, this paper aims to address the problem of MRM strategies for large-scale users in the context of long-term interactions.

2.3. Research on CER

With the continuous improvement of environmental awareness, many enterprises actively reduce carbon emissions by updating and improving technologies in production and transportation. Many scholars have studied the CER's simultaneous impact with these measures (Heydari et al., 2021).

Ma et al. (2023c) discover that fierce competition from suppliers leads to higher levels of carbon emissions, while customers with low carbon preferences promote CER. Wang et al. (2020b) study the decision making and coordination in a green e-commerce supply chain. They put forward a "cost-sharing joint commission" contract as a coordination mechanism to realise system coordination and improve system profit. Lok et al. (2023) propose that implementing a carbon tax can effectively reduce emissions. Based on this, they design an economic order quantity model that considers the impact of product preservation technology to optimise the benefits. Differently, Sun and Yang (2021) find that carbon cap-and-trade policies are more effective in reducing emissions and improving social performance. Wang and Wu (2021) find that producer-led recycling is more conducive to reducing carbon emissions, recycling waste products, and creating profits. Furthermore, the paper argues that recycling waste products is also conducive to reducing carbon emissions. Considering trailers' altruistic behaviour, Feng et al. (2021) suggest that by designing altruistic profit distribution rules, excess carbon credits can be transferred to other retailers, thereby achieving a reduction in overall carbon emissions.

Although CER has attracted scholars' attention, its impact combined with MRM has not yet been investigated. Therefore, this study pays attention to the CER problem in the independent and cooperative modes.

3. Model

Consider a resource manufacturing and matching process, as illustrated in Figure 1, where there are numerous suppliers (*sp*) and seekers (*ss*) on the outsourcing platform (*op*). Each resource provider produces and releases the manufacturing resources on the outsourcing platform, and each resource seeker posts its production outsourcing intentions. The parameters used in this paper are summarised in Table 1.

3.1. Manufacturing and CER

The providers produce resources at the unit cost c and cause a unit initial carbon emission e_0. After the production, the providers sell the products to the seekers at price p through the platform matching.

Under environmental laws and regulations, the providers reduce carbon emissions through various procedures, such as technology upgrading and equipment replacement. Let the unit carbon emission level after CER be e. Following Du et al. (2015) and Liu et al. (2020), the CER cost is $k(e_0 - e)^2$, where k is the CER's cost coefficient. Generally, higher carbon emissions e lead to a lower demand q, reflecting the decreased competitiveness of resources with a high carbon footprint. Therefore, the demand function is modelled as $q = \alpha - p - \beta e$. Here, α is the potential market demand, and an increase in price p can lead to a decrement in resource demand q, consistent with fundamental market principles. Considering that adjustments in manufacturing resource demand q are more prevalent than price p adjustments, referring to Wang et al. (2023), the following inverse demand function is employed:

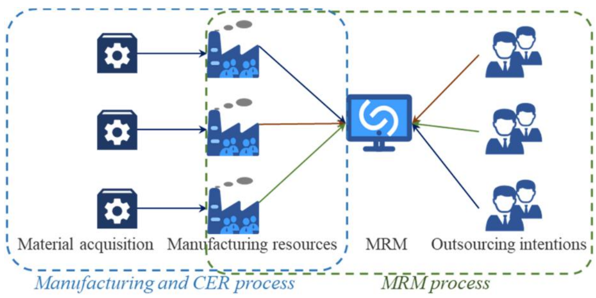

Figure 1. Schematic diagram of resource production and matching.

Table 1. Notation summary.

Superscripts	
$i \in \{A, \bar{A}\}$	$i = A$ represents that seekers accept outsourcing contract, and $i = \bar{A}$ represents that seekers reject outsourcing contract
$j \in \{H, \bar{H}\}$	$i = H$ represents providers accept matching contract, and $i = \bar{H}$ represents providers reject matching contract
$m \in \{F, C\}$	F represents the independent mode, and C represents the cooperative mode
Subscripts	
$l \in \{ss, sp, op, sy\}$	ss represents the service seeker, sp represents the service provider, op represents the outsourcing platform, and sy represents the service system formulated by the provider and platform
Variables	
c	Unit resource's production costs
e_0	Initial carbon emission of unit resource
k	CER's cost coefficient
τ	Maintenance cost of unit resource
η	Revenue and costs sharing ratio, $\eta \in (0, 1)$
α	Potential market size
β	Price sensitivity to the carbon emission, $\beta \in (0, 1)$
U	Seeker's total utility
ϕ	Discount factor representing the seeker's acceptance level of the subsequent trials, $\phi \in (0, 1)$
n	Compensation coefficient, $n \geq 0$
g_l	Entity l's unregulated behaviours' harm level
x	Proportion of seekers choosing to accept outsourcing contract, $x \in [0, 1]$
y	Proportion of providers choosing to accept matching contract, $y \in [0, 1]$
R^m	Matching failure rate
e^m	Unit carbon emission level after CER
p^m	Unit resource's sale price
γ^m	Commission fee
q^m	Production quantity offered by the provider
π_l^{m-ij}	Entity l's profits in the mode m when the seeker and provider choose strategy i and j, respectively

$$p = \alpha - q - \beta e \tag{1}$$

where α is the potential market size, and β is the price sensitivity to the carbon emission.

3.2. MRM process

The platform is committed to matching providers and seekers by suggesting possible matching options and providing necessary services (eg, retrieval and online inquiry services). A successful matching is achieved when both the provider and seeker agree to accept the matching, leading to both the provider generating sales revenue pq and the seeker obtaining a total utility U. In contrast, the matching fails if either entity rejects the matching inquiry. Since numerous providers and seekers are on the platform, if the first matching attempt is unsuccessful, both entities will continue searching for other suitable enterprises to match (Du & Lei, 2022). As a result, this study assumes that successful matching can be achieved through several subsequent trials, but due to the extended waiting time, the provider has a unit holding cost τ for each product, and the seeker obtains a discount utility ϕU, where $\phi \in (0, 1)$ is a discount factor representing the seeker's acceptance level of the subsequent trials (Guo et al., 2019; Li et al., 2022, 2023; Yuan et al., 2021).

To maintain the platform's service quality, the government supervises the behaviour of providers and seekers (Su et al., 2018; Tan et al., 2023). If entity l $(l \in \{ss, sp\})$ is found to have violated behaviours, such as by giving exaggerated propaganda or fake information, that elicits the other entity's refusal to match. The entity l needs to pay a compensation fee ng_l to the other aggrieved party, where g_l represents entity l's unregulated behaviours' harm level and $n \geq 0$ is a compensation coefficient.

Combining the above, providers and seekers have different strategies in the MRM. Let A $(\bar{A})$ denote the set of seekers accepting (rejecting) the outsourcing contract, and let H $(\bar{H})$ denote the set of providers choosing to accept (not accept) the matching contract. Let the proportion of A in the seekers be x where $x \in [0, 1]$, so the population of $\bar{A}$ is $1 - x$. Similarly, the proportion of H in the providers is y where $y \in [0, 1]$, and the population of $\bar{H}$ is $1 - y$.

3.3. Service modes

The independent and cooperative modes are illustrated in Figure 2. These two modes are widely adopted in outsourcing platforms in practice, such as Amazon Mechanical Turk, Tao Factory, and Crowd Supply.

In the independent mode (F), the provider pays a commission fee γ to the platform for each unit of resource outsourced, while the seeker uses the MRM service for free. The provider makes the production and emission quantity decisions (i.e., q, and e) and charges the seeker a price p for each unit of resource. In the cooperative mode (C), the provider and platform coordinate as one system. They jointly make the production and emission quantity decisions, and they share the production costs and sales of the manufacturing resources (Iacocca & Mahar, 2019; Ren et al., 2021). Let the revenue and costs sharing ratio between the provider and the platform be η and $1 - \eta$ $(\eta \in (0, 1))$, respectively.

In the independent service mode, let π_l^{F-ij} denote entity l's profits when the seeker and provider choose strategy i and j, respectively. Thus, each entity's profits under different strategies are as shown in Table 2.

Let subscript sy denote the system formulated by the provider and platform, and π_l^{C-ij} denote entity l's profits in the cooperative mode. Table 3 presents the profits under the strategies for the seeker and system.

4. Equilibrium analysis

During resource production, matching, and transaction, providers and seekers engage in a prolonged selection process, eventually transitioning to a stable state influenced by various factors. Throughout this process, each entity consistently prefers the strategy that offers higher returns. Therefore, this section examines the evolutionary stability of MRM and studies the optimal production and emission quantity decisions. Sections 4.1 and 4.2 examine the independent and cooperative modes, respectively.

