Electronic Markets (2024) 34:1
https://doi.org/10.1007/s12525-023-00685-w

RESEARCH PAPER

The coordination mechanism of value co-creation between developers and users in digital innovation ecosystems

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Received: 11 June 2023 / Accepted: 21 November 2023

Abstract
The interactions between developers and users are a vital driver of complementary innovation and further facilitate the emergence and evolution of digital innovation ecosystems. However, these interactions are somewhat overlooked in research on digital innovation ecosystems. To increase the understanding of their interrelationship, firstly, we explain the foundation of value co-creation between developers and users by introducing service-dominant logic (S-D logic). Then, we analyze the coordination mechanism of their value co-creation using an evolutionary game approach. There are three key findings obtained: First, the underlying logic behind their value co-creation is mutual benefit, and the coordination mechanism elaborates how they select participation strategies by carefully weighing benefits against costs. Second, their engagement behavior is influenced by each other, and their initial choices also determine the evolution outcome of the behavior under certain circumstance. Third, the involvement of developers and users is impacted by similar benefits and costs, such as additional benefits of adopting the active strategy unilaterally, free-riding benefits, additional costs of positive participation, and benefits of ecosystem synergy. However, factors related to platform owners, the loss caused by punishment due to passive participation and the benefits from being featured due to active participation, only affect developers' strategy choices directly. Finally, we discuss managerial implications of our findings.

Keywords Digital innovation ecosystem · Software ecosystem · Value co-creation · Evolutionary game approach · Service-dominant logic (S-D logic)

JEL classification L860

Responsible Editor: Baidyanath Biswas

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Introduction

Digital innovation ecosystems play an important role in the digital economy. There are around 2.6 million applications (apps) on Google Play and about 1.8 million apps in the Apple App Store globally (Apple, (n.d.a); AppBrain, n.d.). In this modern world, people cannot live without mobile phones, where they satisfy various needs by using different apps. Therefore, typical digital innovation ecosystems, known as software ecosystems (SECOs) like the Google's Android and Apple's iOS, have attracted significant interest from both practitioners and researchers (Burstrom et al., 2022; Oh et al., 2016). A vase number of developers and users interact with each other through the provision of software offerings and app utilization. They not only have direct or indirect transaction relationships but are also jointly involved in innovation activities. As a result, both of them can be viewed as innovators. In essence, their interactions involve value co-creation within these two groups of innovators, who mutually exchange information and resources on a common technological platform (Burstrom et al., 2022; Manikas & Hansen, 2013). An in-depth understanding of these interactions holds realistic significance in promoting complementary innovations for the long-term development of the ecosystems.

This interrelationship between developers and users has been contributing to the emergence and evolution of digital innovation ecosystems because co-innovation of complements is integrated into value co-creation process (Romero & Molina, 2011; Vargo et al., 2015). However, research on digital innovation ecosystems primarily focuses on platform leaders and their influences on developers (Tsujimoto et al., 2018), while the interactions between developers and users are somewhat overlooked. To gain a deeper understanding of their innovative interactive relationship, some questions need to be considered. For example, what is the underlying logic of their value co-creation behavior? What influences their participation strategy? How can we encourage their active involvement? An essential coordination mechanism for developers and users co-creating value can help answer these questions, as it reflects the underlying foundation of their interaction, and elaborates on the evolution results and factors of their value co-creation behavior.

To address the aforementioned questions, we provide a detailed explanation and analysis of the coordination mechanism. Firstly, we consider the service-dominant logic (S-D logic) from the theory of value co-creation in marketing fields as a metatheory to elucidate the underlying foundation of this interrelationship. This theory offers a novel perspective to comprehend the essence of these interactions, thus filling the gap in digital innovation ecosystem research. Secondly, we employ an an evolutionary game approach to analyze the factors that determine the outcomes of the coordination mechanism from an evolutionary standpoint. This approach broadens the research methods in the realm of value co-creation, as existing research on S-D logic has predominantly focused on theoretical studies or explanations with limited exploration of specific situations. Thirdly, we propose managerial implications based on the findings obtained from model analysis and numerical analysis. These implications aim to encourage active value co-creation, thereby enhancing complementary innovations.

This article is structured as follows. In "Literature review" section, we review the literature on SECOs and digital innovation ecosystems, delve into the S-D logic of the value co-creation theory, and explore evolutionary game theory. In "Problem description and model construction" section, we describe the problem under study and proceed to construct the corresponding evolutionary game model. "Model analysis" section is dedicated to the analysis of the model, and in "Numerical analysis" section, we conduct further numerical analysis. Finally, we conclude the article by discussing broader implications and presenting our conclusions.

Literature review

Software ecosystem and digital innovation ecosystem

The success of Apple's iOS and Google's Android has drawn the attention of SECO researchers. An SECO is defined as "a set of direct, and indirectly linked, stakeholders creating value for customers and end-users with software products and services that have some level of relationship to each other, in order to serve a market through the exchange of information, resources, and artefacts" (Burstrom et al., 2022, 3). The emergence of a SECO is based on a layered, modular architecture facilitated by boundary resources, such as APIs, metadata, and software development kits (SDK), and apps are the key complementary of the focal platform providing functionality, services, or content (Constantinides et al., 2018). The focal platform plays a dual role: It serves as a two-sided market connecting the application side and the user side (Song et al., 2018) and serves a technology infrastructure for fostering complementary innovations (Gawer, 2014; Luo, 2018). SECOs perform economic and technological functions that are regarded as business ecosystems or innovation ecosystems in research, with the former mainly related to value capture and the latter mainly related to value creation (Gomes et al., 2018).

SECOs are digital innovation ecosystems. An innovation ecosystem is defined as "the evolving set of actors, activities, and artefacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors" (Granstrand & Holgersson, 2020, 3). A platform structure distinguishes digital innovation ecosystems from other types of innovation ecosystems, such as corporate innovation ecosystems and regional innovation ecosystems (Cobben et al., 2022; Oh et al., 2016). Compared with traditional innovation studies, the innovation ecosystem perspective focuses more on value co-creation based on inter-firm arrangements (Ceccagnoli et al., 2012; Shi et al., 2023). This perspective typically places greater emphasis on cooperation and collaboration between focal firms and complementors than those between companies and customers (Adner, 2006; Adner & Kapoor, 2010; Arena et al., 2021). Innovation serves as both the purpose and result of value co-creation, and the process of value co-creation also promotes innovation (Klimas & Czakon, 2022).

An ecosystem perspective is proposed to understand the complex business and innovation communities, and the interactions between different actors holds great significance for the formation and evolution of these communities (Jacobides et al., 2018; Moore, 1993). Digital innovation ecosystem research has consistently focused on platforms, particularly the influences of platform sponsors on the complementary innovation of third-party developers (Tsujimoto et al., 2018). For instance, opening the platform increases developers' innovation ability, even though it limits access charge (Parker and Van Alstyne, 2018). Integrative capabilities for ecosystem orchestration determine not only whether the focal firm can profit from innovation but also influence knowledge mobility and innovation appropriability for developers (Dhanaraj & Parkhe, 2006; Helfat & Raubitschek, 2018). The platform owner's entry into complementary markets can trigger app innovation and encourage the variety of complements in some cases (Foerderer et al., 2018; Wen & Zhu, 2019). The governance and regulation of platform leaders are also important factors (Kira et al., 2021). However, the interaction between developers and users is often overlooked, despite the importance of their value co-creation to complementary innovation. Therefore, in order to comprehend the underlying foundation of these innovative interactions, the S-D logic of value co-creation is applied to provide a theoretical basis (Vargo et al., 2015).

S-D logic and value co-creation

S-D logic is an important marketing theory that explains the value co-creation between businesses and consumers (Lusch et al., 2007; Vargo & Lusch, 2008, 2017). The opposing theory is goods-dominant (G-D) logic, which considers economic activity to be centered around the sale of goods, with value creation and delivery occurring in the process of product production and distribution. In contrast, S-D logic regards producers and consumers as both providers and beneficiaries in value co-creation, blurring the distinction between businesses and customers, and it views economic exchange as mutual service provision (Lusch et al., 2007; Vargo & Lusch, 2004, 2010, 2016). "Service" is redefined as the application of resources for the benefit of others, which differs from the common definition (Vargo & Lusch, 2017). Two types of resources are distinguished: operand resources such as natural resources and operant resources like knowledge and skills, which can act on both operand and operant resources to create benefits (Vargo & Lusch, 2004, 2017).

From an S-D logic perspective, value co-creation is the process of resource integration and service exchange, and both enterprises and consumers act as resource integrators and service providers, and the common purpose of enterprises is value co-creation because they cannot create value only by themselves (Vargo & Lusch, 2011). The means of value described as "value-in-use" or "value-in-context" (Vargo et al., 2008). Importantly, it is uniquely and phenomenologically determined by beneficiaries rather than service providers who propose value proposition (Vargo & Lusch, 2011, 2016). Thus, S-D logic provides a consumer-oriented marketing perspective. Furthermore, the evolution of digital platform ecosystems aligns with the principles of S-D logic. All directly and indirectly interactive actors collaborate produce service offerings and co-create value from a service-for-service perspective (Lusch et al., 2010; Vargo & Lusch, 2010). In essence, at the core of S-D logic is the idea that two parties integrate their own resources to mutually benefit each other based on the real needs of the other.

Most research on the S-D logic of value co-creation theory consists of theoretical studies or explanations, with few specific situations applied. In this study, we apply it to explain the real phenomenon of developers' and users' innovative interactions in digital innovation ecosystems. Value co-creation drives innovation, and innovation aims to enhance value co-creation. The cooperation of value creation and innovation occurs within the same interactive process and evolves iteratively (Lee et al., 2012; Vargo et al., 2015). Co-innovation involves the collaboration of new solution providers and stakeholders. Both value co-creation and co-innovation incorporate the idea of cooperation (Lee et al., 2012; Romero & Molina, 2011). As a result, users are both value co-creators and co-innovators.

