Heliyon 9 (2023) e17512

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Evolutionary game study of crowdsourcing open innovation synergy mechanism

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ARTICLE INFO

Keywords:
Crowdsourcing
Open innovation
Synergy mechanism
Evolutionary game

ABSTRACT

Open innovation crowdsourcing can help enterprises meet the challenges of a rapidly changing environment and improve their innovation performance. This study introduces network externalities as influencing factors of the crowdsourcing open innovation synergy mechanism. This study constructed the game payment matrix of the crowdsourcing open innovation synergy mechanism, and the evolutionary game method obtained the equilibrium solution of the crowdsourcing open innovation synergy mechanism. The impact of changes in the main influencing factors on the issuers' and receivers' willingness to collaborate and innovate was explored through numerical and case studies. The study shows that the higher the synergy benefit and its allocation coefficient need to be within a reasonable range for the willingness to collaborate and innovate to increase; the lower the original cost of both parties, and the higher the cost reduction coefficient under the policy support of the crowdsourcing platform, the higher the willingness to collaborate and innovate; the higher the network externality and the lower the penalty for breach of contract, the higher the desire to collaborate and innovate. The study recommends strengthening non-school education to guide innovation for all, and refining relevant policies to tailor innovation to local conditions. This study provides a new perspective and theoretical guidance for enterprises to build a crowdsourcing open innovation synergy mechanism and is a valuable reference for open innovation management.

1. Introduction

Enterprises traditionally rely on new ideas, a skilled workforce, and the willingness to commit the necessary time, money, and leadership to R&D [1,2]. Crowdsourcing has evolved as a new Internet-based synergy paradigm with the advent of globalization and progress of the Internet [3,4]. According to Jeff Howe, crowdsourcing [4] occurs when a corporation or organization outsources duties formerly handled by workers to a non-specific network of people on a free and voluntary basis. Based on the Internet's ubiquity, the enormous potential, and the commercial worth of users' motivation and capacity to develop, the democratization of innovation represented by "User-Generated Content" (UGC) has rapidly overtaken the old innovation paradigm [5].

Open innovation is a distributed innovation process that uses financial or non-financial mechanisms to manage the flow of knowledge across organizational and sectoral boundaries. Chesbrough [6,7] first discussed this issue in the context of enterprises' increasingly demanding innovation strategies. Open innovation requires a paradigm shift towards open and collaborative processes

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https://doi.org/10.1016/j.heliyon.2023.e17512
Received 15 February 2023; Received in revised form 10 June 2023; Accepted 20 June 2023
Available online 21 June 2023
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[8] that can increasingly replace and compete with producer-driven innovation through practices conducted externally [9] and across organizational boundaries [10]. Open innovation practices encompass internal, external, and collaborative processes that facilitate the flow of knowledge across borders to generate innovation. These practices include, but are not limited to, co-creating innovations among enterprises, leading users and user innovation communities, open-source software/hardware development, crowdsourcing and crowdfunding, patenting and licensing, and R&D collaboration [11–13].

Crowdsourcing open innovation, whether inside or outside the enterprise, must cross the boundaries of the original framework and engage in cross-border knowledge flow with other departments or subjects outside the organization [3]. In the crowdsourcing open innovation ecosystem, the issuer and receiver are sequential parameters. They are interconnected and mutually constrained, showing a synergistic and self-organized movement of the innovation ecosystem at the macro level [14]. When disturbances occur in the innovation ecosystem (new technologies, policy changes, etc.), sequential parameters (issuers and receivers) compete. Finally, only one sequential parameter dominates the entire system to achieve macroscopic synergy [15]. Therefore, establishing a crowdsourcing open innovation synergy mechanism can help realize the evolution of the crowdsourcing open innovation ecosystem with an orderly goal, structure, organization, and function.

Crowdsourcing open innovation can help enterprises adapt to and overcome challenges in a changing environment; open innovation develops effective crowdsourcing collaboration mechanisms to help companies adapt to a rapidly changing environment and overcome new challenges [3]. The evolutionary game approach was used to study the synergy mechanism of open crowdsourcing innovation because it involves knowledge flow across organizational boundaries. From an economic standpoint, crowdsourcing open innovation has both non-pecuniary and pecuniary means. Also included are the "Prisoner's Dilemma" [16] and "Pareto improvement" that come from the dispersed innovation synergy process. Simultaneously, When using sequential parameters (issuer and receiver), the evolutionary game theory's assumption of finite rationality is comparatively in tune with the demands of transparency and teamwork within crowdsourcing open innovation. In the collaborative innovation process, the game for open innovation ecosystem stakeholders is a stochastic, co-learning, iterative game process. The Replicator dynamics mechanism models the adjustment process for stakeholder strategies. Compared to traditional research methods, evolutionary game analysis can capture the evolutionary trajectories and consistent tactics of stakeholder behavior, which is essential for unleashing the power of openness and collaborative synergy [2].

The contributions of this study are as follows. (1) It considers the role of network externalities in crowdsourced open innovation while indexing network externalities to innovation benefits and costs. (2) A game payment matrix was constructed for the issuer and receiver. It analyzes the impact of changes in game participants' willingness to participate in crowdsourced open innovation, while concluding that the benefits of collaborative innovation and its allocation coefficient need to be in a reasonable range for the willingness to collaborate and innovate to be higher. The lower the original costs of both parties and the higher the cost reduction coefficient under the policy support of the crowdsourcing platform for the willingness to collaborate and innovate to be higher. The higher the network externality and the lower the default penalty, the higher the willingness of collaborative innovation and the intention of collaborative cooperation will be reached.

The remainder of this paper is organized as follows: Section 2 presents a literature review, and Section 3 discusses how to build the model. Section 4 analyzes the proposed model. Sections 5 and 6 focus on the numerical analysis and discussion, respectively. Finally, the conclusions are presented in Section 7.

2. Literature review

2.1. Crowdsourcing open innovation

Open innovation has gained increasing attention as a paradigm for improving innovation performance. There are various tools and vehicles for open innovation, such as outsourcing, open source, and crowdsourcing, which are the most specific and usually facilitated by networks, and the potential diversity and core features and variables involved in crowdsourcing [17]. At the same time, crowdsourcing has gradually become a promising open innovation strategy for companies looking for solutions to technical problems. Crowdsourcing provides rapid access to knowledge from outside the organization at a relatively low cost compared to other forms of innovation such as internal sourcing or contract research. Research has found that informal and formal organizational players play a role in developing corporate crowdsourcing by articulating and codifying knowledge [18]. The emergence of open innovation has enhanced communication and interaction between scientists and enterprises, and crowdsourcing has further reinforced this trend. Today, research questions can be asked and answered almost anywhere in the world. As the primary tool for open innovation, crowdsourcing accelerates the search for solutions to specific problems by assimilating external knowledge, particularly by including scientists and researchers in a previously closed but now open system of innovation processes [19].