4.1. Independent mode

4.1.1. Evolutionary stability analysis

Table 4 shows the revenue matrix of the evolutionary game in independent mode. The table

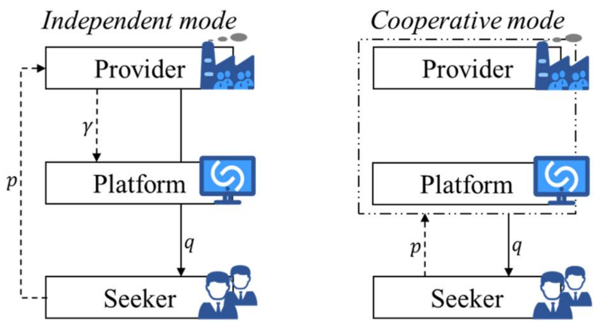

Figure 2. Schematic diagram of independent and cooperative modes.

summarises the revenue functions for the provider and seeker when they accept or reject the matching trial.

Let Π_{ss}^F denote the seeker's surplus in the independent mode, which is given by:

$$\Pi_{ss}^F = x\pi_{ss}^{F-A} + (1-x)\pi_{ss}^{F-\bar{A}} \tag{2}$$

where $\pi_{ss}^{F-A} = y\pi_{ss}^{F-AH} + (1-y)\pi_{ss}^{F-A\bar{H}}$ and $\pi_{ss}^{F-\bar{A}} = y\pi_{ss}^{F-\bar{A}H} + (1-y)\pi_{ss}^{F-\bar{A}\bar{H}}$ are the seeker's expected surplus accepting and rejecting the outsourcing contract, respectively.

Similarly, let Π_{sp}^F be the provider's profits in the independent mode, which is given by:

$$\Pi_{sp}^F = y\pi_{sp}^{F-H} + (1-y)\pi_{sp}^{F-\bar{H}} \tag{3}$$

where $\pi_{sp}^{F-H} = x\pi_{sp}^{F-AH} + (1-x)\pi_{sp}^{F-\bar{A}H}$ and $\pi_{sp}^{F-\bar{H}} = x\pi_{sp}^{F-A\bar{H}} + (1-x)\pi_{sp}^{F-\bar{A}\bar{H}}$ are the provider's profits choosing to provide and not provide resources, respectively.

Five equilibrium points of (x, y) can be derived, where x denotes the proportion of seekers accepting outsourcing contracts and y denotes the proportion of providers offering resources, respectively. Proposition 1 states the evolutionary stable strategies (ESSs) and their stability conditions.

Proposition 1: *$(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$ are the equilibrium points of the evolutionary game. When $\tau q^F - ng_{ss} > 0$ and $U(1-\phi) - ng_{sp} > 0$, there is an additional equilibrium point $(ng_{sp}/(\tau q^F + n(g_{sp} - g_{ss})), ng_{ss}/(U(1-\phi) - n(g_{sp} - g_{ss})))$. The stabilities of equilibrium points are:*

Table 4. Evolutionary game revenue matrix in independent mode.

		Provider's strategy	
		H	$\bar{H}$
Seeker's strategy	A	π_{ss}^{F-AH}, π_{sp}^{F-AH}	$\pi_{ss}^{F-A\bar{H}}$, $\pi_{sp}^{F-A\bar{H}}$
	$\bar{A}$	$\pi_{ss}^{F-\bar{A}H}$, $\pi_{sp}^{F-\bar{A}H}$	$\pi_{ss}^{F-\bar{A}\bar{H}}$, $\pi_{sp}^{F-\bar{A}\bar{H}}$

Table 2. Profits of seeker and provider in independent mode.

Strategy	Seeker's profit	Provider's profit
(A, H)	$\pi_{ss}^{F-AH} = U - pq$	$\pi_{sp}^{F-AH} = (p-\gamma-c)q - k(e_0-e)^2$
$(A, \bar{H})$	$\pi_{ss}^{F-A\bar{H}} = \phi U - pq - ng_{ss}$	$\pi_{sp}^{F-A\bar{H}} = (p-\gamma-c)q - k(e_0-e)^2 - \tau q + ng_{ss}$
$(\bar{A}, H)$	$\pi_{ss}^{F-\bar{A}H} = \phi U - pq + ng_{sp}$	$\pi_{sp}^{F-\bar{A}H} = (p-\gamma-c)q - k(e_0-e)^2 - \tau q - ng_{sp}$
$(\bar{A}, \bar{H})$	$\pi_{ss}^{F-\bar{A}\bar{H}} = \phi U - pq$	$\pi_{sp}^{F-\bar{A}\bar{H}} = (p-\gamma-c)q - k(e_0-e)^2 - \tau q$

Table 3. Profits of seeker and system in cooperative mode.

Strategy	Seeker's profits	System's profits
(A, H)	$\pi_{ss}^{C-AH} = U - pq$	$\pi_{sy}^{C-AH} = (p-c)q - k(e_0-e)^2$
$(A, \bar{H})$	$\pi_{ss}^{C-A\bar{H}} = \phi U - pq - ng_{ss}$	$\pi_{sy}^{C-A\bar{H}} = (p-c)q - k(e_0-e)^2 - \tau q + ng_{ss}$
$(\bar{A}, H)$	$\pi_{ss}^{C-\bar{A}H} = \phi U - pq + ng_{sp}$	$\pi_{sy}^{C-\bar{A}H} = (p-c)q - k(e_0-e)^2 - \tau q - ng_{sp}$
$(\bar{A}, \bar{H})$	$\pi_{ss}^{C-\bar{A}\bar{H}} = \phi U - pq$	$\pi_{sy}^{C-\bar{A}\bar{H}} = (p-c)q - k(e_0-e)^2 - \tau q$

1. $(0,0)$ *and* $(1,1)$ *are ESSs (i.e.,* $(\bar{A},\ \bar{H})$ *and* $(A,\ H)$ *are evolutionarily stable strategies).*
2. $(0,1)$ *and* $(1,0)$ *are unstable points.*
3. $(ng_{sp}/(\tau q^F + n(g_{sp} - g_{ss})), ng_{ss}/(U(1-\phi) - n(g_{sp} - g_{ss})))$ *is the saddle point.*

The evolution process of each equilibrium point is illustrated in Figure 3. Each point (x, y) in Figure 3 indicates the initial condition of providers' and seekers' matching strategies. Different initial points will lead to different ESSs in the evolution process, and the arrows indicate the evolution paths of different initial points. By Proposition 1, when the initial point (x, y) is located in the region $E_1E_2E_5E_4$, the providers' and seekers' equilibrium strategies will converge to $E_1(0, 0)$. In this case, the ESS is $(\bar{A},\ \bar{H})$, which means that the matching ultimately fails for the entities whose initial points are located in $E_1E_2E_5E_4$. When the point (x, y) is located in region $E_2E_3E_4E_5$, the equilibrium strategy will converge to $E_3(1, 1)$, and the ESS is $(A,\ H)$, which indicates that the matching is successful for entities whose initial points are located in $E_2E_3E_4E_5$, given enough time.

The results demonstrate that the willingness with which entities seek a match significantly affects the platform's development. Consequently, the entities' variances in demand and capabilities serve as crucial factors influencing the platform's development. Establishing a comprehensive system for admission and elimination, avoiding indiscriminate member expansion, and precisely selecting target customers not only ensures high-quality resources and services but also enhances matching efficiency and promotes the platform's development. Furthermore, implementing diverse measures to enhance the willingness to match, including establishing interactive communities and incorporating digital technologies, also benefits the platform's development.

Assume the area of region $E_1E_2E_3E_4$ is 1, and that of region $E_1E_2E_5E_4$ is R, so the area of region $E_2E_3E_4E_5$ is $1 - R$. As the entities with initial points in region $E_1E_2E_5E_4$ cannot achieve a successful matching with an evolution process, no matter how long, R stands for the proportion of the instances in which the matching ultimately fails, hereinafter referred to as the *matching failure rate*. The smaller R is, the more successful the MRM process. Given the production quantity q^F, the formulation of R^F in independent mode is given by:

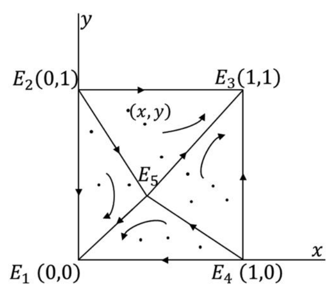

Figure 3. Evolution phase diagram of resource matching.

$$R^F = \frac{1}{2}\left(\frac{ng_{sp}}{\tau q^F + n(g_{sp} - g_{ss})} + \frac{ng_{ss}}{U(1-\phi) - n(g_{sp} - g_{ss})}\right) \tag{4}$$

Matching failure rate R^F is an important indicator of the MRM quality, and Section 5.1 performs a comparative analysis of R^F for the independent and cooperative modes.