During the evolution of cooperation, both developers and users interact and integrate their operant and operand resources to provide services to each other. Among these resources, app knowledge and skills are particularly crucial. Since software offerings provide innovative solutions to satisfy new or existing unmet needs, they are user-oriented (Vargo et al., 2015). Developers benefit not only the monetarily but also gain market knowledge, especially from users' data. All of these benefits are the vital resources for innovation (Brodie et al., 2011; Ye & Kankanhalli, 2020). Hence, users' innovation resources can also be viewed the value-in-use for developers, according to S-D logic. In contrast, users' value-in-use or value-in-context is more apparent, since their diverse needs are directly satisfied by various solutions offered by developers. Developers' innovation supply is evident through the development and improvements of software offerings, resulting in users enjoying more value due to developers' innovation efforts. Thus, the innovative interactions of both groups are also based on the mutual benefit idea of value co-creation, and the provisions of innovation "service" are bidirectional. The recurring cycles of value co-creation and co-innovation drive the evolution of digital innovation ecosystems to a certain extent. Developers and users make different decisions in the process of repeated cooperation.

Evolutionary game theory

Evolutionary game theory elaborates on the how interactive populations transform, diffuse, and stabilize their behavior forms (Gintis, 2009). This theory, derived from classical game theory in economics, is used to explain the problems related to biological evolution, and it has been also employed to clarify the social and economic issues (Smith, 2012). Unlike traditional game theory, evolutionary game theory does not assume that people are perfectly rational. In social evolution, a winning strategy diffuses across populations of players through imitation (Gintis, 2009; Weibull, 1995). Combined with Darwinian notion, evolutionary game theory assumes that evolution is determined by natural selection within a population, and this theory aims to identify the forces of natural selection that lead to the evolution of specific genetic traits (Smith, 2012). The most important concept in this theory is evolutionary stable strategy (ESS). An ESS is a behavioral phenotype determined by the genome rather than the history of previous games, and it represents an equilibrium state of evolution (Weibull, 1995).

In this study, we employ it to explain the coordination mechanism of developers and users' value co-creation behavior in digital innovation ecosystems, and the reasons are as follows: First, every time these two populations behave or choose strategies in value co-creation, it can be seen as a game. They attempt to maximize their benefits based on available information through the close interaction. Second, both groups do not exhibit high-level rationality, and the coordination process has an evolutionary feature. Both players adapt their behavior to strategic environment through trial and error, learning the winning strategy until they reach a stable equilibrium. The driver of evolution is the selection of strategic environment rather than previous game results. The strategic environment in which developers and users operate contains several types of benefits and costs related to players' behavior, as well as the influences of the platform dominance and the entire ecosystem.

Problem description and model construction

Problem description

According to the S-D logic of value co-creation theory, the fundamental basis for the interactions between developers and users in digital innovation ecosystems is mutual benefit. They achieve this by integrating various resources to offer what the other party needs. The benefits gained by each group depend on the value-in-use, as defined by themselves, and what the other group provides. Costs encompass all the resources expended for the provision of benefits. In practice, developers' value-in-use often includes revenue and innovation-related resources, such as feedback and user data. For users, their value-in-use is derived from the solutions that satisfy specific needs. Meanwhile, both groups incur costs when mutually benefiting. Therefore, they coordinate their level of interaction by assessing benefits against costs. In this study, the degree of their interaction participation is categorized into two levels: active and passive involvement in value co-creation, for the purpose of conducting a clear and intuitive analysis. For each group, there are four types of benefits and two kinds of costs based on their varying levels of participation. Additionally, platform leaders also exert influence on developers.

Game theory elucidates the mechanism of how players choose participation strategies by carefully evaluating benefits against costs. In comparison to traditional game theory, evolutionary game theory offers a superior explanation for the decision-making of developers and users. In evolutionary games, participants are seen as bounded rational decision-makers, as opposed to those with perfect rationality in traditional games. They cannot immediately identify the optimal strategies but instead learn and adjust through continuous trial and error in repeated games over time until determining the most appropriate ones. Platform leaders, who provide technical support for app development and update and data acquisition, and serve as the two-side market for the delivery of app products and services, transaction, and information communication play the important role in fostering the prosperity and health of digital innovation ecosystems. Therefore, when making decisions, developers must take into account the influence of platform owners.

Model assumption

To analyze the coordination mechanism of value co-creation between developers and users, within the context of SECOs and using the evolutionary approach, we propose the following assumptions.

Assumption 1: The two core stakeholders, app developers, and users operate under the conditions of incomplete information. They continually adjust their strategies and eventually select the optimal ones through the long-term multiple games.

Assumption 2: App developers have two strategies, including active (DAP) and passive (DNP) participation in the value co-creation. Those employing the DAP strategy invest considerable effort in creating greater user value through innovation consumer solutions. New features and value propositions are integrated into new versions of apps. These efforts encompass in-depth market analysis, aimed at uncovering unmet user needs. Developers achieve this either by establishing internal expert teams or by collaborating with professional data service providers like data.ai. Additionally, they engage in technological innovation to update their apps. However, developers may occasionally adopt the passive strategy to reduce costs. In this scenario, they refrain from undertaking any innovation-related work and may only perform maintenance or make minor app improvements. It is worth noting that some developers might excessively collect or misuse user data, or engage in plagiarism of others' work. Such practices can result in privacy and security issues or lead to copyright disputes, negatively affecting the environment for value co-creation and innovation. Similarly, users also employ active (UAP) and passive (UNP) participation strategies. Active participation entails users being willing to pay more for additional functions, granting more app permissions, and taking the initiative in providing their knowledge to enhance app quality. This can involve actions such as rating and reviewing apps in app stores, providing feedback within apps, and participating in testing of new versions. On the other hand, passive participation in value co-creation involves minimal expenditure and a lack of additional efforts to contribute knowledge or data for app improvement. Passive participants generally download and install apps, use functions, and grant basic permissions without active engagement.

Assumption 3: The proportion of the developers who prefer to adopt the DAP strategy is "x" ($0 \leq x \leq 1$), while the reminder opt for the DNP strategy ($1 - x$). Among users, the proportion using the UAP strategy is represented as "y" ($0 \leq y \leq 1$), while the UNP strategy is adopted by ($1 - y$). According to evolutionary game theory, under specific conditions, players evolve their strategies in repeated games. The proportion of players who adopt a particular strategy changes over time until a stable equilibrium state is reached (Gintis, 2009; Tanimoto, 2015). Therefore, both x and y are the functions of time "t," signifying that x and y change with time, i.e., $x = x(t)$ and $y = y(t)$.

Assumption 4: When both users and developers actively participate in value co-creation, developers obtain and allocate sufficient innovation resources, including revenue generated from in-app purchases and subscriptions, as well as innovation knowledge derived from a wide array of user data and detailed analysis. Simultaneously, users' needs are consistently met through continuous innovative solutions. These are the direct benefits they receive. Furthermore, both parties can reap indirect benefits from the significant enhancement of the overall well-being of SECOs. These benefits encompass a substantial increase in innovation knowledge and resources, a significant enhancement in innovation efficiency, and a high value-in-context within the entire ecosystem. In this scenario, developers and users can each realize synergy benefits "ΔR_d" and "ΔR_u" within the ecosystem, including both direct and indirect advantages.

Assumption 5: Platform leaders establish regulations to control developers' behavior and oversee the ecosystems. They impose penalties on those whose practices infringe upon the rights and interests of other stakeholders, including users and fellow developers, and have a detrimental impact on value co-creation. For example, Google Play has developed and implemented a developer content policy. According to this policy, apps that violate rules such as containing restricted content, being copies of someone else's work, or engaging in deception or malicious activities, or attempting to abuse or misuse any network, device, or personal data, are either prohibited, restricted, or subject to corrective measures (Google, n.d.). Additionally, if developers do not update their apps within a specified period, the apps may be removed from platforms, as outlined in Apple's developer policy for app store improvements (Apple, (n.d.c)). Thus, if developers choose the passive strategy, they risk receiving penalties that can result in losses "F." However, platform leaders also reward developers who innovate significantly and create substantial user value by featuring their apps prominently. For example, Apple promotes the apps developed by winners of the App Store Awards in 2022 (Apple, (n.d.b)). Hence, if developers actively engage in value co-creation and make efforts to innovate, platforms will showcase their apps, making them more accessible to users. Developers can then reap benefits "P" from being featured, which include increased visibility and recognition.

Assumption 6: During value co-creation, developers can receive basic benefits "R_d" which encompass financial income from users who make one-time app purchases, as well as limited user knowledge derived from acquired data and market analysis. Users, in turn, gain basic benefits "R_u" by consuming software offerings to meet their fundamental needs. When developers actively engage in value co-creation while users do not, developers receive the basic benefits R_d along with additional benefits "R_{d1}" ($R_{d1} < \Delta R_d$). These additional benefits R_{d1} include an increased wealth of user knowledge from in-depth market research. Users, in this scenario, obtain basic benefits "R_u" and free-riding benefits "R_{u2}" ($R_{u2} < \Delta R_u$) from the efforts of developers in innovation. Conversely, when users actively participate in value co-creation while developers do not, users receive basic benefits R_u along-side additional benefits "R_{u1}" ($R_{u1} < \Delta R_u$). These additional benefits R_{u1} are derived from premium features, additional content, or digital goods offered through in-app purchases and subscriptions, as well as improvements made in response to their feedback. Developers, in this case, obtain basic benefits R_d and free-riding benefits R_{d2} ($R_{d2} < \Delta R_d$), which include financial income from users' in-app purchases and subscriptions and additional user knowledge derived from ratings, reviews, and feedback. If both developers and users participate passively, they can only gain the basic benefits R_d and R_u, respectively.