Internal organizational applications: Information technology has enabled the development of virtual environments that allow collaboration with external agents and the use of open innovation processes. Crowdsourcing is a vehicular tool that accelerates innovation in a new environment through collaborative efforts. However, companies are still searching for the best way to embed crowdsourcing into their internal processes to create value [20] by explicitly combining crowdsourcing with operations management and project management. The focus was on how crowdsourcing operates as an open innovation mechanism in complex project management. First, a new theoretical framework linking project management and crowdsourcing is developed to extend the understanding of project-based and open innovation frameworks. Second, crowdsourcing projects are flexible and fluid. Third, crowdsourcing operations are viewed in terms of scale, efficiency, and scalability, producing timely and effective outputs owing to innovative technologies and trust among stakeholders [21]. In a nutshell, crowdsourcing gives enterprises entrance to a massive body of information and is a proven, inward-looking, open innovation paradigm. Inbound open innovation helps managers improve their enterprises' innovation capabilities, and their employees' entrepreneurial mentality and develop healthier operations, giving them an edge over their rivals [22].

Application outside the organization: Current research activities and projects often involve interactions between participants from different fields. In the "research value chain," interactions between researchers and other individuals (intentionally or unintentionally) within and outside their respective institutions can be seen as the occurrence of collective intelligence. Crowdsourcing [23] is a particular case of collective intelligence. It harnesses the wisdom of crowds [24] and is already changing the way groups of people produce knowledge, generate ideas, and make them actionable [25]. Open innovation, drawn from business strategies and technological development, can provide planners with new insights into their practices. Open innovation, such as civic engagement, seeks solutions to problems outside the organization's boundaries and passes ideas to partners. An essential technique for open innovation is crowdsourcing. This is the difficulty of approaching an extensive, varied population to develop a more concrete answer than within an organization [26]. A modern user-oriented enterprise [27] combines the characteristics of crowdsourcing open innovation, built on gathering ideas from external sources into the organization and bringing these adopted, adapted, and enriched ideas to market [28] principles. However, under constant pressure to innovate, companies must work harder to tap into user knowledge and capabilities. Crowdsourcing communities provide an arena for a wide range of users to participate actively in the innovation process. However, as this external participation in the innovation process is still in its infancy, organizations need guidance and analytical support to reveal the potential of the open innovation paradigm [29].

2.2. Open innovation synergy mechanism

Open innovation synergy: Sustaining open innovation requires addressing how the contributors' collaborative efforts generate collective creativity. The critical issue in developing a collective imagination is managing and coordinating contributors' actions to maximize innovation output [30]. In open innovation teams, people from different organizations work together to develop new products, services, or markets. Organizational diversity can directly affect the collaborative nature of innovation, and human resources were the first to be noticed as a primary factor in innovation resources [31]. However, the factors influencing open innovation in the scientific field are much greater; individual, team, organizational, domain, and societal dimensions are all influential factors in open innovation collaboration [32]. In addition, the construction of collaborative open innovation platforms [33] facilitates the development of decentralized coordination schemes, enhances contributors' moderate self-confidence and cooperative management of conflicts in collaboration, and triggers more innovative behavior [34].

Symmetrical partnership synergy: Open innovation is an innovation ecosystem that differs from previous ecosystems. Innovation ecosystems generally comprise multiple stakeholders, among which the synergistic relationships among stakeholders belonging to symmetric relationships [35,36] were first noticed. The advanced manufacturing sector pioneered open innovation collaboration between academia and industry [37]. However, the government's role cannot be overlooked as the "Triple Helix of University-Industry-Government Relations" [38] argues that "redundancy is created when various synchronization systems (knowledge, markets, policies) offer various viewpoints on identical evidence. Enhanced duplication increases the synergy and capacity of an innovation system and stimulates invention in an ecosystem by lowering general uncertainty." Indeed, an open innovation ecosystem can be a catalog of functions needed to create an open innovation platform from universities, research institutions, industrial enterprises, and even startups that have applied forms of innovation, such as design thinking and crowdsourcing methods [39]. However, collaborating with peers to gain knowledge is also an attractive option for organizations eager to improve their innovation capabilities [40]. However, as the increasing popularity of open innovation leads to the emergence of new peers in the innovation process, open innovation ecosystems often face three challenges: (1) the emergence of new peer organizations, (2) collaboration with peers, and (3) the challenges associated with the open innovation collaborative platform itself.

Asymmetric partnership synergy: An open innovation ecosystem is characterized by asymmetric stakeholder relationships [41,42]. Open innovation often involves synergies between established and startup SMEs (Small and medium-sized enterprises) [43]. Simultaneously, public policies effectively enhance open innovation synergies among enterprises, regulators, research institutions, and the public sector, especially for start-up SMEs [44]. Considering the cognitive barriers, limited innovation resources, and capabilities of start-up SMEs in conducting open innovation, strengthening collaborative networks, publishing innovation policies, and shaping entrepreneurship [45] effectively promote open innovation synergies among start-ups. The individual dimensions of open innovation synergy are worthy of equal attention and will help managers improve their innovation capacity at work. Personal absorptive capacity and dexterity improve managers' synergy in innovative behavior in the context of open innovation. Managers with the combined functions of gatekeepers and shepherds must integrate the influx of knowledge from outside the organization with the existing knowledge within the firm to fuel innovation activities [46].

2.3. Network externalities

The concept of network externalities was initially considered the source of demand-side economies of scale, where the value of the same product (service) to users increased with the number of other users [47]. Subsequently, the concept was further refined, with changes in the number of users of the same product (service) triggering changes in the utility of that product (service) for the user [48–50]. Metcalfe's Law [51] is used in economics to subdivide network externalities into positive and negative. At the same time, many scholars believe that applying the concept of network externalities in economics has limitations such as technological adoption [52], technological compatibility [53], and related-party transactions within the network [54], which can lead to market failures and thus do not have network externality characteristics. However, these factors do not preclude network externalities from being applied to a variety of industry scenarios such as professional sports business leagues [55], electric utilities [56,57], and intelligent products [58], which use network externalities to study attendance, pricing strategies, and user loyalty.

This study has significant theoretical and practical implications for participants' motivation to collaborate and develop in a crowdsourcing paradigm. However, several issues remain to be resolved. (1) The impact of network externalities on participants' desire to use crowdsourcing was not considered. (2) In the crowdsourcing model, the effect of wanting to choose a strategy couldn't be assessed among gaming issues. Based on earlier research, this study incorporated network externalities into determining the elements of participants' motivation to collaborate and develop in the crowdsourcing paradigm. In contrast to earlier research, this study relates network externalities to participants' costs through indexation. Furthermore, this study explores the impact of network externality variables on collaboration between issuers and receivers in a crowdsourcing model by concentrating on participants' motivation to collaborate and develop. Through simulations and case studies, this study constructs an evolutionary game payment matrix between the issuer and receiver, introduces the influence of network externalities on innovation benefits and costs, identifies an evolving harmonic solution to the two parties' game of synergy, and analyzes the main factors influencing participants' willingness to cooperate and innovate in the crowdsourcing model.

3. Modeling

This study examines the crowdsourcing open innovation [3–5] model developed by issuers and receivers [14] (Fig. 1). Simultaneously, a modeling approach was used to study the innovation [27,28] upgradation path of manufacturing companies from a value network perspective [59–63].