4.1.2. Profit analysis

When the matching succeeds, the entities make production and emission quantity decisions to maximise profits. Once the platform announces the commission fee γ, the provider decides its production quantity q and carbon emission level e. The profit functions of the platform, providers, and system (i.e., providers and platform) are given by:

$$\Pi^F_{op} = \gamma q^F \tag{5}$$

$$\Pi^F_{sp} = q^F(p^F - \gamma - c) - k(e_0 - e^F)^2 - \tau q^F(1 - xy) - yng_{sp}(1 - x) + xng_{ss}(1 - y) \tag{6}$$

$$\Pi^F_{sy} = \Pi^F_{op} + \Pi^F_{sp} \tag{7}$$

Using backward induction to analyse the provider's production and emission quantity decisions yields the results summarised in Lemma 1.

Lemma 1. *In the independent mode, the following properties hold:*

1. *The provider's optimal production and emission quantities are* $q^{F*} = kT/(4k - \beta^2)$ *and* $e^{F*} = e_0 - \beta T/(2(4k - \beta^2))$, *and the optimal price is* $p^{F*} = \alpha - \beta e_0 - T(2k - \beta^2)/(2(4k - \beta^2))$.
2. *The platform's optimal commission fee is* $\gamma^{F*} = T/2$.
3. *The expected profits of the provider, platform, and system are* $\Pi^{F*}_{sp} = kT^2/(4(4k - \beta^2)) - (1 - x)yng_{sp} + x(1 - y)ng_{ss}$, $\Pi^{F*}_{op} = kT^2/(2(4k - \beta^2))$, *and* $\Pi^{F*}_{sy} = 3kT^2/(4(4k - \beta^2)) - (1 - x)yng_{sp} + x(1 - y)ng_{ss}$, *where* $T = \alpha - c - \beta e_0 - \tau(1 - xy)$.

By raising the initial proportion $(x,\ y)$ to matches, providers and seekers can attain increased resource demands q, reduced resource prices p, and higher CER $(e_0 - e)$. As the probability of agreement to match increases, the platform's operation environment improves, enabling the platform to raise commission levels γ and yield higher profits. Given that Proposition 1 states that varying initial matching intentions influence final stable strategies, establishing an effective matching platform requires a favourable industry environment and a sound screening mechanism to foster a long-term, stable, and sustainable resource matching environment.

4.2. Cooperative mode

4.2.1. Evolutionary stability analysis

Table 5 shows the revenue matrix of the cooperative mode, summarising the revenue for both the system and seekers when they accept or reject the matching. Let $\pi_{sy}^{C-H} = x\pi_{sy}^{C-AH} + (1-x)\pi_{sy}^{C-\bar{A}H}$ and $\pi_{sy}^{C-\bar{H}} = x\pi_{sy}^{C-A\bar{H}} + (1-x)\pi_{sy}^{C-\bar{A}\bar{H}}$ denote the system's expected profits when choosing to provide and not provide resources, respectively. The expected profit of the system can be expressed as:

$$\Pi_{sy}^{C} = y\pi_{sy}^{C-H} + (1-y)\pi_{sy}^{C-\bar{H}} \tag{8}$$

Proposition 2 specifies the equilibrium points in the evolution game.

Proposition 2: *The equilibrium points in the cooperative mode are* $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$, *and* $(ng_{sp}/(\tau q^C + n(g_{sp}-g_{ss})), ng_{ss}/(U(1-\phi)-n(g_{sp}-g_{ss})))$ *when* $\tau q^C - ng_{ss} > 0$ *and* $U(1-\phi) - ng_{sp} > 0$. *The stability of five equilibrium points are as follows:*

1. $(0,0)$ *and* $(1,1)$ *are ESSs (i.e.,* $(\bar{A}, \bar{H})$ *and* (A, H) *are evolutionarily stable strategies).*
2. $(0,1)$ *and* $(1,0)$ *are unstable points.*
3. $(ng_{sp}/(\tau q^C + n(g_{sp}-g_{ss})), ng_{ss}/(U(1-\phi)-n(g_{sp}-g_{ss})))$ *is a saddle point.*

Proposition 2 indicates that while the two modes' equilibrium points and evolution direction are the same, the saddle point presents different results. This suggests that the two modes' region R could lead to different results; that is, even if some areas have the same initial state, different stability strategies result. Thus, resource quantities and profits are the fundamental factors influencing resource matching, and the design of platform service modes can only facilitate the matching process. This assists the platform in comprehending the behaviour of both providers and seekers and better providing flexible service modes for matching both entities. Different saddle points make a difference in R, and this impact is analysed thoroughly in Section 5.1. For a given production quantity q^C, the matching failure rate R^C in the cooperative mode is as follows:

$$R^C = \frac{1}{2}\left(\frac{ng_{sp}}{\tau q^C + n(g_{sp}-g_{ss})} + \frac{ng_{ss}}{U(1-\phi) - n(g_{sp}-g_{ss})}\right) \tag{9}$$

4.2.2. Profit analysis

This section analyses each entity's profits in the cooperative mode. First, the platform and the providers jointly decide the revenue-sharing ratio η. Second, they decide the production quantity q and carbon emission level e together. The profit functions of the platform, provider, and system are given by:

$$\Pi_{op}^{C} = (p^C - c)(1-\eta)q^C \tag{10}$$

$$\Pi_{sp}^{C} = (p^C - c)\eta q^C - k(e_0 - e^C)^2 - (1-xy)\tau q^C - (1-x)yng_{sp} + x(1-y)ng_{ss} \tag{11}$$

$$\Pi_{sy}^{C} = \Pi_{op}^{C} + \Pi_{sp}^{C} \tag{12}$$

Computing the equilibrium strategies through backward induction, Lemma 2 states the optimal decisions under the cooperative mode.

Lemma 2. *The following properties hold in the cooperative mode:*

1. *The system's optimal production and emission quantities are* $q^{C*} = 2kT/(4k-\beta^2)$, $e^{C*} = (4ke_0 - \beta(T+\beta e_0))/(4k-\beta^2)$, *and the optimal price is* $p^{C*} = \alpha - ((2k-\beta^2)(T+\beta e_0) + 2\beta k e_0)/(4k-\beta^2)$;
2. *The profits of the platform, provider, and system are* $\Pi_{op}^{C*} = q^{C*}(1-\eta)(q^{C*} + \tau(1-xy))$, $\Pi_{sp}^{C*} = q^{C*2}(4\eta k - \beta^2)/(4k) - \tau q^{C*}(1-\eta)(1-xy) - (1-x)yng_{sp} + x(1-y)ng_{ss}$, *and* $\Pi_{sy}^{C*} = kT^2/(4k-\beta^2) - (1-x)yng_{sp} + x(1-y)ng_{ss}$.

From Lemma 2, it becomes apparent that the proportion of entities willing to match exerts a significant influence on resource demand, price, and profits. This observation aligns with the findings of Lemma 1. Nevertheless, disparities exist in members' decision-making processes under the two modes, primarily attributable to the varied cooperation relationships between the platform and providers. Specifically, a discussion of the interplay between the commission and profit-sharing ratios in both modes is warranted to ensure that each entity can obtain higher profits. Detailed discussions on this matter are provided in Propositions 4 and 5.

5. Service mode comparison

This section explores the economic and environmental impacts of independent and cooperative modes. Sections 5.1 and 5.2 contrast the matching failure rate and the profits under different modes,

Table 5. Evolutionary game revenue matrix in cooperative mode.

		System's strategy	
		H	$\bar{H}$
Seeker's strategy	A	π_{ss}^{C-AH}, π_{sy}^{C-AH}	$\pi_{ss}^{C-A\bar{H}}$, $\pi_{sy}^{C-A\bar{H}}$
	$\bar{A}$	$\pi_{ss}^{C-\bar{A}H}$, $\pi_{sy}^{C-\bar{A}H}$	$\pi_{ss}^{C-\bar{A}\bar{H}}$, $\pi_{sy}^{C-\bar{A}\bar{H}}$

respectively. Section 5.3 compares the carbon emission levels in the two modes.

5.1. Matching failure rate

By substituting the optimal production quantities q^{F*} and q^{C*} into R^F and R^C, this section analyses the matching failure rate with the optimal production quantities. The matching failure rates in the independent and cooperative modes are:

$$R^{F*} = n\frac{k\tau g_{ss}T + \left(4k-\beta^2\right)\left(g_{sp}U(1-\phi) - n\left(g_{sp}-g_{ss}\right)^2\right)}{2\left(U(1-\phi) - n\left(g_{sp}-g_{ss}\right)\right)\left(n\left(g_{sp}-g_{ss}\right)\left(4k-\beta^2\right) + k\tau T\right)} \tag{13}$$

$$R^{C*} = n\frac{2k\tau g_{ss}T + \left(4k-\beta^2\right)\left(g_{sp}U(1-\phi) - n\left(g_{sp}-g_{ss}\right)^2\right)}{2\left(U(1-\phi) - n\left(g_{sp}-g_{ss}\right)\right)\left(n\left(g_{sp}-g_{ss}\right)\left(4k-\beta^2\right) + 2k\tau T\right)} \tag{14}$$

Proposition 3 elucidates the matching failure rates (region R^{F*} and R^{C*}) and their changes with α and n.