Assumption 7: The basic costs for developers participating in value co-creation are incurred during the original version development, maintenance, and updates without continuous innovation efforts. These costs are denoted as "C_d'" ($C_d < R_d$). When developers choose the passive strategy, they only have this type of expenditure, and users do not find new features or value propositions in app descriptions. If developers adopt the active strategy, there are additional costs C_d' ($C_d' < R_{d1}$) associated with innovative improvements. These costs encompass expenses related to technological innovation, the purchase of market analysis services, efforts to encourage user feedback, and more. For users who engage in value co-creation passively, which means they only use the primary functions of apps and provide limited user data, the basic costs "C_u" ($C_u < R_u$) include expenses for one-time purchases, as well as the knowledge and skills required to download, install, and use apps, among other things. If users actively participate in value co-creation, they will incur additional costs C_u' ($C_u' < R_{u1}$). These additional costs include expenses for subscriptions and in-app purchases to access premium features, additional content, or digital goods. Additionally, users invest extra knowledge and skills to use additional functions and features, provide reviews and ratings, offer feedback, participate in testing of new versions, and more.

According to the above all assumptions, the meanings of each parameter are showed in Table 1.

Payoff matrix and replicator dynamic equation

Based on the above seven assumptions, there are four types of games between developers and users when they make decisions to take part in value co-creation in SECOs. The payoff matrix between two sides is showed in Table 2.

Table 1 Meanings of parameters

Game agent	Parameters	Meanings
Developers	R_d	Basic benefits
	R_{d1}	Additional benefits of developers adopting the active strategy unilaterally
	R_{d2}	Benefits of free-riding
	ΔR_d	Synergy benefits that developers gain when both two parties actively participating
	C_d	Basic costs
	$C_d\prime$	Additional costs of adopting the active strategy
	F	The loss caused by platform leaders' punishment due to passive participation
	P	The benefits from being featured by platform leaders due to active participation
Users	R_u	Basic benefits
	R_{u1}	Additional benefits of users adopting the active strategy unilaterally
	R_{u2}	Benefits of free-riding
	ΔR_u	Synergy benefits that users gain when both two parties actively participating
	C_u	Basic costs
	$C_u\prime$	Additional costs of adopting the active strategy

Table 2 The payoff matrix between developers and users

		Users	
		UAP (y)	UNP ($1-y$)
Developers	DAP (x)	$R_d + \Delta R_d - C_d - C_d\prime + P$ $R_u + \Delta R_u - C_u - C_u\prime$	$R_d + R_{d1} - C_d - C_d\prime + P$ $R_u + R_{u2} - C_u$
	DNP ($1-x$)	$R_d + R_{d2} - C_d - F$ $R_u + R_{u1} - C_u - C_u\prime$	$R_d - C_d - F$ $R_u - C_u$

According to Table 2, the expected payoffs of developers when they actively and passively participate and the average profits are as follows:

$$U_{DAP} = y(R_d + \Delta R_d - C_d - C'_d + P) + (1-y)(R_d + R_{d1} - C_d - C'_d + P) \quad (1)$$

$$U_{DNP} = y(R_d + R_{d2} - C_d - F) + (1-y)(R_d - C_d - F) \quad (2)$$

$$U_D = xU_{DAP} + (1-x)U_{DNP} \quad (3)$$

The expected payoffs of users choosing active and passive strategies, and the average profits are as follows:

$$U_{UAP} = x(R_u + \Delta R_u - C_u - C_u\prime) + (1-x)(R_u + R_{u1} - C_u - C_u\prime) \quad (4)$$

$$U_{UNP} = x(R_u + R_{u2} - C_u) + (1-x)(R_u - C_u) \quad (5)$$

$$U_U = yU_{UAP} + (1-y)U_{UNP} \quad (6)$$

In evolutionary game theory, the evolutionary development of a strategy in a group is modelled by the replicator dynamic functions, and according to this, individuals tend to choose the strategy whose expected payoffs are greater than the average payoffs of the whole population, so the replicator dynamic equation of developers playing the strategy DAP and that of users adopting the strategy UAP are as follows:

$$F(x) = dx/dt = x(U_{DAP} - U_D) = -x(x-1)\left[y(\Delta R_d - R_{d1} - R_{d2}) + R_{d1} - C_d\prime + P + F\right] \quad (7)$$

$$G(y) = dy/dt = y(U_{UAP} - U_U) = y(y-1)\left[x(R_{u1} + R_{u2} - \Delta R_u) + C_u\prime - R_{u1}\right] \quad (8)$$

Model analysis

Stability of the main players' strategies

According to the stability theorem of differential equations, the requirements for the ESS of developers are $F(x) = 0$ and $F\prime(x) < 0$, and function (7) $F(x) = -x(x-1)\left[y(\Delta R_d - R_{d1} - R_{d2}) + R_{d1} - C_d' + P + F\right]$ and $F'(x) = -(2x-1)\left[y(\Delta R_d - R_{d1} - R_{d2}) + R_{d1} - C'_d + P + F\right]$.

Proposition 1: In the condition of $\Delta R_d - R_{d1} - R_{d2} > 0$ and $y > y_0$, or that of $\Delta R_d - R_{d1} - R_{d2} < 0$ and $y < y_0$, the developers' stable strategy is "DAP"; in the condition of $\Delta R_d - R_{d1} - R_{d2} > 0$ and $y < y_0$, or that of $\Delta R_d - R_{d1} - R_{d2} < 0$ and $y > y_0$, the evolutionary strategy is stable at "DNP," for which the threshold $y_0 = \frac{-R_{d1} + C'_d - P - F}{\Delta R_d - R_{d1} - R_{d2}}$ (see Appendix A for the proof).

Similarly, the requirements for the ESS of users are $G(y) = 0$ and $G\prime(y) < 0$, and function (8) $G(y) = y(y-1)\left[x(R_{u1} + R_{u2} - \Delta R_u) + C_u' - R_{u1}\right]$ and $G'(y) = (2y-1)\left[x(R_{u1} + R_{u2} - \Delta R_u) + C'_u - R_{u1}\right]$.

Position 2 In the condition of $R_{u1} + R_{u2} - \Delta R_u > 0$ and $x > x_0$, or that of $R_{u1} + R_{u2} - \Delta R_u < 0$ and $x < x_0$, the users' stable strategy is "UNP"; in the condition of $R_{u1} + R_{u2} - \Delta R_u > 0$ and $x < x_0$, or that of $R_{u1} + R_{u2} - \Delta R_u < 0$ and $x > x_0$, the evolutionary strategy is stable at "UAP," for which the threshold $x_0 = \frac{-C'_u + R_{u1}}{R_{u1} + R_{u2} - \Delta R_u}$ (see Appendix A for the proof).

In conclusion, the evolutionary stability of developers' strategy and that of users' strategy mutually influence each other, as indicated by the roles of "x_0" and "y_0" in the above analysis. Additionally, the disparity between synergy benefits and the sum of additional and free-riding benefits, along with the profit margin of the additional benefits and their associated costs, also impact strategy stability. Moreover, when developers evolve their strategy, they take into account the potential losses resulting from platform leaders' penalties due to passive participation, as well as the benefits derived from being featured by platform sponsors due to active participation. Therefore, from an individual population perspective, the factors influencing the value co-creation behaviors of developers and users are similar. The primary distinction lies in how platform dominators' measures impact the evolution of developers' strategies rather than those of users.

Parameters' influence on the main players' strategy choice

We examine the influences of all corresponding parameters on the strategy choices of developers and users according to their replicator dynamic equations. As for developers, the first-order partial derivatives of $\Delta R_d, R_{d1}, P, F, R_{d2}, C_d\prime, R_d$, and C_d are $\frac{\partial F(x)}{\partial \Delta R_d} = xy(1-x)$, $\frac{\partial F(x)}{\partial R_{d1}} = x(1-x)(1-y)$, $\frac{\partial F(x)}{\partial P} = \frac{\partial F(x)}{\partial F} = x(1-x), \frac{\partial F(x)}{\partial R_{d2}} = -xy(1-x), \frac{\partial F(x)}{\partial C_d\prime} = -x(1-x)$, and $\frac{\partial F(x)}{\partial R_d} = \frac{\partial F(x)}{\partial C_d} = 0$, respectively, prompting.

Proposition 3: $\Delta R_d, R_{d1}, P$, and F positively impact developers choosing "DAP" strategy, but on the contrary, R_{d2} and C'_d negatively influence "DAP" choice, and R_d and C_d would not affect their behavior (see Appendix A for the proof).

Therefore, for developers, assuming other parameters remain constant, an increase in the ecosystem's synergy benefits, the additional benefits derived from active value co-creation, the potential loss due to platform leaders' penalties, or the benefits from being featured will encourage them to actively engage in value co-creation. Conversely, a rise in free-riding benefits or additional costs associated with adopting the active strategy will likely lead to the choice of "DNP." The basic benefits and basic costs of co-creating value have relatively minimal effects in comparison.

Based on users' replicator dynamic equations, the first-order partial derivatives of ΔR_u, R_{u1},R_{u2}, C_u', R_u, and C_u are $\frac{\partial F(y)}{\partial \Delta R_u} = xy(1-y)$, $\frac{\partial F(y)}{\partial R_{u1}} = y(1-x)(1-y)$, $\frac{\partial F(y)}{\partial R_{u2}} = -xy(1-y)$, $\frac{\partial F(y)}{\partial C_u'} = -y(1-y)$, and $\frac{\partial F(y)}{\partial R_u} = \frac{\partial F(y)}{\partial C_u} = 0$, respectively, which prompts.

Proposition 4: ΔR_u and R_{u1} have a positive correlation with the probability of users employing "UAP" strategy, while on the contrary, R_{u2} and C_u' negatively affect their choice of "UAP" strategy but leading to their passive behavior, and R_u and C_u do not influence how they perform in value co-creation (see Appendix A for the proof).

Therefore, assuming other parameters remain constant, an increase in the ecosystem's synergy benefits or the separate growth of additional benefits associated with adopting the positive strategy can motivate users to actively participate in value co-creation. Conversely, an increase in free-riding benefits or the additional costs related to positive involvement can incline them toward negative participation. The basic benefits and basic costs of value co-creation have relatively minimal effects on their behavior in this regard.

In summary, there are several close similarities and one small difference in how various parameters influence the strategy choices of both agents. The similarities include the fact that ecosystem synergism and rewards for active participation encourage both developers and users to engage positively in value co-creation. Conversely, free-riding advantages and the additional costs of active participation lead both populations to opt for passive involvement. Additionally, the basic benefits and costs of value co-creation do not significantly impact their decision-making. The key difference is that platform leaders' governance influences developers to choose the active strategy, but it does not have a similar impact on users' choices.