3.1. Model basic assumption

Assumption 1. Participants. The network crowdsourcing model included two types of cooperative game participants: issuers, receivers. The issuer publishes tasks on an online crowdsourcing platform. The receiver primarily undertakes and completes the tasks undertaken through the crowdsourcing platform. Therefore, let the issuer be I, the receiver be R, and the crowdsourcing platform be P.

Assumption 2. Synergy strategy. The issuer (synergy, non-synergy) x, the receiver (synergy, non-synergy) y, the issuer has two strategic choices: cooperate with the receiver to complete the task, do not cooperate with the receiver to complete the task, and its strategy set is (synergy, non-synergy); Similarly, the receiver also has two strategic choices: cooperate to complete the undertaking task, do not cooperate to complete the undertaking task, and its strategy set is (synergy, non-synergy). Therefore, let x, y represent the probability that the contracting party and the contracting party cooperate to complete the task, $x, y \in [0, 1]$, respectively.

Assumption 3. Cost of synergy. C, the give-and-take support factor used by the crowdsourcing platform to reduce user costs is β ($1 \le \beta \le 0$), the network externality of publishing a task through crowdsourcing is θ ($1 \le \theta \le 0$); θ is expressed as the ratio of the number of users involved in the task to the total number of users on the crowdsourcing platform. The cost paid by the issuer to complete the task is $(1-\beta) C_1$, and the cost paid by the receiver to complete the task is $(1-\beta)^{\frac{1}{\theta}}C_2$.

Assumption 4. Synergy gain The total revenue generated after the completion of the posted task is K, the proportion obtained by the issuer is α ($1 \le \alpha \le 0$), the issuer obtains the revenue as αK, the receiver obtains the revenue as $(1-\alpha) K$, π_1, π_2 denote the initial revenue of the issuer and the receiver. G denotes the platform subsidy of the crowdsourcing platform for the issuer.

Assumption 5. Penalty for default. H stands for the default fine that either the issuer or the receiver paid to the other party for contract violation.

3.2. Build a payment matrix

The constructed payment matrix of the crowdsourced open innovation participant cooperative game can further establish its payoff expectation function by replicating the dynamic set of equations.

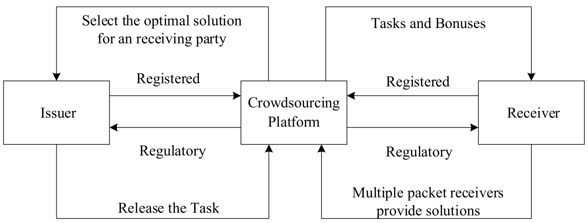

Fig. 1. Crowdsourcing open innovation ecosystem.

4. Model discussion

4.1. Earnings expectation function construction

Table 1 shows the expected return EI_1, the expected return EI_2, and the average expected return EI_3 for the "synergy" strategy chosen by the issuer in the game (see Table 2).

$$EI_1 = y(\pi_1 + \alpha K + G - (1-\beta)C_1) + (1-y)(\pi_1 + G + H - (1-\beta)C_1) \\ = y(\alpha K - H) + \pi_1 + G + H - (1-\beta)C_1$$

$$EI_2 = y(\pi_1 + G - H) + (1-y)(\pi_1 + G) = -yH + \pi_1 + G$$

$$EI_3 = xEI_1 + (1-x)EI_2$$

The expected return ER_1, the expected return ER_2, and the average expected return ER_3 of the receiver choosing the "synergy" strategy are:

$$ER_1 = x\left(\pi_2 + (1-\alpha)K - (1-\beta)^{\frac{1}{\theta}C_2}\right) + (1-x)\left(\pi_2 + H - (1-\beta)^{\frac{1}{\theta}C_2}\right) \\ = x((1-\alpha)K - H) + \pi_2 + H - (1-\beta)\frac{1}{\theta}C_2$$

$$ER_2 = x(\pi_2 - H) + (1-x)\pi_2 = -xH + \pi_2$$

$$ER_3 = yER_1 + (1-y)ER_2$$

4.2. Stable evolutionary strategy solving

The above analysis yields the dynamic replication equation for the issuer.

$$F(x) = \frac{dx}{dt} = x(EI_1 - EI_3) = x(EI_1 - xEI_1 - (1-x)EI_2) \\ = x((1-x)EI_1 - (1-x)EI_2) = x(1-x)(EI_1 - EI_2) \\ = x(1-x)(y\alpha K + H - (1-\beta)C_1) \tag{1}$$

Replication dynamic equation for the receiver:

$$F(y) = \frac{dy}{dt} = y(ER_1 - ER_3) = y(1-y)(ER_1 - ER_2) \\ = y(1-y)\left(x(1-\alpha)K + H - (1-\beta)^{\frac{1}{\theta}C_2}\right) \tag{2}$$

The replicated two-dimensional dynamic system of the issuer and receiver is derived using the Malthusian equation by combining equations (1) and (2) following is:

$$\begin{cases} F(x) = x(1-x)(y\alpha K + H - (1-\beta)C_1) \\ F(y) = y(1-y)\left(x(1-\alpha)K + H - (1-\beta)^{\frac{1}{\theta}C_2}\right) \end{cases} \tag{3}$$

Using the approach Friendman [61] suggested, the evolutionary stability strategy (ESS) of a two-dimensional dynamical system can be obtained from the local stability analysis of the Jacobian matrix of this system, which can be obtained from Equation (3):

$$J = \begin{bmatrix} (1-2x)(y\alpha K + H - (1-\beta)C_1) & x(1-x)\alpha K \\ y(1-y)(1-\alpha)K & (1-2y)\left(x(1-\alpha)K + H - (1-\beta)^{\frac{1}{\theta}C_2}\right) \end{bmatrix} \tag{4}$$

Table 1
Payment matrix of participants' cooperative game in the network crowdsourcing model.

Receiver (R)	Issuer (I)	
	Synergy x	Non-synergy (1-x)
Synergy y	$\pi_1+\alpha K+G-(1-\beta)C_1$ $\pi_2+(1-\alpha)K-(1-\beta)\frac{1}{\theta}C_2$	π_1+G-H $\pi_2+H-(1-\beta)\frac{1}{\theta}C_2$
Non-synergy (1-y)	$\pi_1+G+H-(1-\beta)C_1$ π_2-H	π_1+G π_2

Table 2
Jacobian matrix solution.