Proposition 3: *The following properties hold for R^F* and R^C:

1. *The matching failure rate is higher in independent mode than cooperative mode. (i.e.,$R^{F*} > R^{C*}$).*
2. *The matching failure rates of both independent and cooperative modes decrease in the potential market size and the compensation coefficient (i.e., $\partial R^j/\partial\alpha < 0,\ \partial R^j/\partial n > 0,\ for j = C, F$).*

Proposition 3 shows that the cooperative mode exhibits a relatively lower matching failure rate, primarily attributable to the disparities between the two modes, which engender a greater willingness to match in the cooperative mode. Consequently, entities in the cooperative mode are more likely to achieve a state of successful matching when starting from the same initial conditions. Therefore, the disparities between the two modes are explored in the subsequent propositions. Moreover, while it is readily understandable that a larger potential market size enhances the success rate of matching, it is counterintuitive that an increase in compensation level does not necessarily facilitate matching. The main reason is that the compensation mechanism elevates thresholds, escalates entities' risk costs, and diminishes their motivation to participate in resource matching. Therefore, selecting appropriate service modes for the platform, increasing the resource demand, and seeking more high-quality entities can effectively promote resource matching. Meanwhile, it is crucial to design a reasonable compensation and punishment mechanism for the platform, and excessive punishments are not conducive to promoting resource matching.

5.2. Entity profit

Proposition 4 compares the entities' production quantities and profits in the two modes.

Proposition 4: *The following properties hold for the two modes:*

1. The production quantity is higher in cooperative mode (that is, $q^{C*} > q^{F*}$).
2. The system has higher profits in cooperative mode (that is, $\Pi_{sy}^{C*} > \Pi_{sy}^{F*}$).

Proposition 4 indicates that sharing the production costs and sales in the cooperative mode can increase the provider's motivation to provide the manufacturing resource, which improves the system's profits. This arises due to the cooperative mechanism between the platform and providers, which facilitates the alignment of both entities towards a shared objective, leading to more effective decision making and avoiding the occurrence of price cascading commonly observed in independent mode.

It is worth noting that higher system profits do not necessarily bring higher profits for each side. Therefore, ensuring both sides obtain higher profits is crucial to the cooperative mode, requiring discussion of the conditions to ensure each entity achieves higher profits (Pareto-improved profits) in cooperative mode. To facilitate the analysis, consider two thresholds Z_1 and Z_2, given by:

$$Z_1 = 1 - \frac{3T}{8\left(q^{C*} + \tau(1-xy)\right)} \tag{15}$$

$$Z_2 = 1 - \frac{T}{4\left(q^{C*} + \tau(1-xy)\right)} \tag{16}$$

The inequalities $0 < Z_1 < Z_2 < 1$ hold. Proposition 5 gives the conditions under which both the platform and provider can achieve improved profits in the cooperative mode.

Proposition 5: *The following properties hold under different sharing ratio η:*

1. *If $0 < \eta < Z_1$, the platform has higher profit in the cooperative mode, but the provider's profit is lower in the cooperative mode (i.e., $\Pi_{op}^{C*} > \Pi_{op}^{F*},\ \Pi_{sp}^{C*} < \Pi_{sp}^{F*}$).*
2. *If $Z_1 < \eta < Z_2$, both the platform and provider obtain higher profit in the cooperative mode (i.e., $\Pi_{op}^{C*} > \Pi_{op}^{F*},\ \Pi_{sp}^{C*} > \Pi_{sp}^{F*}$).*
3. *If $Z_2 < \eta < 1$, the platform's profit is greater in the independent mode than the cooperative mode, whereas the provider obtains higher profit*

in the cooperative mode (i.e., $\Pi_{op}^{C*} < \Pi_{op}^{F*}$, $\Pi_{sp}^{C*} > \Pi_{sp}^{F*}$).

Proposition 5 reveals that higher profits can be achieved in the cooperative mode for both the provider and platform with a medium sharing ratio η. If the sharing ratio η is either too high or too low, it will harm one side's profit, and reduce its motivation to participate in the cooperative mode. The present study further identifies the range in which both the platform and providers achieve higher profits, building upon the findings of Zhao and Han (2020), who determine that the revenue-sharing contract can coordinate the supply chain under certain conditions. However, when the ratio falls outside this range, one side's disproportionate dominance can hurt the other party's profits. Therefore, the platform should negotiate the revenue-sharing ratio with providers based on their contributions. Moreover, the platform should establish comprehensive rules to settle disagreements regarding revenue and prevent the dominant side from abusing its influence.

5.3. Carbon emission

Analysis of the carbon emissions in different modes yields the results in Proposition 6.

Proposition 6: *Considering carbon emission in the two modes, the following properties hold:*

1. *The cooperative mode results in a higher CER level (that is, $e^{F*} > e^{C*}$).*
2. *If $8ke_0 \geq \beta(3(\alpha - c - \tau(1 - xy)) - \beta e_0)$, the total carbon emissions in the cooperative mode are higher (that is, $e^{C*}q^{C*} \geq e^{F*}q^{F*}$); otherwise, the independent mode contributes to a higher total carbon emission.*

Proposition 6 states that the platform has a higher CER level when operating in the cooperative mode. Similarly, Liu et al. (2020) find that stronger cooperation leads to higher CER levels. However, a higher CER level does not always equate to lower total carbon emissions. Total carbon emission is higher in the cooperative mode under certain conditions, such as a high CER coefficient. Therefore, entities should have a comprehensive goal involving both maximising profits and CER, and evaluate the cost and benefits of carbon reduction, as beyond some threshold, high costs will prevent a sustainable, long-term solution. Continuously exploring new CER solutions and fostering technological cooperation are essential for effectively attaining emission reduction targets while advancing economic goals.

6. Conclusion

Numerous manufacturing resource providers and seekers use platform manufacturing resource matching (MRM) services for convenience and efficiency. Typically, there are two MRM modes: independent mode and cooperative mode. In independent mode, the platform charges MRM fees to the provider in the form of a commission. In cooperation mode, the platform reaches an agreement on profit-cost sharing with providers and provides matching services. While the outsourcing platform provides convenient MRM services, production remains a prerequisite for MRM. Manufacturing resource production often entails high carbon emissions, a crucial factor influencing entities' willingness and profits to match. Therefore, many entities have begun investing in and exploring carbon reduction technologies. This paper establishes an evolutionary game model for resource matching between providers and seekers to discuss and compare the independent and cooperative modes' resource-matching evolutionary stable strategies (ESSs) and matching failure rates. Furthermore, this paper establishes a sequential game model for the decision-making problem between the platform and providers, analysing and comparing the entities' profits and emission reduction strategies.

The results show that the two service modes' evolution paths and ESSs are the same, but their saddle points are different. This indicates that both service modes have the same ESSs, but the cooperative mode facilitates the matching attainment for entities in the same initial matching state. Secondly, choosing the cooperative mode can enable the platform and providers to achieve higher total profits, and setting a reasonable range of profit-cost sharing ratios is essential to guarantee profits. Finally, in the cooperative mode, providers can achieve higher carbon emission reduction levels. However, the increased quantity of matched resources in this mode may lead to higher total carbon emissions compared to the independent mode. Therefore, entities must comprehensively consider market size and carbon emission levels, and they must formulate measures to mitigate their environmental impact.

This paper considers the matching and operation process of common manufacturing resources through two service modes: the independent mode and the cooperative mode. Future work could involve the following aspects. First, when a seller's market emerges or sellers hold the dominant position, seekers may be incentivised to cooperate with the platform to facilitate transactions with providers, presenting an avenue for further exploration in future research endeavours. Second, this paper offers insights into manufacturing outsourcing services, but it could be strengthened by considering industry-specific factors. For instance, chemical manufacturing requires unique safety considerations. Expanding the scope to include diverse industries and manufacturing resources would provide a more comprehensive understanding of outsourcing decisions across various economic sectors.