Furthermore, although the factors in strategy stability and those in strategy selection are the same, the stability analysis of the main players' strategies in "Stability of the main players' strategies" section focuses more on the joint influences of these factors while the analysis of major agents' choices in this section emphasizes the separate effect of individual factors.

Stability analysis of equilibrium points in the evolutionary game system

According to the stability theory of ordinary differential equations, the equilibrium points can be obtained when let function (7) $F(x) = dx/dt = 0$ and function (8) $G(y) = dy/dt = 0$, and then, four equilibrium points, $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$ are gained on the two-dimensional platform $M = \{(x,y), 0 \le x \le 1, 0 \le y \le 1\}$, and another equilibrium point $E_5(x^*,y^*) = \left(\frac{R_{u1}-C_u'}{R_{u1}+R_{u2}-\Delta R_u}, \frac{R_{d1}-C_d'+P+F}{R_{d1}+R_{d2}-\Delta R_d}\right)$ can be obtained under the condition of $R_{u2} + C_u' - \Delta R_u > 0$ as well as $R_{d2} + C_d' - \Delta R_d - P - F > 0$.

The equilibrium points calculated by replicator dynamic functions may not meet evolutionary stable state conditions. According to Friedman (1991), in economic and social applications, Jacobian Matrix (J) can be used to evaluate the asymptotic stability and find ESS. The Jacobian Matrix (J) of this game is:

$$J = \begin{bmatrix} \frac{\partial F}{\partial x} & \frac{\partial F}{\partial y} \\ \frac{\partial G}{\partial x} & \frac{\partial G}{\partial y} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{9}$$

where

$$a_{11} = -(2x-1)\left[y\left(\Delta R_d - R_{d1} - R_{d2}\right) + R_{d1} - C_d' + P + F\right] \tag{10}$$

$$a_{12} = x(x-1)\left(R_{d1} + R_{d2} - \Delta R_d\right) \tag{11}$$

$$a_{21} = y(y-1)\left(R_{u1} + R_{u2} - \Delta R_u\right) \tag{12}$$

$$a_{22} = (2y-1)\left[x\left(R_{u1} + R_{u2} - \Delta R_u\right) + C_u' - R_{u1}\right] \tag{13}$$

When a stable point fulfils the two conditions, $det(J) = a_{11}a_{22} - a_{12}a_{21} > 0$ and $tr(J) = a_{11} + a_{22} < 0$, it is the ESS. The values of the Jacobian Matrix (J) elements for each stable point are listed in Table 3.

Table 3 The values of the Jacobian Matrix (J) elements for each stable point

Stable point	a_{11}	a_{12}	a_{21}	a_{22}
$E_1(0,0)$	$R_{d1} - C_d' + P + F$	0	0	$R_{u1} - C_u'$
$E_2(0,1)$	$\Delta R_d - R_{d2} - C_d' + P + F$	0	0	$C_u' - R_{u1}$
$E_3(1,0)$	$C_d' - R_{d1} - P - F$	0	0	$\Delta R_u - R_{u2} - C_u'$
$E_4(1,1)$	$R_{d2} - \Delta R_d + C_d' - P - F$	0	0	$R_{u2} - \Delta R_u + C_u'$
$E_5(x^*,y^*)$	0	a_{12}^*	a_{21}^*	0

The values of a^*_{12} and a^*_{21} are listed separately

$$a_{12*} = \frac{\left(C_u' - R_{u1}\right)\left(R_{u2} + C_u' - \Delta R_u\right)\left(R_{d1} + R_{d2} - \Delta R_d\right)}{\left(R_{u1} + R_{u2} - \Delta R_u\right)^2} \tag{14}$$

$$a_{21*} = \frac{\left(R_{u1} + R_{u2} - \Delta R_u\right)\left(R_{d1} - C_d\prime + P + F\right)\left(\Delta R_d - R_{d2} - C_d' + F + P\right)}{\left(R_{d1} + R_{d2} - \Delta R_d\right)^2} \tag{15}$$

For $E_5(x^*, y^*)$, the value of its a_{11} and a_{22} is zero, so it is not ESS in the game since it does not fulfil the condition $tr(J) = a_{11} + a_{22} < 0$. Similarly, another point $E_1(0,0)$ also is not ESS, and the reason is that according to assumptions 6 and 7, $C_d' < R_{d1}$ and $C_u' < R_{u1}$, both its a_{11} and a_{22} are larger than zero, which leads to the value of the $tr(J)$ not meeting the requirement. Thus, according to above analysis, $E_2(0,1)$, $E_3(1,0)$, and $E_4(1,1)$ can be ESS in four cases as follows (the stability analysis details of the four cases are listed in Appendix B).

In case (1), $E_2(0,1)$ and $E_3(1,0)$ are the ESS of the evolutionary game system under the conditions $\Delta R_d + P + F < R_{d2} + C_d'$ and $\Delta R_u < R_{u2} + C_u'$ (for proof, refer to Appendix B). Therefore, if a real-life scenario can be abstracted into this context, suggesting that the cumulative effects of ecosystem synergism and platform leaders' influence are smaller than those of developers' free-riding advantages and their additional efforts to actively co-create value, and that the impacts of ecosystem synergism are also less significant than those of users' free-riding advantages and their extra efforts to select the positive strategy, then the evolutionary outcome in this scenario will be that developers choose the passive strategy while users adopt the active one. Conversely, it could also be the case that developers act actively, but users do not. Furthermore, if the condition $\Delta R_d + P + F < R_{d2} + C_d'$ plays a more pivotal role than the other condition, the evolutionary outcome will be $E_2(0,1)$. However, if the impact of the condition $\Delta R_u < R_{u2} + C_u'$ on the system outweighs that of the other condition, the result will be $E_3(1,0)$.

In the conditions, $\Delta R_d + P + F < R_{d2} + C_d'$ and $\Delta R_u > R_{u2} + C_u'$, of case (2), $E_2(0,1)$ is the ESS of the evolutionary game system, and the former condition determines how the two populations evolve their strategies (refer to Appendix B for the proof). Thus, if a real-world scenario closely resembles this case, implying that the combined impacts of ecosystem synergism and platform dominators' regulation are smaller than those of free-riding advantages and the additional efforts resulting from active value co-creation for developers, then developers will tend to refrain from participating in value co-creation negatively. In contrast, users will take the opposite action after a period of adjustment.

In the conditions, $\Delta R_d + P + F > R_{d2} + C_d'$ and $\Delta R_u < R_{u2} + C_u'$, of case (3), $E_3(1,0)$ is the ESS of the system, with the latter condition playing a key role in strategy evolution (refer to Appendix B for the proof). Therefore, if this case accurately represents the primary characteristics of a real-world scenario, suggesting that the influences of ecosystem synergism are outweighed by the impacts of users' free-riding advantages and their additional efforts to engage positively, then users are highly likely to passively participate in value co-creation. Conversely, developers may behave differently in this scenario.

In case (4), the conditions are $\Delta R_d + P + F > R_{d2} + C_d'$ and $\Delta R_u > R_{u2} + C_u'$, and $E_4(1,1)$ is the ESS of the system (refer to Appendix B for the proof). Therefore, if the real world exhibits remarkable similarities to this case, indicating that the combined impacts of ecosystem synergism and platform leaders' governance outweigh those of developers' free-riding advantages and their additional efforts for active value co-creation, and simultaneously, that the influences of ecosystem synergism surpass those of users' free-riding advantages and their additional efforts to adopt the positive strategy, then both populations will actively engage in value co-creation.

In summary, the overall evolutionary directions of the system are influenced by specific conditions. Comparing cases (1) and (2), as well as cases (1) and (3), we can observe that $E_2(0,1)$ as the ESS of the evolutionary game system is determined by condition $\Delta R_d + P + F < R_{d2} + C_d'$, while $E_3(1,0)$ as the ESS is determined by condition $\Delta R_u < R_{u2} + C_u'$. Furthermore, $E_4(1,1)$ as the ESS is decided by two conditions $\Delta R_d + P + F > R_{d2} + C_d'$ and $\Delta R_u > R_{u2} + C_u'$ synchronously. Combined with the analysis of the primary players' strategy stability (refer to "Stability of the main players' strategies" section), we can conclude that the key conditions, containing developer-related factors, primarily determine the evolution of developers' strategies within the system. Users' decisions are influenced by those of developers, and vice versa. This is how the system achieves its potential evolutionary outcomes. Similarly, in the real world, if environmental conditions have a greater and more direct impact on one of the two parties, the behavior of that party will influence the other and shape the system's results. However, for both developers and users, although their additional benefits from active value co-creation influence the stability and selection of strategies within their respective populations, factors that are not part of the ESS conditions might not affect the evolutionary outcomes at the system level. The reasons for this will be explored further, combining with the related results of numerical analysis in "The effects of developers' related factors on game equilibrium" and "The effects of user-related factors on game equilibrium" sections.

Furthermore, while case (4) represents the most ideal scenario where digital innovation ecosystems exhibit maximum innovation efficiency, case (1) might be the closest reflection of today's reality in many instances. This is because, when compared to the influences of free-riding advantages and the additional costs associated with active value co-creation, the advantages of ecosystem synergism and the governance by platform leaders may not significantly affect developers and users. The reasons behind this are twofold. Firstly, in the real world, the indirect benefits of ecosystem synergism may not be immediately apparent to developers and users for a certain period of time. Secondly, regulations and rewards can sometimes have limited impact on developers, especially considering the vast number of apps within a SECO, making comprehensive governance challenging.

Numerical analysis

The preceding theoretical analysis elucidates the outcomes of strategy evolution concerning developers and users co-creating value in SECOs, as well as the factors that influence these results. In this section, a numerical simulation of the evolutionary game model is carried out using MATLAB R2020a to illustrate how the decisions of developers and users mutually influence each other, and how the parameters discussed in the model analysis affect the ESS. All parameters are provided in accordance with the assumptions, and their initial values, as shown in Table 4, are based on the conditions $\Delta R + P + F < R_{d2} + C'_d$ and $\Delta R < R_{u2} + C'_u$ in case (1).