Equilibrium point	|J|	trJ
$E_1(0,0)$	$(H-(1-\beta)C_1)\,(H-(1-\beta)^{1/\theta}C_2)$	$(H-(1-\beta)C_1)+(H-(1-\beta)^{1/\theta}C_2)$
$E_2(0,1)$	$-(\alpha K + H-(1-\beta)C_1)\,(H-(1-\beta)^{1/\theta}C_2)$	$(\alpha K + H-(1-\beta)C_1)-(H-(1-\beta)^{1/\theta}C_2)$
$E_3(1,0)$	$-(H-(1-\beta)C_1)\,((1-\alpha)K + H-(1-\beta)^{1/\theta}C_2)$	$-(H-(1-\beta)C_1)+((1-\alpha)K + H-(1-\beta)^{1/\theta}C_2)$
$E_4(1,1)$	$(\alpha K + H-(1-\beta)C_1)\,((1-\alpha)K + H-(1-\beta)^{1/\theta}C_2)$	$-(\alpha K + H-(1-\beta)C_1)-((1-\alpha)K + H-(1-\beta)^{1/\theta}C_2)$
$E_5(\frac{(1-\beta)^{\frac{1}{\theta}}C_2-H}{(1-\alpha)K},\frac{(1-\beta)C_1-H}{\alpha K})$	0	0

Matrix determinant:

$$\det J = (1-2x)(1-2y)(y\alpha K + H - (1-\beta)C_1)\left(x(1-\alpha)K + H - (1-\beta)^{\frac{1}{\theta}C_2}\right) \\ +xy(1-x)(1-y)\alpha K(1-\alpha)K$$

Traces of the matrix:

$$trJ = (1-2x)(y\alpha K + H - (1-\beta)C_1) + (1-2y)\left(x(1-\alpha)K + H - (1-\beta)^{\frac{1}{\theta}C_2}\right)$$

Analysis of the dynamic equation system represented by the replicated dynamic equations above yields the determinant and trace of its Jacobian matrix, as shown in the table. Based on the stability determination conditions of the dynamic system, a stability analysis was performed for five local equilibrium points and point E_5: As the conventional Jacobian matrix local stability analysis method failed, a differential analysis method was applied to determine. Differentiating Equations (1) and (2) for y and x, respectively, and substituting them into the coordinates of point E_5, yields:

$$\frac{dF(x)}{y} = x(1-x)\alpha K \tag{5}$$

$$\frac{dF(y)}{x} = y(1-y)(1-\alpha)K \tag{6}$$

The analysis shows that equations (5) and (6) > 0 and E_5 is unstable.

In system (3), let F(x) = F(y) = 0, and we obtain the local equilibrium points E_1 (0, 0), E_2 (0,1), E_3 (1,0), E_4 (1,1), and E_5 $(\frac{(1-\beta)^{\frac{1}{\theta}}C_2-H}{(1-\alpha)K}, \frac{(1-\beta)C_1-H}{\alpha K})$. The system evolutionary stability point (ESS), per evolutionary theories of games, is the equilibrium point that fulfills the Jacobian matrix when all eigenvalues are negative.

4.3. Equilibrium point stability analysis

The evolutionary stability can be discussed and analyzed in two cases based on the results of the dynamical system analysis.

First, 0<(1-β)C_1–H<αK and 0< $(1-\beta)^{\frac{1}{\theta}}C_2 - H$ < (1-α)K, that is, when the difference between the default penalty and the respective cost of the issuer and the receiver is more significant than zero and less than the respective gain.

Using Friedman's suggested regional assessment of stability technique, five equilibrium points in system S = {(x, y); 0 ≤ x, y ≤ 1} are (0, 0), (0, 1), (1, 0), (1, 1), $(\frac{(1-\beta)^{\frac{1}{\theta}}C_2-H}{(1-\alpha)K}, \frac{(1-\beta)C_1-H}{\alpha K})$. The Jacobian matrix equilibrium results are shown in Table 3.

From the table, points (0, 0) and (1, 1) are stable when the difference between the default penalty and the respective costs of the issuer and receiver is more significant than zero and less than the respective gain. These match the two tactics of the issuer and receiver (non-synergy, non-synergy), while (synergy, synergy), respectively. Point (0, 1) (1, 0) is the evolutionary instability point, and point

Table 3
Equilibrium results where the difference between the default penalties and the respective costs of the receiver and the issuer is greater than zero and less than the respective benefits obtained.

Equilibrium point	|J|	trJ	Results
$E_1(0,0)$	+	–	ESS
$E_2(0,1)$	+	+	Instability point
$E_3(1,0)$	+	+	Instability point
$E_4(1,1)$	+	–	ESS
$E_5(\frac{(1-\beta)^{\frac{1}{\theta}}C_2-H}{(1-\alpha)K},\frac{(1-\beta)C_1-H}{\alpha K})$	0	0	Saddle Point

$\left(\frac{(1-\beta)^{\frac{1}{\theta}}C_2-H}{(1-\alpha)K}, \frac{(1-\beta)C_1-H}{\alpha K}\right)$ is the saddle. Fig. 1 depicts the naturalistic episode grid.

Thus illustrated by Fig. 2, the two-dimensional dynamical structure merges to point O (0, 0), assuming the starting position is situated in the ADBO area. The willingness to cooperate and innovate between the issuer and the receiver tends to evolve into the "non-synergy" strategy. The two-dimensional dynamical system converges to point C assuming the original configuration is the ADBC area (1, 1). The willingness to cooperate and innovate between the issuer and the receiver tends to evolve into the "synergy" strategy.

Second, (1-β)C_1–H<0, $(1-\beta)^{\frac{1}{\theta}}C_2 - H$ <0 or (1-β)C_1–H>αK, $(1-\beta)^{\frac{1}{\theta}}C_2 - H >$ (1-α)K or (1-β)C_1–H<0, $(1-\beta)^{\frac{1}{\theta}}C_2 - H >$(1-α)K or (1-β)$C_1$–H>αK, $(1-\beta)^{\frac{1}{\theta}}C_2 - H <$0, i.e., when the difference between the default penalty and the respective cost of at least one of the issuer and the receiver is less than zero or greater than the gain obtained.

Within the model S=(x, y); 0×, y1), four equilibria may be found as (0, 0), (0, 1), (1, 0), and (1, 1), respectively. The Jacobian matrix equilibrium results are shown in Table 4.

Table 4 shows that points (0, 1), (1, 0), and (1, 1) are stable, and points (0, 0) are unstable when the default penalty and the respective cost of at least one of the issuer and the receiver are less than zero or greater than the gain obtained. Since the difference between the default penalty and the respective cost of at least one of the issuer and the receiver is less than zero or greater than the gain obtained, (non-synergy, non-synergy) also applies. The evolutionary phase diagram is shown in Fig. 3.

5. Numerical analysis

5.1. Date and parameters values

AUDI Automotive wants to develop L4-level autonomous driving and needs to collect and label road data. Baidu's collection fleet has Class A mapping qualification. It can legally and compliantly collect road data and seek synergy with Baidu Intelligent Cloud. The collection vehicle was equipped with 64 + 16 lines of LIDAR and collects 2500 km of road data. In the labeling stage, to provide Shanxi with an extraordinary human resources + resource platform human resources deployment program, a total of 5000 human resources were labeled through continuous frame prediction, obstacle attribute verification, automatic audit, and other auxiliary algorithms to improve the quality and efficiency of labeling, cumulative completion of more than 30 million elements labeling, and high-quality submission of data results.

This research utilizes the modeling program MATLAB2019a to more accurately portray the emergence process and legislation of the willingness to collaborate and participate on both the issuer's and the receiver's sides. Changing various parameter values, with the issuer acting as member I and the receiver as member R, examined the key variables influencing each party's propensity to work together and create new ideas.