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Appendix A: Technical proofs

A1. Proof of proposition 1

According to the Malthusian dynamic equation (Friedman, 1991), the replicator dynamic equations of providers and seekers are given by:

$$f^F(x) = x\left(\pi_{ss}^{F-A} - \Pi_{ss}^F\right) = x(1-x)\left(\pi_{ss}^{F-A} - \pi_{ss}^{F-\bar{A}}\right) \tag{A1}$$

$$f^F(y) = y\left(\pi_{sp}^{F-H} - \Pi_{sp}^F\right) = y(1-y)\left(\pi_{sp}^{F-H} - \pi_{sp}^{F-\bar{H}}\right) \tag{A2}$$

Using Equations (A1) and (A2) to describe providers' and seekers' evolutionary game process, five equilibrium points of (x, y) can be derived, where x denotes the proportion of seekers accepting outsourcing contracts and y denotes the proportion of providers offering resources, respectively. Next, the Jacobi matrix is employed to judge the equilibrium points' stability of the replicator dynamic equations (Hassan et al., 2014). The Jacobi matrix of the system is:

$$J = \begin{bmatrix} \dfrac{\partial f^F(x)}{\partial x} & \dfrac{\partial f^F(x)}{\partial y} \\ \dfrac{\partial f^F(y)}{\partial x} & \dfrac{\partial f^F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)\left(y\left(n(g_{ss}-g_{sp}) + U(1-\phi)\right) - ng_{ss}\right) & x(1-x)\left(n(g_{ss}-g_{sp}) + U(1-\phi)\right) \\ y(1-y)\left(n(g_{sp}-g_{ss}) + \tau q^F\right) & (1-2y)\ \left(n\left(x(g_{sp}-g_{ss}) - g_{sp}\right) + x\tau q^F\right) \end{bmatrix} \tag{A3}$$

Using the trace $Tr(J)$ and determinant $Det(J)$ of the Jacobian matrix, the stability analysis of the equilibrium points can be conducted, and Table A1 shows the results. The equilibrium point is an ESS when the determinant is positive and the trace is negative. Proposition 1 presents the stability conditions for the equilibrium points.

A2. Proof of lemma 1

By substituting Equation (1) into Equation (6), the first derivative of e^F and q^F can be obtained, respectively. The Hessian matrix is $H_1 = \begin{pmatrix} \partial^2\Pi_{sp}^F/\partial e^{F2} & \partial^2\Pi_{sp}^F/\partial e^F\partial q^F \\ \partial^2\Pi_{sp}^F/\partial q^F\partial e^F & \partial^2\Pi_{sp}^F/\partial q^{F2} \end{pmatrix} = \begin{pmatrix} -2k & -\beta \\ -\beta & -2 \end{pmatrix}$. When $4k - \beta^2 > 0$ is satisfied, H_1 is negative definite, and Π_{sp}^F has an optimal solution. Letting $\partial\Pi_{sp}^F/\partial e^F = 0$ and $\partial\Pi_{sp}^F/\partial q^F = 0$ yields the following:

$$e^F(\gamma) = \frac{4ke_0 \ - \beta(\alpha - c - \gamma - \tau(1-xy))}{4k - \beta^2} \tag{A4}$$

$$q^F(\gamma) = \frac{2k\left((\alpha - c - \gamma) - \beta e_0 - \tau(1-xy)\right)}{4k - \beta^2} \tag{A5}$$

Substituting the above two equations into Equation (5) yields $\partial^2\Pi_{op}^F/\partial\gamma^2 = -4k/(4k - \beta^2) < 0$. Therefore, Π_{op}^F is a concave function of γ. Combining this with $\partial\Pi_{op}^F/\partial\gamma = 0$ shows:

$$\gamma^{F*} = \frac{\alpha - c - \beta e_0 - \tau(1-xy)}{2} \tag{A6}$$

Therefore, the optimal results can be obtained.

A3. Proof of lemma 2

By substituting Equation (1) into Equation (12), differentiation of the resulting expression yields the first derivatives of e^C and q^C respectively. The Hessian matrix is $H_2 = \begin{pmatrix} \partial^2\Pi_{sy}^C/\partial e^{C2} & \partial^2\Pi_{sy}^C/\partial e^C\partial q^C \\ \partial^2\Pi_{sy}^C/\partial q^C\partial e^C & \partial^2\Pi_{sy}^C/\partial q^{C2} \end{pmatrix} = \begin{pmatrix} -2k & -\beta \\ -\beta & -2 \end{pmatrix}$. When the

Table A1. Stability analysis in independent mode.

Equilibrium point	$Det(J)$	$Tr(J)$	Stability
$(0,0)$	$n^2g_{sp}g_{ss} > 0$	$-n(g_{sp}+g_{ss}) < 0$	ESS
$(0,1)$	$ng_{sp}(U(1-\phi) - ng_{sp}\ ) > 0$	$(1-\phi)U > 0$	Unstable point
$(1,0)$	$ng_{ss}(\tau q - ng_{ss}) > 0$	$\tau q > 0$	Unstable point
$(1,1)$	$(ng_{ss} - \tau q)(ng_{sp} - U(1-\phi)) > 0$	$-(U(1-\phi) - ng_{sp})$ $-(\tau q - ng_{ss}) < 0$	ESS
$\left(\dfrac{ng_{sp}}{\tau\ q + n(g_{sp}-g_{ss})}, \dfrac{ng_d}{U(1-\phi) - n(g_{sp}-g_{ss})}\right)$	$\frac{-n^2g_{sp}g_{ss}\ \ (\tau q - ng_{ss})\ \ (U(1-\phi) - ng_{sp})}{(U(1-\phi)+n(g_{ss}-g_{sp}))(n(g_{sp}-g_{ss})+\tau q^F)} < 0$	0	Saddle point

relation $4k-\beta^2>0$ is satisfied, H_2 is negative definite, and Π_{sy}^C has an optimal solution. Letting $\partial\Pi_{sy}^C/\partial e^C=0$ and $\partial\Pi_{sy}^C/\partial q^C=0$, the results can be obtained.

A4. Proof of proposition 3

1. Taking the partial derivative of R^j with respect to α, $\frac{\partial R^F}{\partial \alpha}=\frac{-kn\tau g_{sp}(4k-\beta^2)}{2(k\tau(\alpha-c-\beta e_0-\tau(1-xy))-n(g_{ss}-g_{sp})(4k-\beta^2))^2}$ and $\frac{\partial R^C}{\partial \alpha}=\frac{-kn\tau g_{sp}(4k-\beta^2)}{(2k\tau(\alpha-c-\beta e_0-\tau(1-xy))-n(g_{ss}-g_{sp})(4k-\beta^2))^2}$. Therefore, $\partial R^F/\partial\alpha<0$ and $\partial R^C/\partial\alpha<0$.
2. Taking the partial derivative of R^j with respect to n, $\partial R^j/\partial n=\frac{1}{2}(q^j\tau g_{sp}/(d^j\tau+n(g_{sp}-g_{ss}))^2+g_{ss}U(1-\phi)/(U(1-\phi)-n(g_{sp}-g_{ss}))^2)$. Therefore, $\partial R^j/\partial n>0$.

A5. Proof of proposition 4

Transforming q^{F*} and e^{F*} into a function of γ yields the results $q^{C*}-q^F(\gamma)=2k\gamma/(4k-\beta^2)>0$, and $\Pi_{sy}^{C*}-\Pi_{sy}^{F*}=k(\alpha-c-\beta e_0-\tau(1-xy))^2/(4(4k-\beta^2))>0$. Therefore, $q^{F*}<q^{C*}$, and $\Pi_{sy}^{F*}<\Pi_{sy}^{C*}$. The results are obtained.

A6. Proof of proposition 5

1. $\Pi_{sp}^{C*}-\Pi_{sp}^{F*}$ can be rewritten as follows: $\Pi_{sp}^{C*}-\Pi_{sp}^{F*}=\gamma q^{C*}-k\gamma^2/(4k-\beta^2)-q^{C*}(1-\eta)(q^{C*}+\tau(1-xy))$. When $\Pi_{sp}^{C*}-\Pi_{sp}^{F*}>0$ is satisfied, $\eta>1-\frac{3T}{8(q^{C*}+\tau(1-xy))}=Z_1$.
2. $\Pi_{op}^{C*}-\Pi_{op}^{F*}$ can be rewritten as follows: $\Pi_{op}^{C*}-\Pi_{op}^{F*}=q^{C*}(1-\eta)(\tau(1-xy)+q^{C*})-q^{C*2}(4k-\beta^2)/(2k)+2q^{C*}\gamma-2k\gamma^2/(4k-\beta^2)$. When $\Pi_{op}^{C*}-\Pi_{op}^{F*}>0$, $\eta<1-T/(4(\tau(1-xy)+q^{C*}))=Z_2$.

Therefore, $Z_1<Z_2<1$. When $8(2kT/(4k-\beta^2)+\tau(1-xy))-3T>0$ is met, $Z_1>0$; when $Z_1<\eta<Z_2$ is satisfied, $\Pi_{op}^{C*}>\Pi_{op}^{F*}$, $\Pi_{sp}^{C*}>\Pi_{sp}^{F*}$; when $0<\eta<Z_1$ is satisfied, $\Pi_{op}^{C*}>\Pi_{op}^{F*}$, $\Pi_{sp}^{C*}<\Pi_{sp}^{F*}$; when $Z_2<\eta<1$ is satisfied, $\Pi_{op}^{C*}<\Pi_{op}^{F*}$, $\Pi_{sp}^{C*}>\Pi_{sp}^{F*}$. The results are obtained.

