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Numerical simulation and governance framework for multi stakeholder symbiotic evolution in digital innovation ecosystems

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The symbiotic evolution of stakeholders within digital innovation ecosystems (DIES) is crucial for achieving ecological sustainability. Thus, we integrate the Lotka-Volterra symbiotic evolution model into digital DIES research by constructing both three-actor and four-actor dynamic interaction frameworks and simulating multiple symbiotic evolution scenarios. This study indicates that: (1) The principal actors in DIES are core digital enterprises, innovation partners, digital product users, and digital platforms, with their interdependencies governed by symbiotic coefficients. (2) Introducing the digital platform into the four-actor symbiotic model significantly increases the system's maximum carrying capacity and equilibrium scale. Parasitic symbiosis and commensal symbiosis may temporarily enhance individual actors' competitiveness, but they undermine the overall stability of cooperation, whereas mutually beneficial symbiosis provides the optimal pattern for system evolution. (3) Building on these insights, we propose a governance framework centered on resource balancing, value sharing, and trust cooperation, and demonstrate its practical applicability through an Alibaba Cloud case study. This work not only broadens the scope of symbiosis theory within a digital-economy context but also provides actionable guidance for designing efficient, resilient DIES.

Keywords Digital innovation ecosystem, Lotka–Volterra model, Symbiotic evolution, Governance mechanism

Digital technologies are reshaping the global innovation paradigm at an unprecedented pace. As big-data algorithms drive product iteration, cloud computing platforms dissolve organizational boundaries, and blockchain restores collaborative trust, the era of siloed "closed-door" innovation is no longer viable. In its place, DIES characterized by multi-stakeholder collaboration and value co-creation have emerged[1–4]. Within these ecosystems, core digital enterprises, innovation partners, user communities, and digital platforms interconnect through data flows, shared technologies, and integrated application scenarios to form a network where innovation itself becomes interaction. The Digital China Development Report 2024, published by the National Data Administration, reports that over the past three years the Digital China Development Index has grown steadily by more than 10% annually. In 2024 data production reached 41.06 zettabytes, a 25% increase year-on-year, accompanied by simultaneous gains in both the quantity and quality of high-value datasets. This momentum validates the strategic foresight of the Fourteenth Five-Year Plan for Digital Economy Development, which calls for accelerating digital industrialization and positions digital innovation as the engine of industrial upgrading and international competitiveness. Against this backdrop, enterprises no longer confine their value creation to internal R&D, they collaborate with multiple stakeholders within DIES to achieve shared value creation[5]. Stakeholders must establish varying degrees of interdependence to secure survival in a continuously iterating ecosystem[6]. Digital platforms empower this interdependence by enabling both internal and external linkages and integrating collaborative processes into open innovation[7]. These dynamic exchanges and tight integrations among participants drive iterative innovation[8–10] and foster sustained value co-creation[11].

However, the complexity of multi-stakeholder interactions in DIES has given rise to new development challenges. While digitalization profoundly alters how resources are mobilized, it also intensifies resource competition[12]. Issues such as platform monopolies and the absence of effective transaction mechanisms have emerged, seriously harming consumers and other market participants, creating information asymmetries and impeding the diffusion of innovation[13]. In this context, understanding how diverse "economic species" can coexist

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and achieve balanced growth within digital ecosystems has become a central concern for both governments and enterprise operators[14]. Therefore, the research questions of this study are: (1) How is the DIES structured, and what are the internal actors? (2) What are the symbiotic relationships and patterns among subjects at different stages? What symbiotic evolution patterns are observed among the actors? (3) How much does the four-actor symbiotic pattern improve ecosystem scale compared with a three-actor configuration, and what role does the digital platform play? (4) How to develop effective governance plans for potential risks associated with different symbiotic models?