When adopting the "synergy" strategy, the preliminary distribution of the vital model variables and the distribution coefficient of the sender's revenue is 0.6. This is based on the consideration and realization of synergy. The receiver's revenue is distributed according to the "synergy" strategy with a 0.4 distribution coefficient. Owing to the platform's support policy, the synergy costs 0.3. The difficulty ratings for task completion were 0.6. and 10. Platform subsidies were 70. The cost to the sender without considering other factors is 200, and the cost to the receiver without considering other factors is 200. The cost of synergy is 0.3 due to the support policy of the platform, the difficulty factor of completing the posted tasks is 0.6, the subsidy of the platform is 70, the cost of the issuer is 200 without considering other factors, the cost of the receiver is 150 without considering other factors, despite the contract's breach, the "non-synergy" component must pay the "synergy" component a penalty of 0.6. 80 is fine that the "non-synergy" component must pay toward the "synergy" component, and the revenue after the synergy is 400. The parameters are listed Table 5.

5.2. Sensitivity analysis

5.2.1. The effect of synergy benefits and their distribution coefficients on both parties' motivation to collaborate and invent

Fig. 4 simulates the impact of a change in the synergy revenue K between the issuer and receiver on their propensity to collaborate and invent while keeping the other parameters constant. The cooperative revenue threshold from 260 to 265 is illustrated in Fig. 4. When cooperative revenue exceeds this threshold value, the issuer and receiver do not cooperate. The neutral location eventually reaches (0, 0). When cooperative revenue exceeds this threshold value, both parties converge more quickly due to the decline in K, and

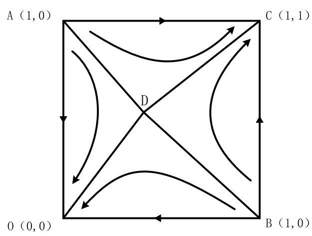

Fig. 2. Evolutionary phase diagram when the difference between the default penalty and the respective costs of the issuing and receiving parties is more significant than zero and less than the respective benefits obtained.

Table 4
Equilibrium results where the difference between the default penalty and the respective costs of at least one of the contracting and receiving parties is less than zero or greater than the benefits received.

Equilibrium point	|J|	trJ	Results
$E_1(0,0)$	+	−	ESS
$E_2(0,1)$	+		Instability point
$E_3(1,0)$	+		Instability point
$E_4(1,1)$	+		Instability point

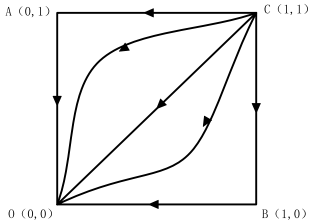

Fig. 3. Evolutionary phase diagram of the difference between the default penalty and the respective costs of at least one of the contracting and receiving parties is less than zero or greater than the benefits obtained.

Table 5
Simulation parameters assignment.

Parameters	Parameter Meaning	Assignment
α	Synergy revenue distribution coefficient	0.5
β	Synergy cost reduction factor	0.3
θ	Network Externalities	0.5
C_1	Original cost to the issuer	200
C_2	The original cost of the receiver	150
K	Synergy revenue	270
H	Penalty for breach of contract	80

Note: Let the initial willingness of the two parties of the issuer and receiver be $x = 0.3$ and $y = 0.5$, respectively.

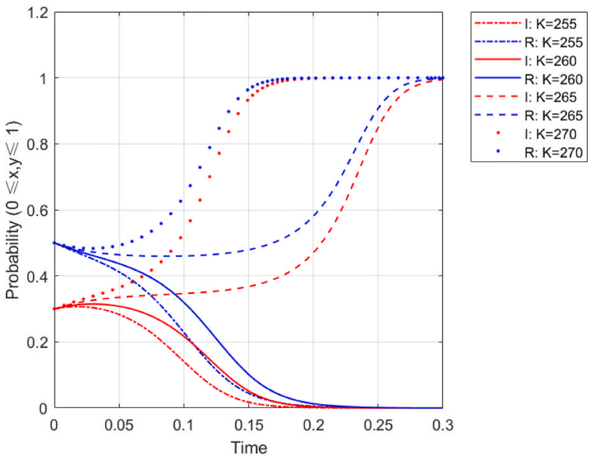

Fig. 4. Evolution of the willingness of both parties to collaborate and innovate when the benefits of collaboration K change.

both the issuer and the receiver have a smooth time before rising quickly. Finally, both parties have a tendency to work together, and point (1, 1) becomes the equilibrium point. An increase in K causes both the parties to converge more quickly. The equilibrium point converges to point (1, 1), and as K increases, the rates of convergence on both sides increase. As a result, both sides' willingness to collaborate and invent shifts from non-synergy to synergy because, in the crowdsourcing mode of a synergy game, as the synergy gain increases, both sides increasingly share the gain. The simulation results show that the higher the synergy revenue, the stronger is the willingness of the issuer and receiver to cooperate and innovate.

Figs. 5 and 6 simulate the impact of changing the income allocation coefficient of synergy between the issuer and receiver on each party's motivation for working together and inventing while keeping the remaining variables constant. Figs. 5 and 6 show that when cooperative benefit K is constant, the benefit distribution coefficient α has two thresholds: 0.4–0.5 and 0.7–0.8. There are three cases at this time, (1) when the benefit distribution coefficient α is less than 0.4–0.5, x, y converge to 0, and eventually, both the issuer and the receiver choose not to cooperate, but since the receiver's share of the benefit is larger than the issuer's at this time, the receiver's willingness will first (2) When x and y trend toward zero and the profit division ratio is greater than 0.7–0.8, the issuer and the recipient eventually decide against cooperating, but at this time the issuer's share of the benefits is greater than the receiver's, and the issuer's willingness will first rise and then fall as the receiver's willingness falls; (3) When the benefit distribution coefficient α is between 0.5 and 0.7, x and y converge to 1. When α is on the left side of 0.6, the willingness of both the issuer and receiver to cooperate and innovate will rise steadily; when α is on the right side of 0.6, the willingness of the receiver will first fall and then rise because the benefits obtained by the issuer are greater than those obtained by the receiver, and the speed of convergence of the issuer is faster than that of the receiver; finally, both the issuer and receiver will choose to cooperate. The simulator outputs demonstrate how a tweak in the revenue allocation percentage impacts the issuer and receiver's ultimate strategy decisions. The issuer is more sensitive to the revenue allocation. In the synergy process, the issuer is the initiation point of the task and is more affected by the revenue allocation coefficient. The issuer will stop the task once it feels "unprofitable." In the synergy process, as the issuer and receiver choose the revenue distribution coefficient according to the ratio in the range of [0.5, 0.7], the issuer is slightly higher than the receiver, which is also consistent with the fact that the issuer is slightly higher than the receiver at present. The more acceptable both parties are, the more likely they are to cooperate.