A7. Proof of proposition 6

Comparing carbon emissions of cooperative and independent modes can be done as follows:

1. Transforming q^{F*} and e^{F*} into a function about γ results in $e^{C*}-e^F(\gamma)=-\beta\gamma/(4k-\beta^2)<0$. Therefore, $e^{F*}>e^{C*}$.
2. Through the transformation of e^{F*}, q^{F*}, and e^{C*}, the following can be shown:

$$e^{C*}=\frac{-\beta}{2k}q^{C*}+e_0 \tag{A7}$$

$$q^{F*}=q^{C*}-\frac{2k\gamma}{4k-\beta^2} \tag{A8}$$

$$e^{F*}=\frac{\gamma\beta}{4k-\beta^2}+e^{C*} \tag{A9}$$

Therefore $e^{C*}q^{C*}-e^{F*}q^{F*}=k(\alpha-c-\beta e_0-\tau(1-xy))(e_0(8k+\beta^2)-3\beta(\alpha-c-\tau(1-xy)))/((2(4k-\beta^2)^2))$. When $e_0(8k+\beta^2)-3\beta(\alpha-c-\tau(1-xy))>0$, $e^{C*}q^{C*}-e^{F*}q^{F*}>0$. The results are obtained.

A8. Proof of proposition 7

The replicator dynamic equations of providers and seekers are:

$$f^L(x)=\dot{x}=x(1-x)\left(S_{ss}^{L-A}-S_{ss}^{L-\bar{A}}\right) \tag{A10}$$

$$f^L(y)=\dot{y}=y(1-y)\left(\Pi_{sp}^{L-H}-\Pi_{sp}^{L-\bar{H}}\right) \tag{A11}$$

From $f^L(x)=0$ and $f^L(y)=0$, the equilibrium points $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$ and $(z_{12}ng_{sp}/(z_{11}\tau q+n(z_{12}g_{sp}-z_{11}g_{ss})), z_{22}ng_{ss}/(z_{21}U(1-\phi)-n(z_{21}g_{sp}-z_{22}g_{ss})))$ can be obtained. Using $f^L(x)$ and $f^L(y)$ and taking partial derivatives with respect to x and y, respectively, the Jacobi matrix of the system can be written as:

$$J = \begin{pmatrix} \frac{(2x-1)\{[z_{21}[ng_{sp}-U(1-\phi)]-z_{22}ng_{ss}]y+z_{22}ng_{ss}\}}{(z_{21}-z_{22})y+z_{22}} & \frac{xz_{21}z_{22}(1-x)[(1-\phi)U-n(g_s-g_d)]}{[(z_{21}-z_{22})y+z_{22}]^2} \\ \frac{yz_{11}z_{12}(1-y)(\tau q-n(g_{ss}-g_{sp}))}{[(z_{11}-z_{12})x+z_{12}]^2} & \frac{(2y-1)[z_{12}ng_{sp}+x[z_{11}(ng_{ss}-\tau q)-z_{12}ng_{sp}]]}{[(z_{11}-z_{12})x+z_{12}]} \end{pmatrix}$$

Through the Jacobian matrix's $Det(J)$ and $Tr(J)$, $(0,0)$ and $(1,1)$ are evolutionary stable strategies, $(0,1)$ and $(1,0)$ are unstable points, and $(z_{12}ng_{sp}/(z_{12}ng_{sp}+z_{11}(\tau q-ng_{ss})), z_{22}ng_{ss}/(z_{22}ng_{ss}+z_{21}(U(1-\phi)-ng_{sp})))$ is the saddle point. The evolutionary phase diagram resembles that in Figure 3. The expression for area R^L is:

$$R^L = \frac{1}{2}\left(\frac{z_{12}ng_{sp}}{z_{12}ng_{sp}+z_{11}(\tau q-ng_{ss})}+\frac{z_{22}ng_{ss}}{z_{22}ng_{ss}+z_{21}\left(U(1-\phi)-ng_{sp}\right)}\right) \tag{A12}$$

Appendix B: Extensions

This section delves into four expanded scenarios: (1) Seekers' net surplus comparison: Independent vs. cooperative mode, (2) Effects of providers' delayed decision on evolutionary stabilities, (3) Effects of finite provider and seeker populations on evolutionary stabilities, and (4) Effects of market fluctuations and limited supply on entities' strategies.

B1. Seekers' net surplus comparison: Independent vs. cooperative mode

The MRM process between providers and seekers in the two main modes and the benefits distribution process between the platform and providers have been fully considered. This section further analyses their net surplus obtained in both modes. Combining Table 2 and Table 3 with Equation (2), the seekers' net surplus in mode m $(m = C, F)$ is as follows:

$$\Pi_{ss}^m = \left(\phi + xy(1-\phi)\right)U - p^m q^m - x(1-y)ng_{ss} + (1-x)yng_{sp}, m = C, F \tag{B1}$$

Comparing the seekers' net surplus in the two modes yields

$$\Pi_{ss}^{C*} - \Pi_{ss}^{F*} = -q^{F*}\frac{2k\left(\alpha-\beta e_0+3c+3\tau(1-xy)\right)+\beta^2\left(\alpha-\beta e_0-3(c+\tau(1-xy))\right)}{2\left(4k-\beta^2\right)} \tag{B2}$$

Therefore, if $k > -(\beta^2(\alpha-\beta e_0-3(c+\tau(1-xy))))/2(\alpha-\beta e_0+3(c+\tau(1-xy)))$, then $\Pi_{ss}^{C*} < \Pi_{ss}^{F*}$; otherwise, $\Pi_{ss}^{C*} \geq \Pi_{ss}^{F*}$. In addition, the variation of seekers' net surplus with the change of emission reduction cost coefficient is: $\partial(\Pi_{ss}^{C*}-\Pi_{ss}^{F*})/\partial k = T\beta^2\ (3T\beta^2+2(\alpha-\beta e_0)(4k-\beta^2))/2(4k-\beta^2)^3 > 0$.

Although reasonable profit distributions in the cooperative mode can enable the platform and providers to achieve higher profits, seekers may not necessarily achieve such a higher surplus. The reason is that the surplus difference for seekers in the two modes comes from resource quantity and corresponding price. When the emission reduction cost coefficient k increases, the decrement in the price p in the independent mode is higher than that in the cooperative mode, which makes seekers more profitable in the independent mode with higher emission reduction difficulties. This suggests that although the cooperative mode brings better profits for the platform and providers, it may cause harm to the profits of seekers, thereby reducing their willingness to participate in resource matching. In a buyer's market, this problem becomes even more severe. Therefore, when choosing a service mode, it is necessary to comprehensively consider the profits of all entities to avoid adverse effects on the platform.

B2. Effects of providers' delayed decision on evolutionary stabilities

In real-world settings, enterprises often refrain from immediate action based solely on observed phenomena. Instead, they make final decisions by integrating changes in profits across various stages. Building upon this premise, this section refers to the literature by Ma and Xu (2023) and assumes that providers adopt adaptive decision and delay strategies for resource quantity and carbon emission reduction. First, derive the first-order conditions of the provider's profits Π_{sp} with respect to the variables q and e :

$$\frac{\partial \Pi_{sp}}{\partial q} = \alpha - 2q - \beta e - \gamma - c - \tau(1-xy) \tag{B3}$$

$$\frac{\partial \Pi_{sp}}{\partial e} = -\beta q + 2k(e_0 - e) \tag{B4}$$

Setting $\partial\Pi_{sp}/\partial q = 0$ and $\partial\Pi_{sp}/\partial e = 0$ yields $q' = (\alpha-\beta e-\gamma-c-\tau(1-xy))/2$ and $e' = e_0 - \beta q/2k$.

Specifically, when the difference between q' and $q(t-\mu_q)$ is greater than 0, and similarly for e' and $e(t-\mu_e)$, the provider opts for continued increments in resource quantity q and carbon emission reduction e, where μ represents the delay decision parameter. Conversely, the provider reduces both resource quantity and carbon emission reduction. This dynamic adjustment process of the provider can be expressed as follows:

$$q^*(t) = v(q)\left(q' - q(t-\mu_q)\right) = vq\left(q' - q(t-\mu_q)\right) \tag{B5}$$
$$e^*(t) = v(e)\left(e' - e(t-\mu_e)\right) = ve\left(e' - e(t-\mu_e)\right) \tag{B6}$$

where v is the providers' adjustment degree to resource quantity and carbon emission reduction. By setting Equations (B5) and (B6) to 0, the equilibrium points are derived, namely: $E_1(0,0)$, $E_2(0,(\tau xy + a - c - \gamma - 1)/2)$, $E_3(e_0, 0)$, and $E_4((4ke_0 - \beta(a - c - \gamma - \tau(1-xy)))/\ (4k - \beta^2),\ 2k(a - c - \gamma - \beta e_0 - \tau(1-xy))/(4k-\beta^2))$. Given their economic significance, only positive equilibria are relevant. Therefore, this section focuses the discussion on the point E_4. By processing Equations (B5) and (B6), the Jacobian matrix is as follows:

$$J = \begin{bmatrix} v\left(\dfrac{\alpha - \beta e - \gamma - c - \tau(1-xy)}{2} - 2q(t-\mu_q)\right) & \dfrac{-\beta vq}{2} \\ -\dfrac{\beta ve}{2k} & v\left(e_0 - \dfrac{\beta q}{2k} - 2e(t-\mu_e)\right) \end{bmatrix} \tag{B7}$$

For the point E_4, the trace $Tr(J)$ and determinant $Det(J)$ of the Jacobian matrix are as follows:

$$Tr(J) = -v\frac{2ke_0(2-\beta) + (2k-\beta)(a - c - \gamma - \tau(1-xy))}{4k - \beta^2} \tag{B8}$$
$$Det(J) = \frac{v^2\left(a - \beta e_0 - c - \gamma - \tau(1-xy)\right)\left(4ke_0 - \beta(a - c - \gamma - \tau(1-xy))\right)}{2\left(4k - \beta^2\right)} \tag{B9}$$

Combining these with the Proof of Lemma 1 shows that trace $Tr(J) < 0$ and determinant $Det(J) > 0$. Thus, E_4 serves as the ESS point under the adaptive delay strategy. Further, by considering Lemma 1, it becomes evident that the platform's behaviour remains unaffected by provider delay decisions.