Table 4 The initial values of all parameters

Parameter	Value	Parameter	Value
x	0.5	P	30
y	0.5	F	45
R_d	200	R_u	200
ΔR_d	300	ΔR_u	230
R_{d1}	250	R_{u1}	200
R_{d2}	190	R_{u2}	150
C_d	160	C_u	120
C_d'	200	C_u'	90

The effects of main players' initial strategy choice on game equilibrium

The initial value of the percentage of developers actively co-creating value x is varied at 0.1, 0.3, 0.5, 0.7, and 0.9 to ascertain how the initial strategy choice of their own population influences the ESS of SECOs. Figure 1a, b show that the ESS of the system changes from $E_2(0,1)$ to $E_3(1,0)$ under the conditions of case (1), and similarly, the initial value of the percentage of users with active participation y is set at the same value as that of x (0.1, 0.3, 0.5, 0.7, and 0.9), and Fig. 1c, d show the change of ESS from $E_3(1,0)$ to $E_2(0,1)$. The results are consistent with the ESS of case (1) and the analysis that the strategy choices of developers and users can affect each other in "Stability of the main players' strategies" section. However, in "Stability analysis of equilibrium points in the evolutionary game system" section, we deduce that if the developer-related condition $\Delta R_d + P + F < R_{d2} + C'_d$ is more important than the user-related condition $\Delta R_u < R_{u2} + C'_u$, the ESS will be $E_2(0,1)$ and otherwise that will be $E_3(1,0)$, but we overlook the influences of the players' initial choice. Further, according to the results showed in Fig. 1a–d, under the conditions $\Delta R_d + P + F < R_{d2} + C'_d$ and $\Delta R_u < R_{u2} + C'_u$ in case (1), the ESS is also impacted by the initial choices of the two main players. When the proportion of users actively co-creating value remain unchanged, as the proportion of developers behaving actively increases, the ESS would evolve to $E_3(1,0)$, and by contrast, $E_2(0,1)$ would be the ESS.

The effects of developer-related factors on game equilibrium

The other parameters remain unchanged and the value of additional benefits of developers' unilateral active value co-creation 'R_{d1}' is varied at 210, 230, 250, 270, and 290, which does not make any difference to the conditions $\Delta R_d + P + F < R_{d2} + C'_d$ and $\Delta R_u < R_{u2} + C'_u$ of case (1), and the ESS changes from $E_2(0,1)$ to $E_3(1,0)$, as shown in Fig. 2a, b. This result has consistency with the positive influence of R_{d1} on developers actively co-creating value in "Parameters' influence on the main players' strategy choice" section and the ESS of case (1) in "Stability analysis of equilibrium points in the evolutionary game system" section. However, the previous analysis of the impact of R_{d1} does not show whether it can change developers' ESS, and its influence on the ESS of system under case (1) conditions is also ignored. The numerical analysis clearly illustrates that R_{d1} can positively affect developers' strategy choice evolving from DNP to DAP, and meanwhile, users' strategy choice is from UAP to UNP. The change of users' decision is directly influenced by that of developers according to the stability

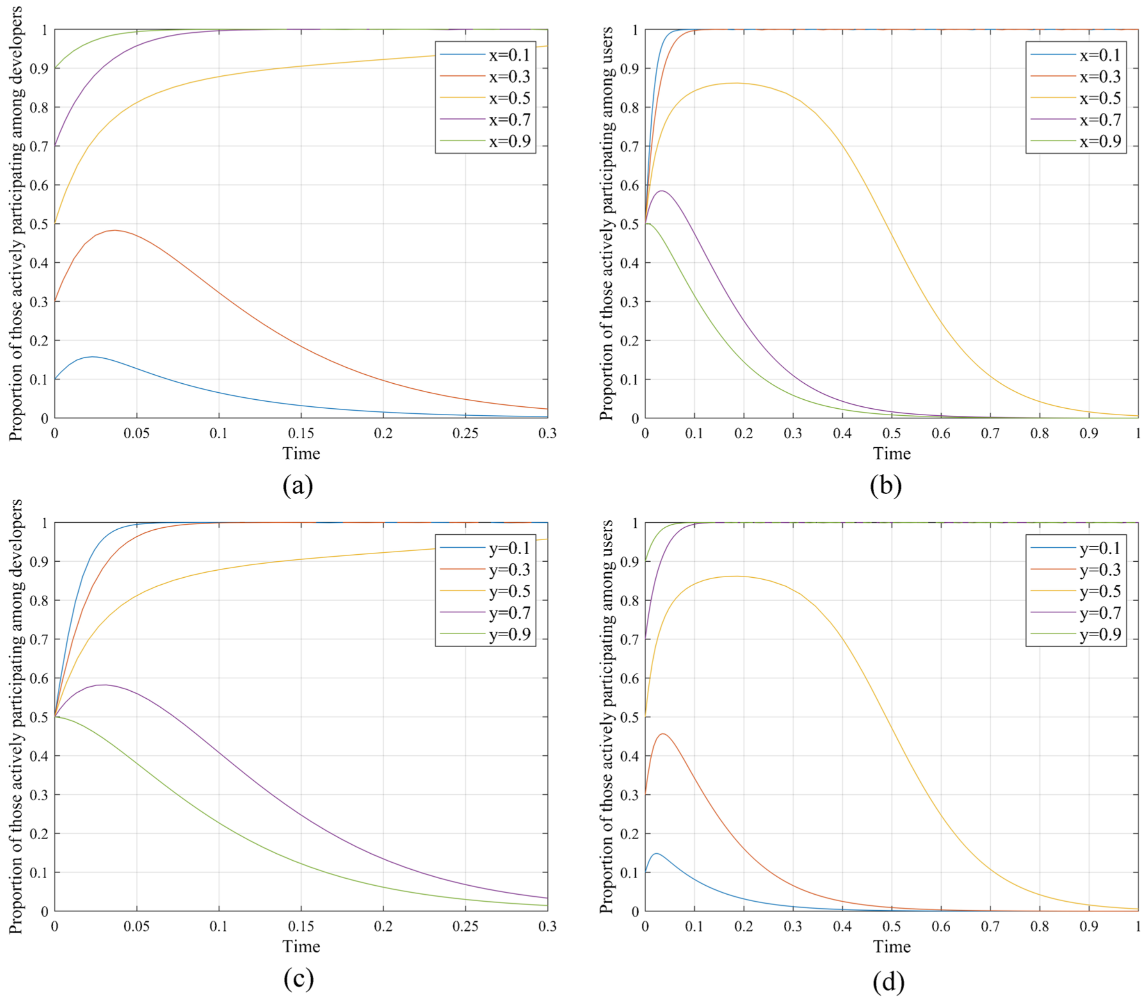

Fig. 1 The effects of the initial value of x on the ESS of developers (**a**) and users (**b**), and the effects of the initial value of y on the ESS of developers **c** and users (**d**). x is the proportion of developers actively co-creating value, and y is the proportion of users positively participating value co-creation

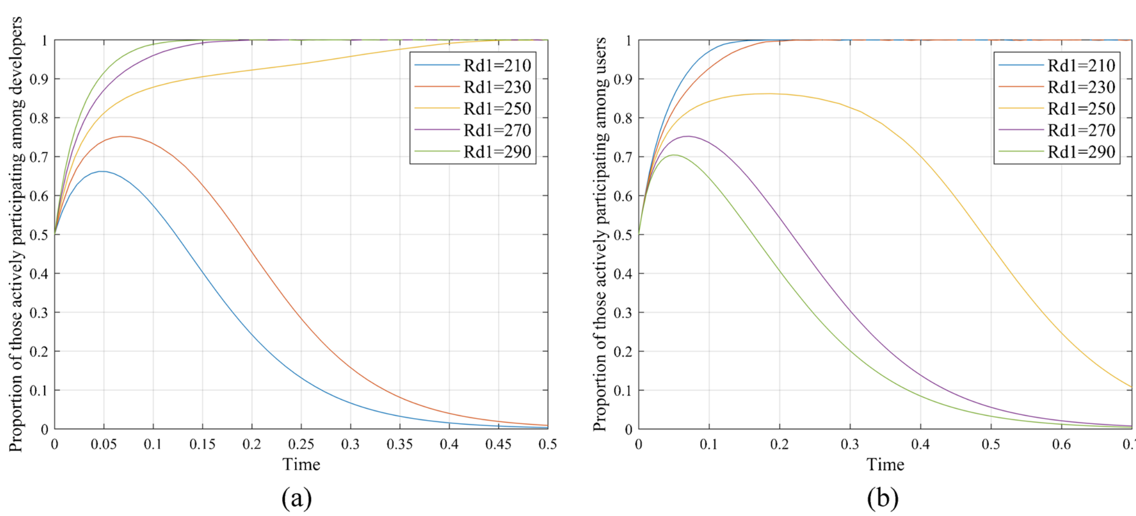

Fig. 2 The effects of R_{d1} on the ESS of developers **a** and users **b**. R_{d1} is the additional benefit of developers adopting the active strategy unilaterally