5.2.2. Impact of original cost and cost reduction factor on the willingness of both parties to collaborate and innovate

Fig. 7 simulates the effect of changing the issuer's initial expenditure C_1 upon the willingness of the issuer as well as the receiver to collaborate and invent while keeping everything else constant. The threshold level associated with the issuer's initial expenditure C_1 ranges from 200 to 205, illustrated by Fig. 7. When C_1 falls below the specified value, x and y converge to 1 and the equilibrium point tends to point (1, 1). At this time, the decrease of C_1 makes the convergence of x and y, and the receiver converges faster than the issuer. When C_1 is better than this threshold value, the equilibrium point shifts to be located (0, 0) as x and y approach zero. In the process of synergy between the issuer and receiver, the issuer's original cost increases with an increase in the issuer's willingness to cooperate and innovate; the increase in C_1 causes x and y to converge more quickly. Thus the synergy between the issuer and receiver's readiness to team up and create progressively transforms into non-synergy. The simulation findings indicate that the readiness of both parties to work together on solutions increases as the issuer's initial expenditure decreases.

Fig. 8 simulates the effect of changing the receiver's initial cost C_2 on the issuer and the receiver's willingness to collaborate and invent, keeping all other variables the same. Fig. 8 illustrates that the receiver's initial expenditure C_2 threshold amount ranged from 150 to 155. The equilibrium point appears to sit at (1, 1) when C_2 is greater than the above worth, causing x and y convergence to 1. Owing to the decrease in C_2, the x- and y-convergence speeds accelerate, and the receiver converges ahead of the issuer. X and Y converge to zero when C_2 is more prominent than this cutoff level, and the equilibrium point moves in the direction of point (0, 0). An increase in C_2 accelerated the convergence of x and y. The issuer and receiver's willingness to cooperate and innovate gradually changes from synergy to non-synergy. This is because, during the synergy process between the issuer and receiver, the receiver's willingness to cooperate and innovate decreases as the receiver's original cost increases. According to the simulation findings, both parties are more willing to work together to innovate when the receiver's initial cost is reduced.

With all other factors being fixed, Fig. 9 simulates the impact of changing the synergy cost-cutting ratio on the willingness of the issuer and the receiver to collaborate and innovate. The acceptable threshold of the synergy cost-cutting ratio is between 0.2 and 0.3,

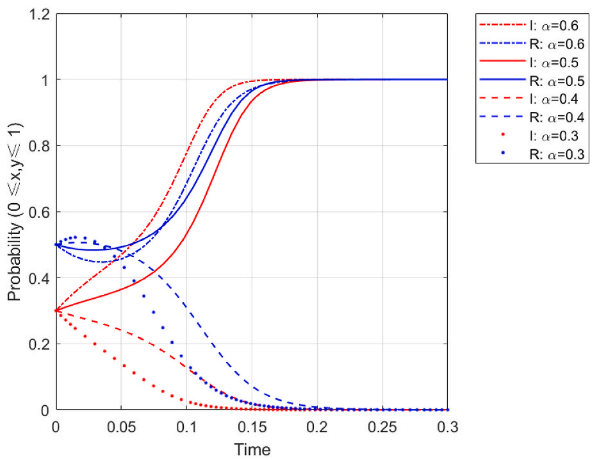

Fig. 5. Evolution of the willingness to cooperate and innovate between the parties when the coefficient of benefit distribution α changes (0.4–0.5) (1).

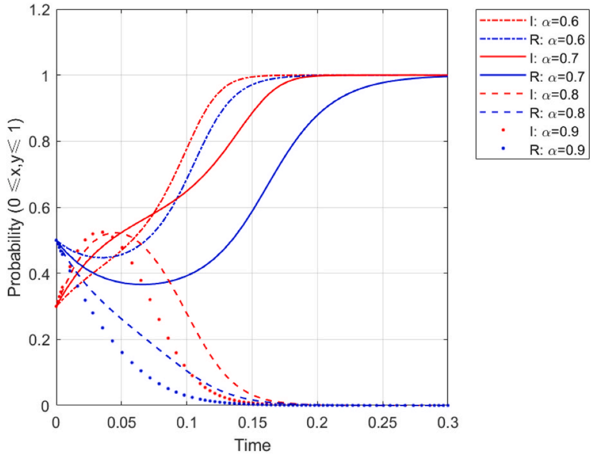

Fig. 6. Evolution of willingness to cooperate and innovate between parties when the coefficient of benefit distribution α changes (0.7–0.8) (2).

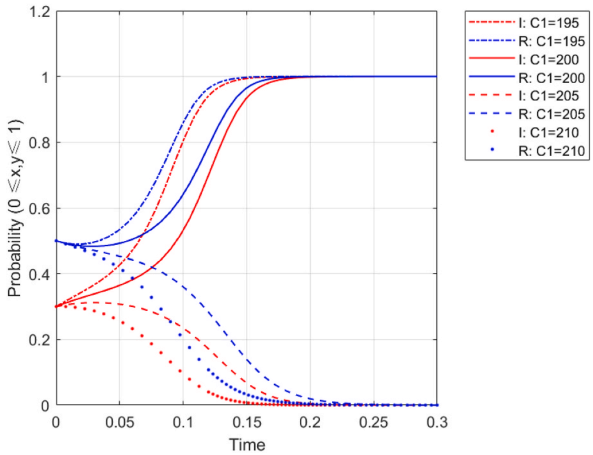

Fig. 7. Evolution of the willingness to cooperate and innovate between the parties when the original cost C_1 of the issuer changes.

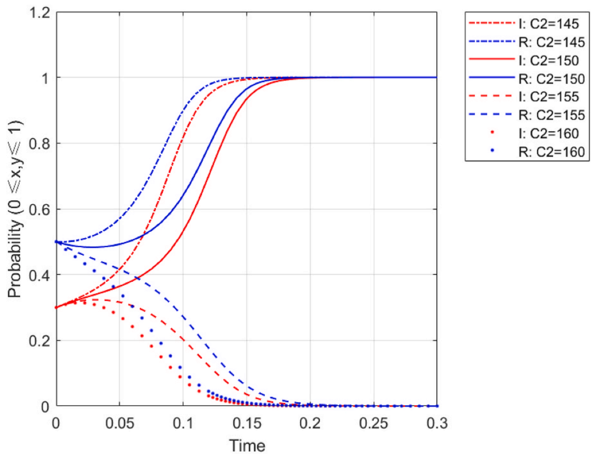

Fig. 8. Evolution of the willingness to cooperate and innovate between the two parties when the original cost C_2 of the receiver changes.