This study draws on symbiosis theory and the Lotka-Volterra model to examine symbiotic relationships and evolutionary mechanisms within DIES. The contributions of this study are: (1) A conceptual model of the DIES is constructed. This clarifies the elements that constitute the DIES. (2) Introduce both three-actor and four-actor Lotka-Volterra models to construct a symbiotic evolution framework, exploring the interactive dynamics among multiple stakeholders and filling the gap in research on the digital platform as a fourth actor. (3) Propose a governance framework to guide the evolution of symbiotic patterns among ecosystem participants and demonstrate its practical applicability through a case study of Alibaba's digital ecosystem, with the aim of steering DIES toward mutually beneficial symbiosis and sustainable evolution.

Literature review

Innovation ecosystem

Moore[15] was the first to introduce the concept of a business ecosystem, emphasizing that a firm and its partners, suppliers, customers and other stakeholders form an organic whole that undergoes symbiotic evolution. Subsequent scholars expanded this perspective to innovation ecosystems[16]highlighting the cooperation and competition among multiple actors. In a digital context, firms no longer rely solely on internal capabilities for innovation but achieve technological breakthroughs through cross-organizational collaboration[17,18]. Academic research on innovation ecosystems has focused on three dimensions: types and structures, dynamic evolution, and strategy and business models. From the standpoint of types and structures, scholars have examined the composition and operational mechanisms at the firm, industry, regional, and national levels. Core firms enhance system creativity by integrating internal and external resources, building innovation platforms, and defining participation and governance rules, thereby promoting virtuous cycles[19]. Fransman proposed an information and communication technology innovation ecosystem composed of five elements: industrial systems, hardware, software, innovative talent, and the external environment[20]. Fukuda and Watanabe[21] analyzed U.S. and Japanese science and technology policies and identified four principles of national innovation ecosystems: substitution for sustainable development, co-evolution for self-replication, organizational inertia coupled with competitive stress-induced learning, and heterogeneity-driven collaboration. Regarding dynamic evolution, participants emerge and interact over time, with social networks and value-chain interactions driving value-chain reconstruction[22]. These interactions significantly enhance ecosystem innovation performance and value creation[23,24]. On the strategy and business-model front, nurturing and restructuring the system is essential for sustaining competitive advantage. Complementary technologies can increase commercial value but also introduce potential costs, requiring a balance between opportunities for technological complementarity and the costs of managing interdependence[25]. Yet, traditional frameworks struggle to explain the novel collaborative effects and governance challenges introduced by the digital wave's emphasis on data resources and platform hubs[26].

Symbiosis theory

Symbiosis theory offers a foundational lens for understanding multi-actor interaction mechanisms. Caullery[27] defined symbiosis as the links among populations with different interests, distinguishing independent, parasitic symbiosis, commensal symbiosis, and mutually beneficial symbiosis relationships. Scott[28] characterized symbiosis as an equilibrium condition among two or more interdependent populations. Chen et al.[29] examined the game dynamics of knowledge sharing and resource collaboration among three principal actors in a DIES. Whereas traditional Logistic and one-dimensional Logistic models describe the growth trajectory of a single population[30]the Lotka-Volterra competitive-symbiosis model extends this analysis to multiple populations competing for finite resources. This model has been widely applied to study dynamic interactions in knowledge transfer[31]technology innovation[32]and evolutionary competition[33]. In this study, we innovate on existing work by applying the Lotka-Volterra model to uncover the symbiotic evolution patterns among multiple actors in DIES. By contrasting the evolutionary trajectories of three-actor and four-actor configurations, we reveal how mutualistic symbiosis enhances overall system efficiency, thereby offering a mathematical foundation for ecosystem governance.