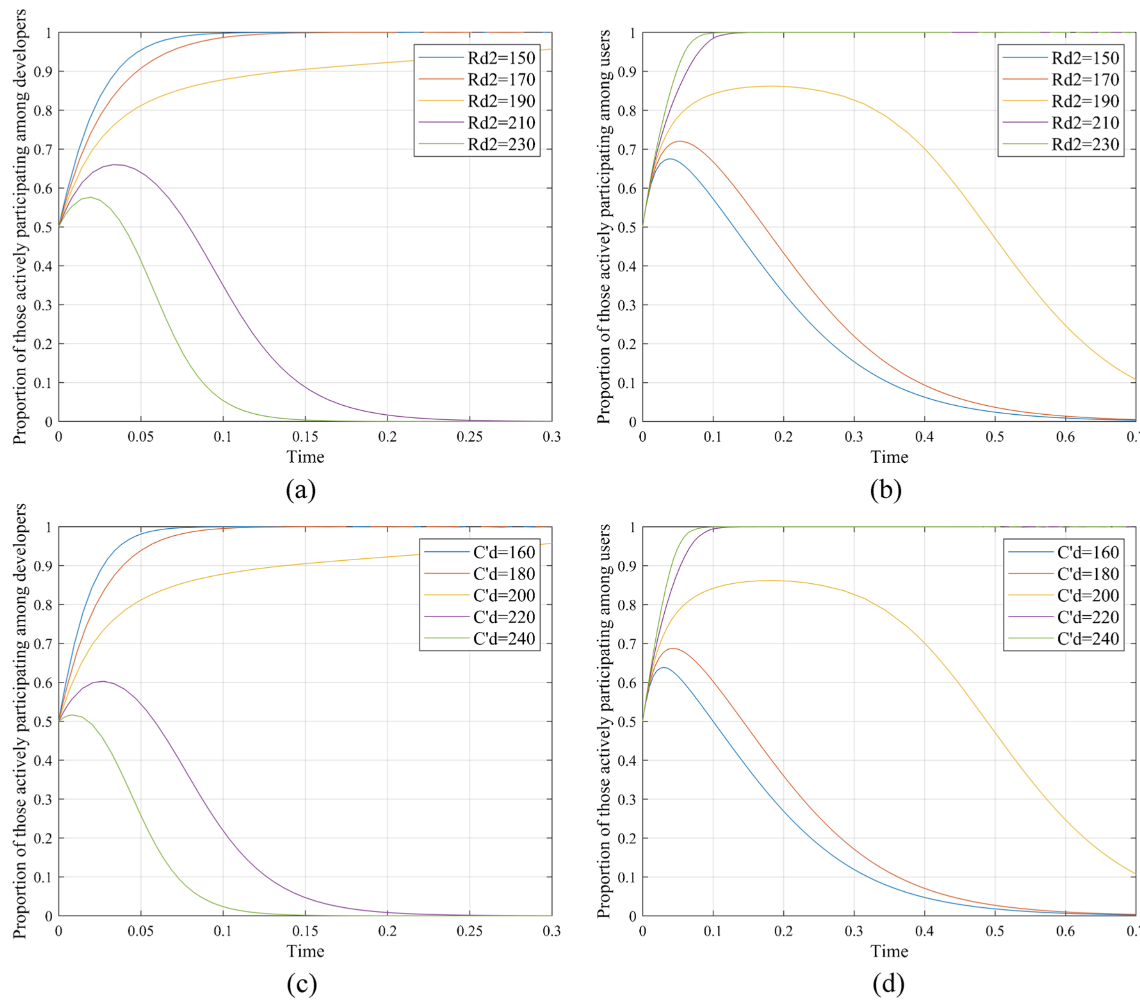

Fig. 3 The effects of R_{d2} on the ESS of developers (**a**) and users (**b**), and the effects of $C_d\prime$ on the ESS of developers (**c**) and users (**d**). R_{d2} is the benefit of developers free riding in value co-creation, and C'_d is the additional cost of developers adopting the active strategy

analysis in "Stability of the main players' strategies" section, so R_{d1} just plays an indirect role in this change.

When other parameters are constant, developers' free-riding benefits R_{d2} are set to different values (150, 170, 190, 210, and 230), while the condition $\Delta R_d + P + F > R_{d2} + C'_d$ turns into $\Delta R_d + P + F < R_{d2} + C'_d$, and as shown in Fig. 3a, b, the strategy evolutionary result changes from $E_3(1,0)$ to $E_2(0,1)$, which verifies the negative influence of R_{d2} on developers' active behavior in value co-creation in "Parameters' influence on the main players' strategy choice" section and is also consistent with the ESS analysis of case (3) and case (1) in "Stability analysis of equilibrium points in the evolutionary game system" section. In addition, according to the stability analysis in "Stability of the main players' strategies" section, the change of users' strategy choice is impacted by that of developers' decision, and the effect of R_{d2} on users' decision-making is indirect. Likewise, the value of additional costs of developers' active value co-creation C'_d is varied at 160, 180, 200, 220, and 240, which have the same effect on the changes of the condition and the ESS, as developers' free-riding benefits R_{d2} do, and the related analyses above are also confirmed in the same way.

The effects of user-related factors on game equilibrium

Figure 4a, b show that when other parameters are constant, the value of additional benefits of users adopting the active strategy unilaterally R_{u1} is set at 180, 190, 200, 210, and 220 with the conditions $\Delta R_d + P + F < R_{d2} + C'_d$ and $\Delta R_u < R_{u2} + C'_u$ of case (1) unchanged, and the ESS becomes $E_3(1,0)$ from $E_2(0,1)$. There are some close resemblances between the effect of R_{u1} and that of R_{d1}. The first is that both of them have a positive correlation with the active

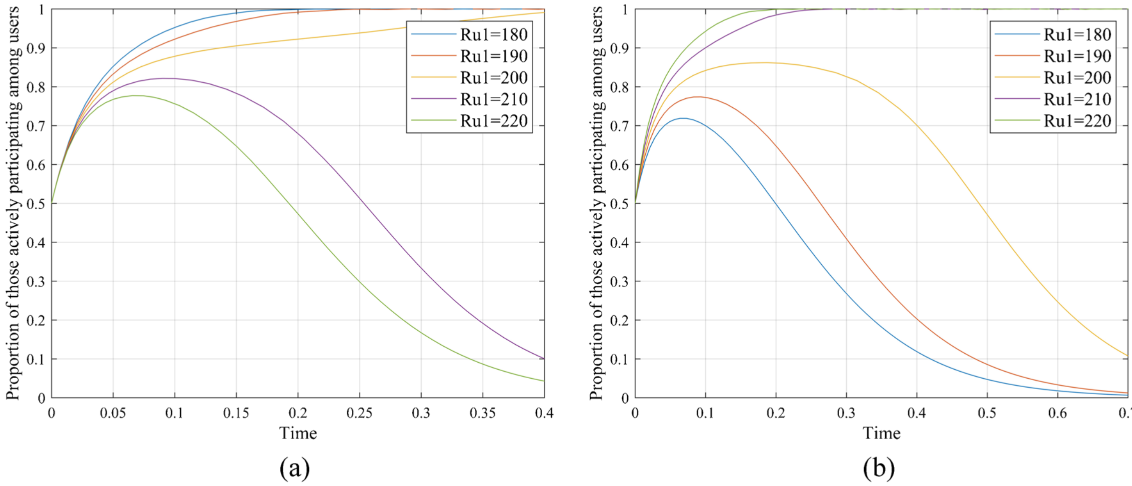

Fig. 4 The effects of R_{u1} on the ESS of developers (**a**) and users (**b**). R_{u1} are the additional benefits of users adopting the active strategy unilaterally

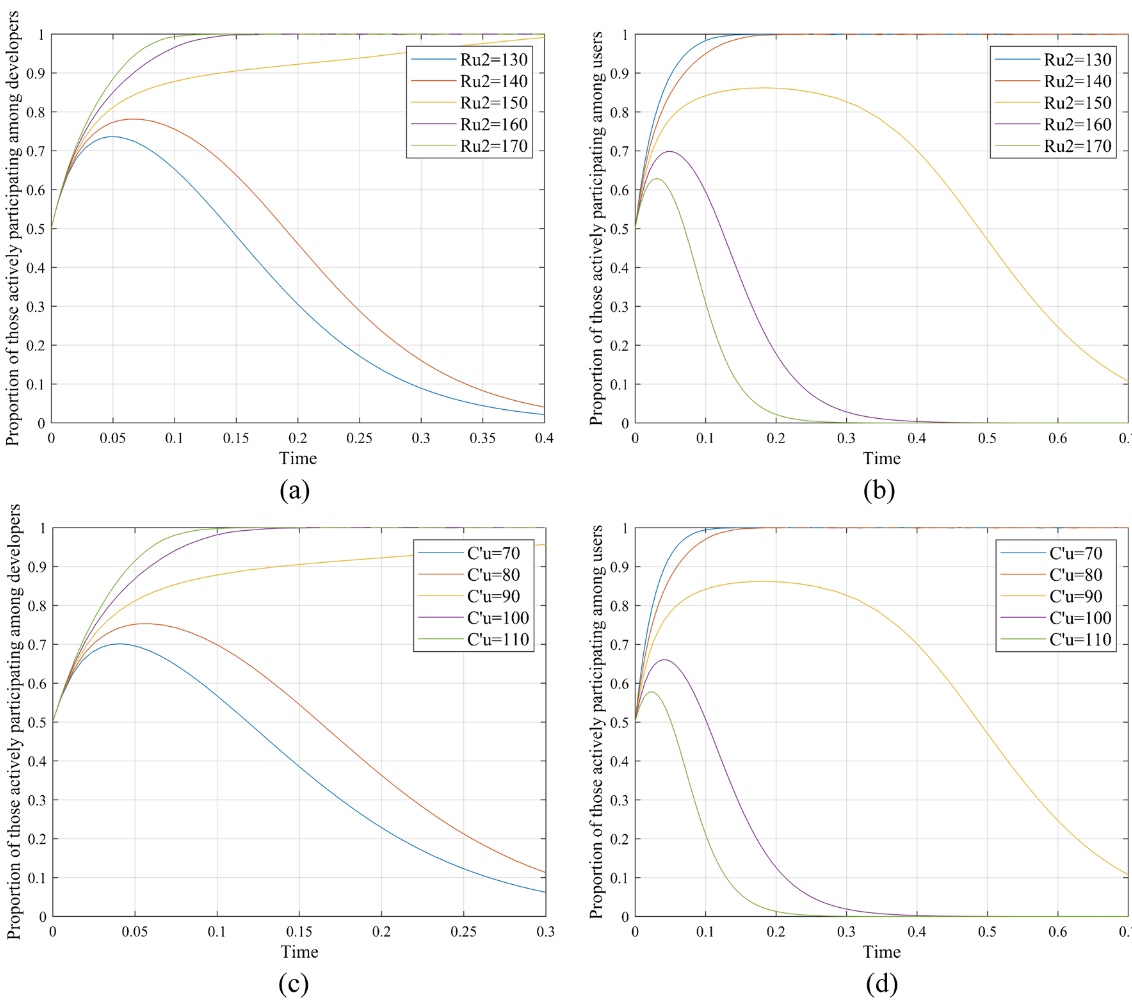

Fig. 5 The effects of R_{u2} on the ESS of developers (**a**) and users (**b**), and the effects of C'_u on the ESS of developers (**c**) and users (**d**). R_{u2} is the benefit of users free riding in value co-creation, and C'_u is the additional cost of users adopting the active strategy

value co-creation of their directly related parties just as the results of the parameters' influence analysis are obtained in "Parameters' influence on the main players' strategy choice" section, and their numerical analysis results are also consistent with the ESS of case (1). The second is that both of these two parameters do not alter the conditions of case (1) but change the ESS, so the numerical analysis of R_{u1} also complements the factors that can transform the ESS in case (1). The third is that they directly influence the strategy choice of their corresponding party, and indirectly impact the behavior of the other party.