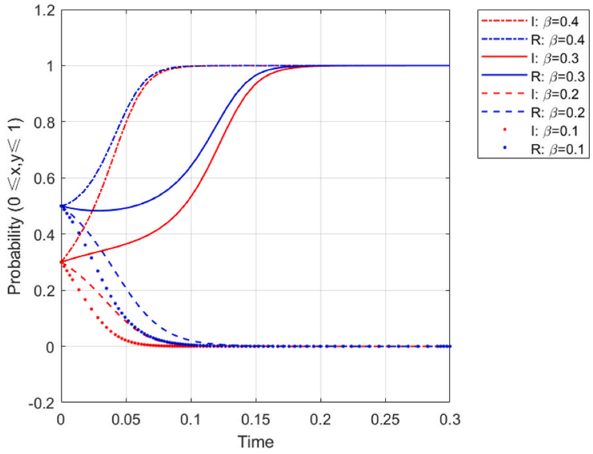

Fig. 9. Evolution of the willingness to cooperate and innovate between the parties when the coefficient of decrease in the cost of synergy β changes.

illustrated in Fig. 9. X and Y convergence to 1 when falls below this cutoff point, and the balance positions are (1, 1) when they are below this cutoff. When it is less important than this threshold value, x and y converge to 0, and the balance position shifts to point (0, 0) when the convergence of x and y accelerates. Due to the issuer's low initial willingness, both parties' willingness will increase the of β, accelerating the convergence of x and y. The issuer and receiver's willingness to cooperate and innovate gradually changes from synergy to non-synergy. This is because both parties' willingness to cooperate and innovate increases as the coefficient of the synergy cost between the issuer and the receiver decreases. The simulation findings demonstrate that the readiness of both parties to work together and create increases with the savings ratio of synergy.

5.2.3. The impact of network externalities and default penalties on the willingness of both parties to collaborate and innovate

With all other factors remaining constant, Fig. 10 simulates the impact of a change in network externality on the willingness of the issuer and receiver to collaborate and create. The network externality threshold level, illustrated in Fig. 10, is between 0.4 and 0.5. When it falls below this cutoff point, x and y eventually reach zero. When it is less significant than this cutoff worth, x, and y converge to 1, and the equilibrium position refers to the point (1, 1). When it is more significant than this cutoff worth, x, and y converge to 1, and the equilibrium position tends to the point (0, 0). Currently, due to the issuer's limited preliminary eagerness, both sides' eagerness will increase just a little bit, accelerating the convergence of x, y, and the willingness to cooperate and innovate between the issuer, the receiver gradually changes from non-synergy to synergy. This is because in the process of synergy between the issuer and receiver, the readiness of both sides to develop and work together increases with an increase in network externalities. This is because a high network externality indicates that many users are involved in a task. The issuer and recipient will benefit more from completing the innovation task, encouraging them to work together to fulfill it. The simulation results show that the higher the network externality, the stronger is the readiness of both sides to develop and work together.

Fig. 11 simulates how changes in default penalty H will affect the issuer's and receiver's willingness to collaborate and invent while maintaining all other settings. The upper limit of the default penalty, H, is between 75 and 80, according to Fig. 11. When H rises over

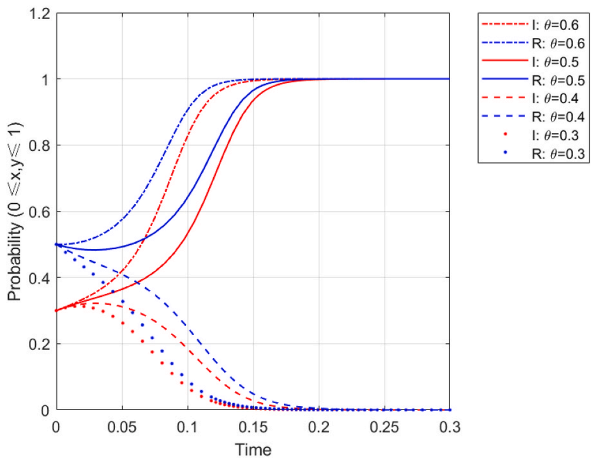

Fig. 10. Evolution of willingness to cooperate and innovate between parties when network externality θ changes.

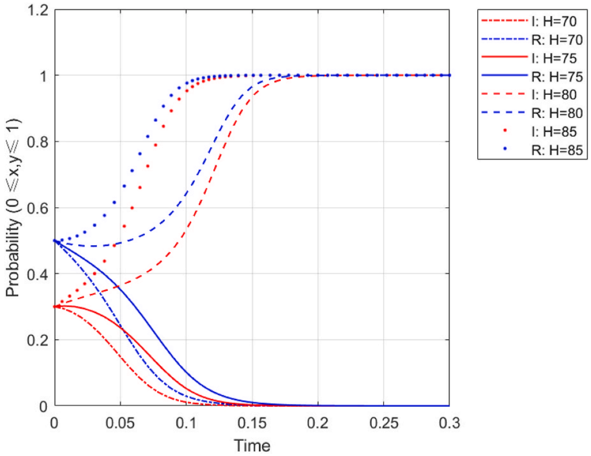

Fig. 11. Evolution of the willingness to cooperate and innovate between the parties when the default penalty H changes.

this limit, x and y tend to zero out, and the equilibrium point is (0, 0). The current decline in H quickens the merging of x and y. The point of balance prefers to be (1, 1) when H is more significant than this limit, causing x and y to converge to 1. Currently, both sides' readiness might briefly increase in H due to the issuer's small beginning readiness, which is why accelerating the convergence of x and y, and the willingness of the issuer and receiver to cooperate and innovate changes gradually from non-synergy to synergy. This is because the issuer and receiver are willing to collaborate and create synergistically as the default penalty increases. This is because an excessively high penalty will increase the contingent costs for both the issuer and the receiver. The original purpose of crowdsourcing was to reduce costs for both parties. An excessively high penalty goes against the original purpose of crowdsourcing. The outcomes of the simulation demonstrate that both sides are more likely to work together and invent when the default penalty is smaller.

6. Discussion

In this study, two other typical cases were selected separately for simulation to test the applicability of the developed model.

Case one: To improve the recognition and translation accuracy of Tibetan dialects, Deepl Translation cooperated with Baidu Cloud to recruit 870 Tibetans to record 1000 sentences individually, which were collected using tools developed by the client. The overall collection volume was 870,000 Tibetan voices, covering three Tibetan dialect areas, namely Amdo, Khampa, and Weizang; collection in Tibetan areas would face serious challenges such as high-security risks and high-quality control difficulties. The Baidu team first contacted local resources to lay out the points and dispatched project managers to guide collection in Tibet and Qinghai. The entire cycle took 1.5 months, and 920,000 pieces of data were finally delivered, with an acceptance rate higher than 95%, meeting the customer's delivery requirements [63].

Case two: Using face recognition unlocking technology, new models released by OPPO cell phone manufacturers need to collect multinational face photos for model training. Regarding the data security-related laws and regulations of the collection places, the Baidu Intelligent Cloud quickly started the project and coordinated the resource input, dispatched project managers to Argentina, Ukraine, Russia, Brazil, Uganda, Zambia, Philippines, Egypt, India, and Mexico, and used the customers' confidential model to complete the collection of 20,000 people of three nationalities within two months. The data were delivered as planned, and data acceptance was 100% qualified, which helped the model to be released smoothly [63].

The results show that in different case studies, the crowdsourcing model is an effective way to induce synergy between the two parties. From a practical standpoint, studying the elements that affect the crowdsourcing model participants' willingness to collaborate and innovate is essential. As a supplement to previous studies, this study incorporates network externalities, establishes a game payment matrix of synergy between the issuer and receiver, finds the game equilibrium solution of synergy through the evolutionary game method, examines the stability criteria of the balanced approach and the impact that each element's modification has on the issuer and receiver's willingness to collaborate and innovate, and obtains the following perspectives and insights.