DIES

A DIES integrates digital innovation with innovation-ecosystem principles[34]. The penetration of digital technologies has driven innovation ecosystems toward data-driven, networked structures. Data resource flows, the central role of digital platforms, and nonlinear innovation pathways enable breakthroughs in three dimensions of traditional innovation ecosystems. At the element level, data resources replace physical inputs as the primary carrier of value creation, reshaping innovation pathways and enhancing actors' ability to respond dynamically to their environment[35]. Gupta et al.[36] further revealed that coordinated data flows: through discovery, sharing, and allocation, activate the complementary strengths of heterogeneous actors, driving systemic value emergence and underscoring data as a critical strategic asset for ecosystem evolution. At the architectural level, digital platform ecosystems leverage digital technologies and control over multiple actors' digital resources to foster connections and value creation under network effects, overcoming the spatial and temporal limits of linear innovation processes[37]. In the Xiaomi ecosystem example, strategic interactions between the platform owner and its complementors show that coordinated resource allocation, system integration and scenario alignment drive the symbiotic evolution of the platform ecosystem[38]. At the actor level, unlimited connectivity and intelligent analytics empower diverse roles based on function, activity, and structural position, collectively driving value creation[39]. Research on actor relationships in DIES has primarily examined value co-creation and stakeholder coopetition. Digitalization reshapes co-creation logic, shifting innovation from siloed firm-level efforts to interactions and sharing within heterogeneous ecosystems[40]. To achieve value co-creation, it is essential to dynamically optimise and coordinate the technology innovation platform, the scientific research innovation layer and the support layer. Differential game theory has been employed to build decision-making models that respond to the evolving dynamics of digital technology innovation and resource integration[41]. However, asymmetries in resource flows and asymmetric symbiotic relationships among actors limit the performance of DIES, underscoring the need to identify pathways for multi-party collaboration[42]. In addition, foundational research in sociophysics and the statistical physics of human cooperation demonstrates that individual and collective behaviours can be represented by statistical physics models. These models show how cooperation can transcend classical game-theoretic constraints such as the prisoner's dilemma across diverse network structures and strategy spaces, thereby realising synergy at the group level[43,44]. This perspective provides valuable guidance for exploring symbiotic cooperation mechanisms among multiple stakeholders in DIES, especially concerning multi-stakeholder symbiosis and resource allocation.

In summary, research on the interrelationships within DIES from a symbiotic evolution perspective remains limited. Most studies concentrate on bilateral interactions led by a core enterprise, examining partial coopetition and value co-creation among select actors[45,46]. A comprehensive, systematic deconstruction of the multiple stakeholders in DIES is still lacking, particularly regarding the digital platform's role as an ecosystem hub and the systematic analysis of its technology spillover effects on expanding the system's carrying capacity. Moreover, there remains a paucity of research on differentiated, dynamic governance strategies tailored to the various symbiotic patterns identified through simulation analyses. To address these gaps, this study develops a four-actor symbiotic evolution model to examine mechanisms of symbiotic evolution among multiple populations in DIES. We simulate symbiotic evolution under various patterns, identify inherent limitations, and design corresponding governance mechanisms. We then conduct an explanatory case study of Alibaba's digital ecosystem to illustrate practical implications and offer pathways for stakeholders to achieve sustainable.

Research hypothesis and model construction

Concept model

Digital technologies have deeply permeated every aspect of innovation, driving ecosystems away from linear collaboration toward networked symbiotic evolution. In DIES, multiple actor groups coexist, these actors integrate technologies, share resources and coordinate application scenarios to achieve value co-creation. Their complex symbiotic relationships not only enhance innovation performance but also give rise to governance challenges such as imbalanced resource allocation and coordination friction. Appropriate system design and management can prevent harmful cascading effects and foster beneficial self-organization within the ecosystem[47].

We select the Lotka-Volterra model because it directly captures the complex dynamic interactions and evolutionary relationships among multiple participants in DIES through nonlinear differential Eq.[48]. In contrast, agent-based models can reflect firm heterogeneity and decision rules but demand extensive micro-level empirical data and parameter calibration, requirements that are difficult to meet in innovation-ecosystem research. Furthermore, as interaction complexity grows, the scalability and interpretability of AMB models decline sharply when analyzing global stability[49]. Network analysis methods excel at uncovering ecosystem topology and actor connectivity but struggle to represent nonlinear evolution and critical transitions over time. The Lotka-Volterra model combines clear parameter interpretability, effective visualization of nonlinear dynamics, and rigorous analysis of critical conditions, making it the preferred tool for describing the intricate symbiotic interactions among ecosystem actors.