Figure 5a, b show that when other parameters are unchanged, users' free-riding benefits R_{u2} are set to different values (130, 140, 150, 160, and 170) while the condition $\Delta R_u > R_{u2} + C'_u$ turns into $\Delta R_u < R_{u2} + C'_u$ with the change of the scenario from case (2) to case (1), and the ESS transforms from $E_2(0,1)$ to $E_3(1,0)$. This confirms the negative impact of R_{u2} on users' active value co-creation in "Parameters' influence on the main players' strategy choice" section and is also consistent with the ESS analysis of case (2) and case (1) in "Stability analysis of equilibrium points in the evolutionary game system" section. Moreover, R_{u2} exerts an indirect influence on developers' value co-creation behavior through the interaction between users' strategy choice and that of developers. Similarly, the value of additional costs of users adopting the active strategy C'_u is set at 70, 80, 90, 100, and 110 with other parameters constant, and the result is just like that of the R_{u2} verification, because these two parameters produce the same effect that they can both change the condition from $\Delta R_u > R_{u2} + C'_u$ to $\Delta R_u < R_{u2} + C'_u$ and turn the ESS, so the related model analyses are also confirmed in the same way.

The effects of ecosystem- and platform leader-related factors on game equilibrium

Figure 6a, b show that the value of the ecosystem synergy benefits obtained by developers ΔR_d varies at 260,

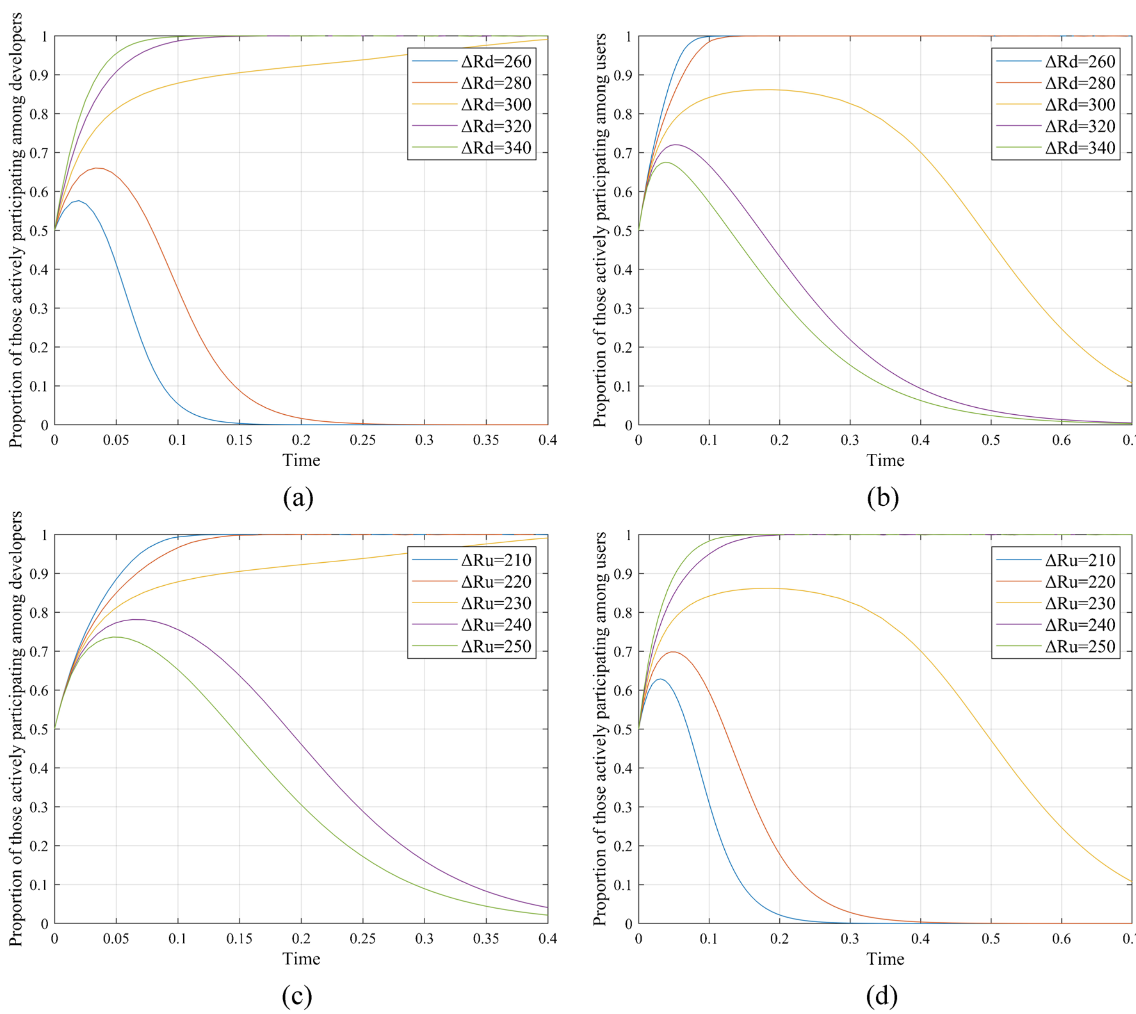

Fig. 6 The effects of ΔR_d on the ESS of developers (**a**) and users (**b**), and the effects of ΔR_u on the ESS of developers (**c**) and users (**d**). When both of the two parties positively co-creating value, ΔR_d is ecosystem synergy benefit enjoyed by developers and ΔR_u is that gained by users

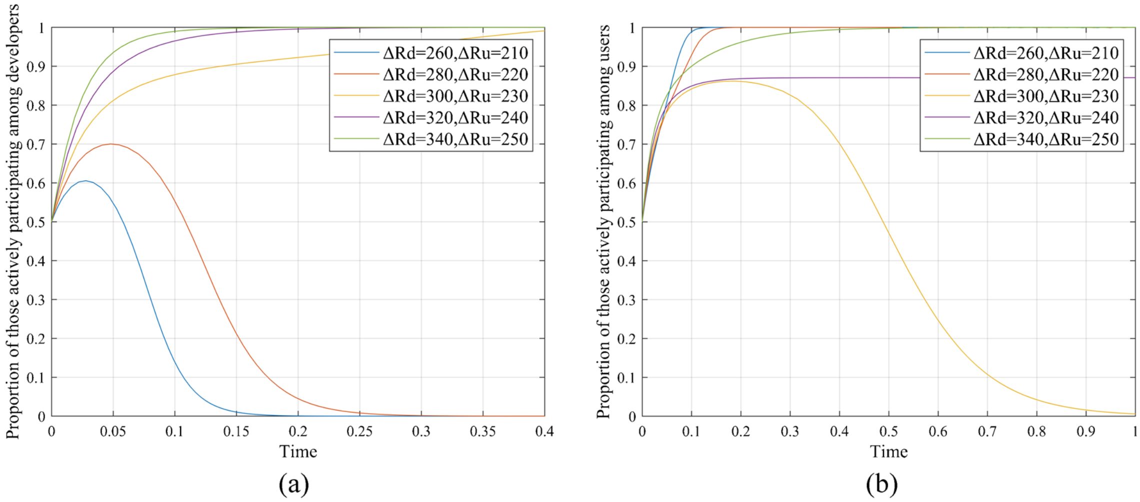

Fig. 7 The combined effects of ΔR_d and ΔR_u on the ESS of developers (**a**) and users (**b**). ΔR_d is ecosystem synergy benefit enjoyed by developers, and ΔR_d is that gained by users, when both of the two parties positively co-creating value

280, 300, 320, and 340 with other parameters unchanged; the ESS turns from $E_2(0,1)$ to $E_3(1,0)$ as the condition $\Delta R_d + P + F < R_{d2} + C'_d$ becomes $\Delta R_d + P + F > R_{d2} + C'_d$ with the scenario from case (1) to case (3), which is consistent with the positive impact of ΔR_d on developers' active participation in value co-creation and the ESS analysis of cases (1) and (3). Similarly, when the value of ecosystem synergy benefits obtained by users ΔR_u is set at 210, 220, 230, 240, and 250 with other parameters constant, the ESS evolves from $E_3(1,0)$ to $E_2(0,1)$ as the condition converts from $\Delta R_u < R_{u2} + C'_u$ to $\Delta R_u > R_{u2} + C'_u$ with the scenario from case (1) to case (2), and the result also matches the analyses of the evolutionary game model like ΔR_d.