(1) High synergy revenue. Its distribution coefficient needs to be reasonable [0.4,0.8], the higher the willingness to cooperate and innovate, and the synergy intention will be reached. Therefore, the issuer must choose the project release with the highest possible cooperative pre-revenue. The issuer should design the revenue allocation coefficient with full consideration of the gain of both parties; that is, it maintains its revenue, protects the receiver's enthusiasm to receive the contract, and amortizes the reasonable cost of the receiver to realize the ordinary profit of both parties.

(2) The lower the original cost of both parties and the higher the cost reduction factor under the policy support of the crowdsourcing platform, the higher the willingness to cooperate and innovate, and the synergy intention will be reached. Therefore, both the issuer and receiver should reduce their original costs as much as possible in the synergistic process by optimizing the process and adopting new technologies. As an intermediary, the crowdsourcing platform should rationalize and formulate

effective platform support policies for the characteristics of the online crowdsourcing business and strive to reduce the costs of both parties in crowdsourcing synergy so that both parties can achieve synergy. Appropriate platform subsidies can effectively promote synergy between issuers and receivers. The main ways platform subsidies are manifested are through the policies through monetary supports. It is beneficial to increase the synergy and invention readiness of the issuer and receiver to strengthen platform regulatory assistance. Immediate monetary support ought to be kept within an appropriate level.

(3) The synergy intention will only be met when the network externality is high and the motivation to collaborate and develop is high. The penalty for contract breach is low. Therefore, a higher network externality for the issuer indicates higher revenue from releasing the innovation project, thus prompting the issuer to seek the receiver as a collaborator. For the receiver, the higher the number of participating users, the lower is the cost incurred by a single contracting party to complete an innovation project. The synergies work along tis line. When the two parties cooperate, it is not appropriate to set an excessive amount when it comes to the part of the penalty for breach of contract, to reduce the contingent cost of both parties and prompt them to reach synergy. Both parties' propensity to work together and develop is increased when platform network externalities are properly promoted. Crowdsourcing platform subsidies are conducive for guiding platform users to increase network externalities. However, excessive network externalities increase the platform's burden. Diminishing marginal benefits reduces the willingness of the issuer and receiver to participate in collaborative innovation.

The crowdsourcing open innovation evolutionary game model is similar to that in the domestic and international literature. (1) At the domestic level, the results of this study are comparable to those of Cheng et al. [62] and Liu et al. [63]. However, in this study, the originator and receiver were considered as similar subjects for analysis. (2) Foreign level. This study is similar to those of Piller [27], Egger and Walcher [28], Christensen and Karlsson [3], Thompson and Bentzien [14], and Temiz [5]. Therefore, this study introduces network externalities as an index of innovation benefits and costs, based on the above domestic and international studies, considering the Internet-based practices of crowdsourced open innovation. The interactive influence of participants' willingness to engage in crowdsourced open innovation provides further support for research on the synergistic mechanisms of crowdsourced open innovation [64,65].

7. Conclusion

The research on the crowdsourcing open innovation collaborative mechanism first effectively promotes the theoretical construction of an open innovation ecosystem; second, it improves the practice of enterprise innovation, knowledge sharing, and transformation of innovation results by providing an important reference basis; and finally, it uses empirical research to broaden its application scope.

7.1. Theoretical implications

Although research on crowdsourcing and open innovation has been conducted, this study has several theoretical implications. First, unlike earlier studies [19], this study fully considers the Internet-based nature of crowdsourced open innovation work and introduces network externalities to improve the crowdsourced open innovation game model, which is a crucial claim for addressing crowdsourced open innovation in the digital network era. Second, the interactive influence of the participants' willingness to participate was considered, which adds a unique contribution to this study. Third, unlike many crowdsourced open innovation synergy studies, we made a secondary subdivision of the synergy benefit allocation coefficients in the study of the synergy benefit allocation coefficient link and conducted a bipolar analysis of the role of allocation coefficients in synergy, enriching the study of allocation rationality found in the literature [14].

7.2. Practical implications

The current research makes several subsequent practical improvements. (1) The findings are pertinent to businesses that enhance innovation performance. Considering that innovation performance plays a crucial role in the survival and growth of firms, the content of the reformulated research results can be used by firm management, STI personnel, and third-party evaluation agencies to strengthen and improve firm innovation performance, allowing firms to continuously adapt to the rapidly changing environment and overcome new challenges. (2) Considering that crowdsourced open innovation is a form of innovation democratization, the public can understand the main influencing factors of crowdsourced open innovation through the reformed literature so that they can participate more actively and effectively in the original internal innovation activities of the enterprise and realize the internal and external "double cycle" of enterprise innovation.

7.3. Recommendations

(1) Refine relevant policies and tailor innovations to local conditions. The OI paradigm has become diversified. Crowdsourcing, outsourcing, open sources, and crowdfunding are different types of carriers. Other open innovation paradigms are bound to emerge along with new technologies such as digital technology. Relevant functional departments of the government should refine relevant policies and management methods according to the actual situation and local conditions to actively adapt and match the development of open innovation.

(2) Research strengths and weaknesses. This study focuses on crowdsourcing open innovation synergy and identifies the relevant stakeholders in crowdsourcing open innovation. Based on the concept of fast and slow variables of system synergy theory, the relevant stakeholders are categorized into issuers (main sequence covariates) and receivers (follower covariates) according to the characteristics of open and collaborative paradigms in crowdsourcing. Network externalities are introduced into the replication dynamic equation in an exponential form. Owing to experimental conditions and time constraints, no empirical study was conducted, leaving many ideas unproven.
(3) Expected future research. In future research, we intend to fully consider new domestic and international forms and dynamics, new disruptions to the open innovation ecosystem, and both fast and slow variables, such as digital technology and universal participation in and the democratization of innovation. We also intend to comprehensively collect and analyze data on pertinent innovations to conduct active empirical studies.

Although the crowdsourced open innovation gaming paradigm was created using a rigorous simulation-based methodology, we acknowledge some limitations. Notably, the study cases were gathered in China, a particular nation. As a result, care ought to have been used while expanding this research to additional regions. To broaden the scope of this investigation's utilization, pertinent empirical research should be done to confirm the findings in various locations.

Funding statement

This work is partially supported by grants from China's National Natural Science Foundation [Grant no. 71874073]; National Social Science Foundation of China [Grant no. 19BGL084]; Social Science Foundation of Jiangsu Province [Grant no.21GLB008]; Philosophy and Social Science Research in Colleges and Universities of Jiangsu Province [Grant no.2019SJA1938]; Zhenjiang City, the sixth "169 Project" funding [Grant no. Zhenjiang talent [2021] No. 4].

Author contribution statement

Junmin Wu: Conceived and designed the experiments.

Yanyan Jiang, Lichi Zhang: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

Declaration of competing interest

The authors declare no conflict of interest.

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