Next, this section examines the evolving matching behaviour of providers and seekers and its subsequent impact on the platform, where $\gamma^* = (\alpha - c - \beta e_0 - \tau(1-xy))/2$ and $\Pi^*_{op} = (k(\alpha - c - \beta e_0 - \tau(1-xy))^2)/2(4k - \beta^2)$. Firstly, when the probability of agreeing to match $(x,\ y)$ increases during the evolution, the platform increases its commission level and obtains higher profits. Secondly, the higher the initial carbon emissions e_0, maintenance costs τ, and production costs c of the provider, the more they force the platform to lower its commission level, leading to a corresponding decrease in profits. Thirdly, potential market size α is also a crucial factor in determining platform profits. The platform raises commission levels in a higher market demand environment, obtaining more profits.

B3. Effects of finite provider and seeker populations on evolutionary stabilities

Providers and seekers are the main participants in MRM. However, blacklisting competing companies is a common and effective way to suppress them in today's constant geopolitical frictions and frequent economic fluctuations. Therefore, this section considers the case with a finite number of providers and seekers. As discussed in Sections 4.1.1 and 4.2.1, the evolution process is independent of the service modes. Therefore, this section focuses on the independent mode in this evolutionary analysis. The properties discussed below would also hold in the cooperative mode.

As discussed in Section 3, when there are an infinite number of seekers and providers, proportions x and y of them, respectively, accept manufacturing outsourcing contracts. However, in a finite number scenario, the group size cannot be normalised to 1 because the relative size of seekers and providers also matters. Adapting the model discussed in Section 3, let the changes in the proportion of seekers and providers accepting the outsourcing contract denoted as z_x and z_y, respectively. In addition, the changes in the proportion of seekers and providers rejecting the outsourcing contract are denoted as z_{1-x} and z_{1-y}. Therefore, the probability of seekers accepting and rejecting the outsourcing contract is $z_x x$ and $z_{1-x}(1-x)$, respectively, and the probability of providers providing and not providing resources is $z_y y$ and $z_{1-y}(1-y)$, respectively. Then, the seekers' surpluses accepting and rejecting the outsourcing contracts are:

$$\pi^A_{ss} = \frac{z_y y(U - pq) + z_{1-y}(1-y)(\phi U - pq - ng_{ss})}{z_y y + z_{1-y}(1-y)} \tag{B10}$$
$$\pi^{\bar{A}}_{ss} = \frac{z_y y(\phi U - pq + ng_{sp}) + z_{1-y}(1-y)(\phi U - pq)}{z_y y + z_{1-y}(1-y)} \tag{B11}$$

The expected profits of providers providing and not providing the resources are:

$$\pi^H_{sp} = \frac{z_x x\left((p-\gamma-c)q - k(e_0-e)^2\right) + z_{1-x}(1-x)\left((p-\gamma-c)q - k(e_0-e)^2 - \tau q - ng_{sp}\right)}{z_x x + z_{1-x}(1-x)} \tag{B12}$$
$$\pi^{\bar{H}}_{sp} = \frac{z_x x\left((p-\gamma-c)q - k(e_0-e)^2 - \tau q + ng_{ss}\right) + z_{1-x}(1-x)\left((p-\gamma-c)q - k(e_0-e)^2 - \tau q\right)}{z_x x + z_{1-x}(1-x)} \tag{B13}$$

The same method as used for Proposition 1 can be used in the scenario of a finite number of providers and seekers. The results show $(0,0)$ and $(1,1)$ are ESSs, $(0,1)$ and $(1,0)$ are unstable points, and $((z_{1-x}ng_{sp}/(z_{1-x}ng_{sp} + z_x(\tau q - ng_{ss})), (z_{1-y}ng_{ss}/(z_{1-y}ng_{ss} + z_y(U(1-\phi) - ng_{sp})))$ is the saddle point when $\tau q - ng_{ss} > 0$ and $U(1-\phi) - ng_{sp} > 0$.

The value of the matching failure rate R^* is $(((z_{1-x}ng_{sp})/((z_{1-x}ng_{sp}+z_x\ (\tau q-ng_{ss})))+(z_{1-y}ng_{ss})/((z_{1-y}ng_{ss}+z_y(U(1-\phi)-ng_{sp}))))/2$.

When the number of providers and seekers is finite, the equilibrium points and ESSs $(A,\ H)$ and $(\bar{A},\ \bar{H})$ remain as in Proposition 1. With a finite number of participants, if the proportion change of seekers or providers choosing to accept outsourcing contracts is less (i.e., $z_x > z_{1-x}$ and $z_y > z_{1-y}$), the matching failure rate R^{L*} becomes smaller, and the area $1-R^*$ becomes larger. Therefore, the number of seekers and providers choosing ESS $(A,\ H)$ increases. For example, an enterprise may lose the opportunity to match and cooperate with some enterprises in a region due to geopolitical events. When the matching willingness in the remaining regions is high, this enterprise is more likely to encounter enterprises willing to match and so achieve a successful match. However, it remains imperative to ensure an adequate number of cooperative enterprises, and failing to do so may leave the enterprise grappling with the challenge of insufficient cooperative partners.

B4. Effects of market fluctuations and limited supply on entities' strategies

External factors such as geopolitical events and global economic changes can easily affect the resource matching and trading process, causing market fluctuations and supply constraints. Therefore, this section considers fluctuations in resource demand, product cost, and supply constraints to explore their impacts on resource matching and pricing decisions.

When the matching resource quantity q and product cost c fluctuate, the resource turnover changes from pq to $p(q+\delta_q)$, the production cost changes from cq to $(c+\delta_c)(q+\delta_q)$, and the storage cost changes from τq to $\tau(q+\delta_q)$, where δ_c and δ_q represent the fluctuation parameters of resource demand and product cost, respectively. Referring to Section 4.1.1, the seekers' and providers' ESSs can be obtained under the fluctuation. Compared to the independent mode, the fluctuations do not alter the equilibrium points, which remain at $(0,0)$, $(0,1)$, $(1,0)$, and $(1,1)$, and the saddle point changes to $(ng_{sp}/(\tau(q+\delta_q)+n(g_{sp}-g_{ss})),\ ng_{ss}/(U(1-\phi)-n(g_{sp}-g_{ss})))$ when $\tau(q+\delta_q)-ng_{ss}>0$ and $U(1-\phi)-ng_{sp}>0$. The analysis reveals that when the resource quantities fluctuate and $\delta_q>0$, the saddle point moves towards the direction of the point $E_1(0,0)$, which makes the area of failure matching rate R smaller. In such a circumstance, both seekers and providers can achieve a higher probability of successful matching. When $\delta_q<0$, the saddle point moves towards the direction of $E_3(1,1)$, and the probability of successful matching decreases. As the seekers' demand increases, their dependence on providers increases, and thus their willingness to cooperate with providers also increases, achieving a higher resource matching success rate.

Based on fluctuations in resource demand and product cost, this section further analyses the impact of supply constraints on the decision making of the platform and providers. Supply constraints are a significant means of economic competition. Assuming that the resource quantities provided cannot exceed the threshold Q, the provider's profits can be expressed as:

$$\begin{aligned} \max\Pi_{sp}(q,e) = {} & (q+\delta_q)\big(\alpha-(q+\delta_q)-\beta e-\gamma-(c+\delta_c)\big)-k(e_0-e)^2 \\ & -\tau(q+\delta_q)(1-xy)-yng_{sp}(1-x)+xng_{ss}(1-y) \\ & s.t. (q+\delta_q)\le Q \end{aligned} \tag{B14}$$

According to the Karush–Kuhn–Tucker conditions, the equilibrium decisions are $q=Q-\delta_q$, $e=e_0-\beta Q/(2k)$, $p=\alpha+\delta_q-\beta e_0-Q(2k-\beta^2)/(2k)$ and $\Pi_{sp}^*=\ Q(\alpha-Q-\beta e_0+\frac{\beta^2 Q}{2k}-\gamma-(c+\delta_c))-k(\frac{\beta Q}{2k})^2-\tau Q(1-xy)-yng_{sp}(1-x)+xng_{ss}(1-y)$. The equilibrium results show that the supply constraint constitutes an important factor in limiting the resource price and emission reduction. This reflects that geopolitical competition events and global economic changes make enterprises unable to achieve optimal profits. When these events happen, enterprises should take measures to mitigate the negative impacts, such as establishing flexible transaction contracts and effective communication mechanisms.