In the real world, ecosystem synergy is very likely to increase both of developers and users' benefits at the same time, so ΔR_d and ΔR_u are set at different values at 260, 280, 300, 320, and 340 and 210, 220, 230, 240, and 250, respectively, when other parameters remain unchanged. Figure 7a, b show that as ΔR_d and ΔR_u simultaneously increase, the three stages of ESS transformation are from $E_2(0,1)$ to $E_3(1,0)$ without any change in the conditions ($\Delta R_d + P + F < R_{d2} + C'_d$ and $\Delta R_u < R_{u2} + C'_u$) of case (1), from $E_3(1,0)$ to $E_6\left(1,y'\right)$ with the conditions changing to $\Delta R_d + P + F > R_{d2} + C'_d$ and $\Delta R_u = R_{u2} + C'_u$, and from $E_6\left(1,y'\right)$ to $E_4(1,1)$ with the switch to the conditions ($\Delta R_d + P + F > R_{d2} + C'_d$ and $\Delta R_u > R_{u2} + C'_u$) of case (4), which is also consistent with the ESS analysis of the system in "Stability analysis of equilibrium points in the evolutionary game system" section. Just to be clear, $E_6\left(1,y'\right)$ means that the user population adopt a mixed strategy through continuous evolution, and over 80% of them would actively involve value co-creation while the rest would choose the passive strategy, and this evolutionary result is led by the conditions $\Delta R_d + P + F > R_{d2} + C'_d$ and $\Delta R_u = R_{u2} + C'_u$.

The benefits that developers gain from being featured by platform leaders to reward active value co-creation P are set at different values 0, 15, 30, 45, and 60 when other parameters are constant, and the ESS evolves from $E_2(0,1)$ to $E_3(1,0)$ as shown in Fig. 8a, b. When the loss of the punishment that developers receive from platform dominators due to passive value co-creation F varies at 15, 30, 45, 60, and 75 with other parameters unchanged, the transformation of ESS is quite similar to that in the situation of P varying showed in Fig. 8c, d. These results are consistent with those in the analyses of the evolutionary game model, and users' strategy choice is indirectly influenced by P and F as well.

In summary, the results of numerical analysis confirm some of the main findings from the model analysis above, and three new findings have also been discovered. First, in addition to the factors discussed in the model analysis, the initial strategy choices of developers and users can also influence the evolutionary outcomes in case (1). Second, contrary to the results of the model analysis, it has been further demonstrated that the benefits of developers actively co-creating value unilaterally R_{d1} and those of users' unilateral active involvement R_{u1} can not only positively influence the corresponding party's active strategy choices but also alter the ESS of the system. These influences of these two factors on the ESS of the system were not deduced and were neglected in "Stability analysis of equilibrium points in the evolutionary game system" section. This is because an assumption implicit in the system's ESS analysis is that for both developers and users, the additional costs of active participation are lower than the benefits of unilateral active

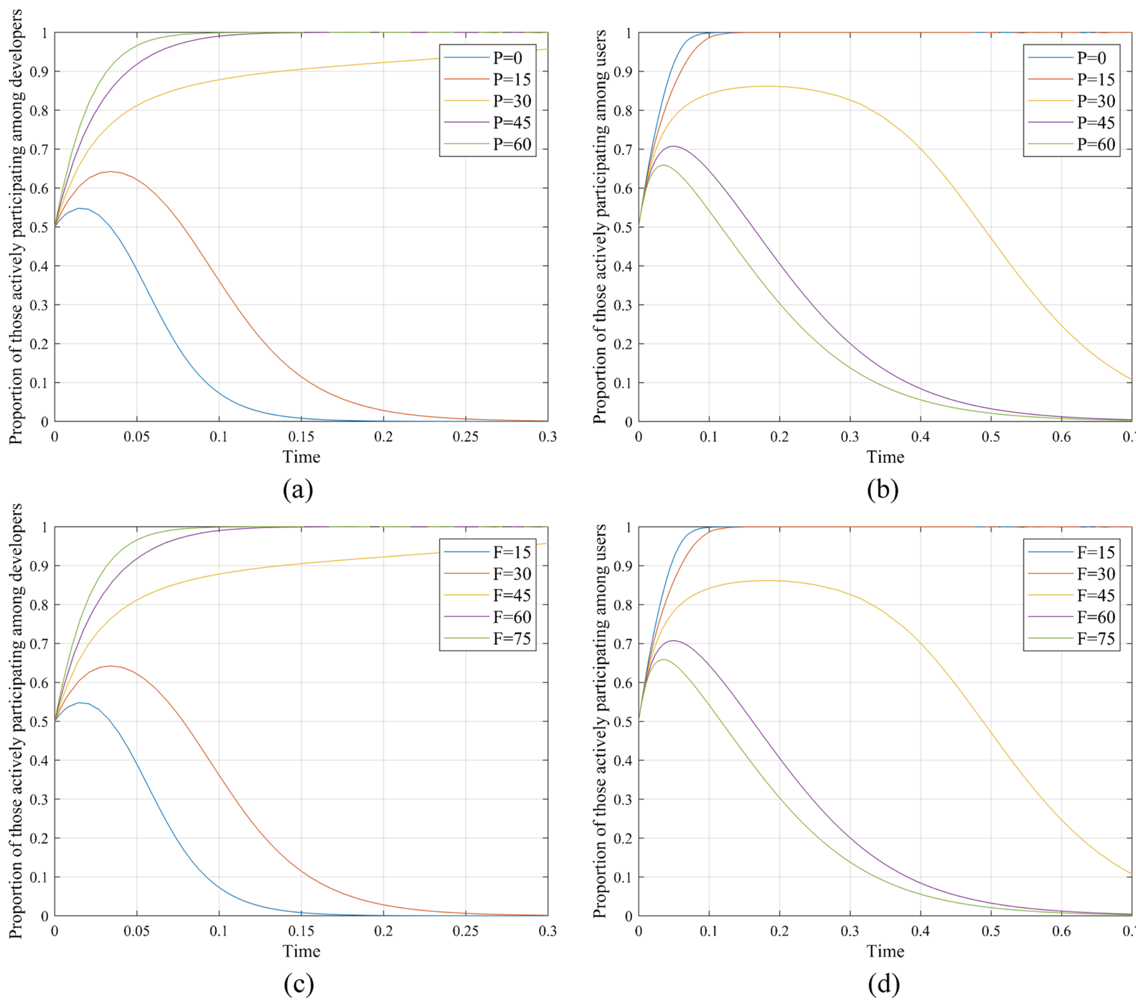

Fig. 8 The effects of P on the ESS of developers (**a**) and users (**b**), and the effects of F on the ESS of developers (**c**) and users (**d**). P is the benefit that developers gain from being featured by platform leaders to reward active value co-creation, and F is a loss of the punishment that developers receive from platform leaders due to passive value co-creation

value co-creation ($C'_d < R_{d1}$ and $C'_u < R_{u1}$). Thus, we find that these two factors directly affect their respective party's decision-making and then indirectly impact the other's choice due to the interaction of the two groups' behavior. Third, the growth of the two factors of ecosystem synergy is analyzed as a complement to the related model analysis. In reality, simultaneous increases in the ecosystem synergy benefits gained by developers and those obtained by users are more common. It has been found that when both developers and users can simultaneously enjoy increasing ecosystem synergy benefits, the ESS will also transform. This is because as these factors grow, the condition determining ESS in case (1) will change from one to the other, and the context will shift from case (1) to other cases. Hence, the ideal scenario, case (4), can be realized through the simultaneous growth in the ecosystem synergy benefits of developers and users.

Discussion and conclusion

Based on the analyses above, we have identified the logic, potential outcomes, and key factors associated with developers and users' value co-creation. Additionally, we propose several managerial implications primarily derived from these findings. First, the underlying logic of the coordination mechanism for value co-creation between developers and users is that they adjust their behavior for mutual benefit based on payoffs. Reciprocity plays a critical role in obtaining value for themselves, and the trade-off between benefits and costs determines the degree of their participation.

Second, while the specific values of these factors may not always be readily available in the real world, the findings do provide insights for understanding the reasons behind developers' and users' innovative interactive behavior. In real-life scenarios, it is common for developers to actively participate in value co-creation while users do not. Based on the findings regarding parameter influence in "Parameters' influence on the main players' strategy choice" section, one possible reason for this disparity could be that it requires a significant amount of time and effort for users to propose suggestions for improvement. This suggests that the costs associated with active value co-creation by users are quite high. Additionally, developers' strategy choices may be influenced by users' behavior. Furthermore, according to the findings on systems' ESS in "Stability analysis of equilibrium points in the evolutionary game system" section, another explanation could be that, for users, the impact of ecosystem synergism is lower compared to the advantages they gain from free-riding and the extra effort required to choose a positive strategy. In other words, ecosystem synergism may not exert a significant enough influence in such situations.

Third, according to the findings, developers and platform leaders should take the initiative in implementing measures to encourage value co-creation. Following comprehensive analysis, we have determined that, in order to enhance users' participation, developers can reduce the additional costs associated with users adopting an active strategy. This can be achieved by using questionnaires to provide users with hints aimed at reducing the difficulty of expressing their user experience and offering suggestions. At times, multiple factors can be altered simultaneously to stimulate active involvement. Moreover, while changing certain factors may promote active participation, it can be challenging to implement measures, particularly when it comes to addressing the issue of free-riding benefits for both developers and users.

Fourth, to achieve the ideal situation where both developers and users actively co-create value, our research suggests that the most effective approach is to simultaneously increase the ecosystem synergy benefits for both groups. It may prove challenging for only platform leaders or developers to take actions to achieve this goal, as it is more likely to depend on the overall ecosystem's efficiency and growth. Despite the difficulty of achieving this, raising ecosystem synergy benefits for both parties would be a worthwhile endeavor, as it can foster the long-term development of robust digital innovation ecosystems.

In conclusion, to enhance our understanding of complementary innovation within digital innovation ecosystems, it is crucial to grasp the coordination mechanism of value co-creation between developers and users. In this study, we introduced S-D logic and found that the underlying logic of their interaction is mutual benefit. Employing an evolutionary game approach, we discovered that they coordinate their value co-creation behavior by carefully considering benefits and costs. We also analyzed the key factors and derived potential outcomes of their interactive behavior. Finally, we discussed the managerial implications of our findings. Furthermore, in future research, it would be valuable to explore measures for increasing ecosystem synergy benefits in more depth. Additionally, alternative perspectives on explaining their interaction could be explored to achieve a comprehensive understanding.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12525-023-00685-w.

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