Appendix C: Numerical studies

This section employs numerical analysis to validate the robustness of the theoretical analysis results. It also conducts sensitivity analyses on key parameters to further assess the reliability of the conclusions.

This section conducts a series of numerical analyses with parameters adopted by the classical literature (eg, Iacocca & Mahar, 2019; Liu et al., 2020). The seeker obtains a utility $U=4000$ when the match succeeds in the first trial. If the first trial fails, the seeker incurs a discounted utility with discount factor $\phi=0.9$ (Basu et al., 2019). The potential market size is $\alpha=50$ (Li & Zhang, 2023), and the unit production and holding costs are $c=15$ and $\tau=0.5$, respectively. In addition, the unregulated behaviours' harm level of the provider and seeker are $g_{sp}=3000$ and $g_{ss}=400$, respectively. The compensation coefficient is $n=0.05$. In these numerical studies, the carbon emissions per unit product is $e_0=65$, the price impact coefficient is $\beta=0.5$, and the CER cost coefficient is $k=1.5$. In the cooperative mode, the revenue-sharing ratio is set to be $\eta=0.6$. Following Sun and Yang (2021), the initial proportion of providers and seekers choosing to match is $(0.5,0.5)$.

The analytical framework employed in this section is similar to that in Section 5. Section C1 analyses the Matching failure rate in both independent and cooperative modes. Section C2 examines the production quantity and system profit under independent and cooperative modes. Section C3 investigates the range within which the platform and providers can achieve higher profit in the cooperative mode. Lastly, Section C4 compares the carbon emission between independent and cooperative modes.

C1. Matching failure rate

Figure C1 presents the successful matching rates (i.e., R^{F*} and R^{C*}) under varying market size α and compensation coefficient n in the independent and cooperative modes.

It can be seen from Figure C1 that R^j is higher in the independent mode, indicating a higher successful matching rate in cooperative mode. In addition, in both service modes, the matching failure rates decrease as the potential market size increases and increase as the compensation coefficient increases.

C2. Production quantity and system profit

Figure C2 presents the production quantity and system profit (i.e., q^m and Π_{sy}^m, $m \in \{F, C\}$.) under varying market size α and compensation coefficient n in the independent and cooperative modes. Figure C2 shows that the system generates

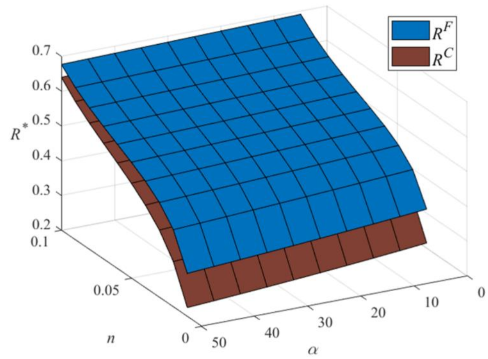

Figure C1. Effects of α and n on successful matching rate.

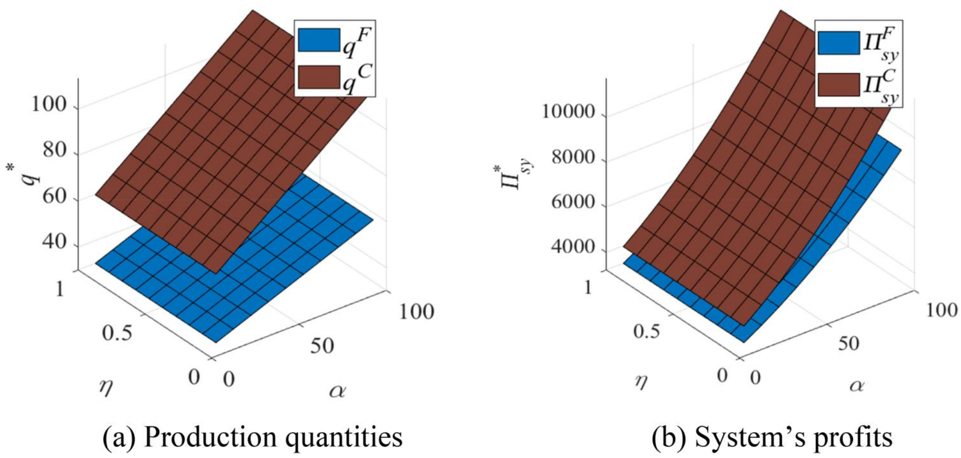

Figure C2. Effects of η and α on production quantities and system's profits.

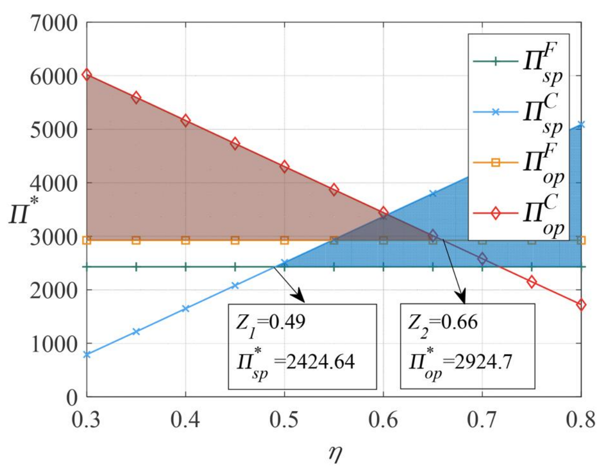

Figure C3. Effects of η on profits of the platform and provider.

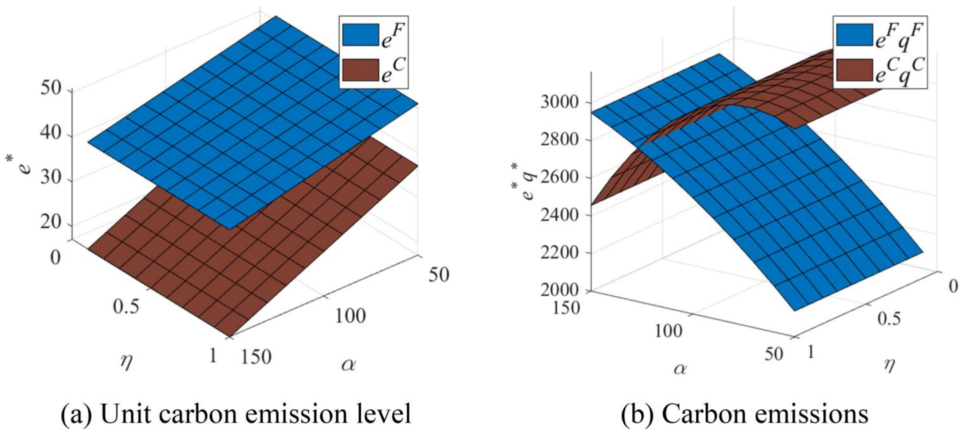

Figure C4. Effects of η and α on unit carbon emission level and carbon emissions.

greater resource quantities and profits when operating in cooperative mode compared to independent mode. However, this fact does not mean that both the provider's and platform's profits are higher in the cooperative mode.

C3. Entity profit

Figure C3 presents the effects of the sharing ratio η on the profits of the platform and provider (i.e., Π_{sp}^m and Π_{cp}^m, $m \in \{F, C\}$) in the independent and cooperative modes.

Figure C3 investigates the provider and platform profits in the cooperative mode with different profit-sharing ratios. The red area illustrates the scenarios where the platform can achieve greater profits when operating in cooperative mode compared to operating independently, while the blue area illustrates the scenarios where the provider obtains higher profits in cooperative mode. Figure C3 shows that when $\eta \in (0.49, 0.66)$, both the outsourcing platform and providers can achieve higher profits in cooperative mode.

C4. Carbon emission

Figure C4 presents the unit and total carbon emissions (i.e., Π_{sp}^m and Π_{cp}^m, $m \in \{F, C\}$) under varying market size α and compensation coefficient n in the independent and cooperative modes.

Figure C4 presents the CER level and carbon emissions of the two modes, and the results show that the CER is more significant when operating in cooperative mode. When the potential market is large enough, the total emissions are lower in cooperative mode; otherwise, the total emissions are lower in independent mode.