A DIES comprises symbiotic units, symbiotic patterns, and the symbiotic environment. The primary symbiotic units consist of core digital enterprises, innovation partners, digital product users, and the digital platform. Core digital enterprises serve as drivers of the ecosystem, they are typically industry leaders or technology giants that spearhead digital innovation activities and include both digitally enabled firms and traditionally digitalized enterprises. Innovation partners act as participants, encompassing raw-material suppliers, financial institutions, government agencies, universities, and research institutes that furnish various resources and R&D support for digital innovation. Digital product users function as value co-creators, and their needs and feedback are pivotal to driving ecosystem innovation. The digital platform serves as an enabling infrastructure, providing the technical substrate that supports actor interaction, resource flows, and value co-creation. Interactions within this symbiotic environment generate new symbiotic energy through innovation behaviors such as value creation and capture, which then circulate among actors to sustain the ecosystem's long-term development. A conceptual illustration of this model is presented in Fig. 1.

Furthermore, various actors within DIES exhibit independent relationships as well as parasitic symbiosis, commensal symbiosis and mutually beneficial symbiosis. To tackle the unique challenges associated with each pattern, we develop an initial framework that maps symbiotic patterns to corresponding governance mechanisms, as illustrated in Fig. 2. The framework rests on the premise that targeted governance designs can remediate the intrinsic weaknesses of each symbiotic pattern and guide the ecosystem's progress toward sustainable collaborative evolution.

As digitalization progresses, competitive and cooperative symbiosis has become the prevailing evolutionary trend. The innovation-driven growth of the core digital enterprise population and other populations conforms to the logistic growth law, as expressed in Eq. (1). The logistic growth curve of symbiotic evolution appears in Fig. 3.

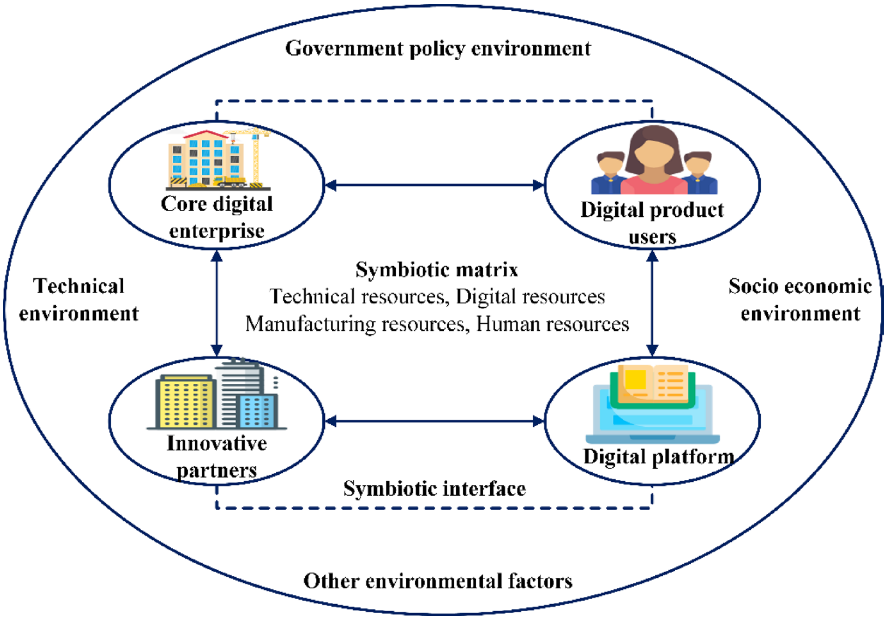


Fig. 1. Conceptual model of the composition of actors in the DIES from a symbiotic perspective.

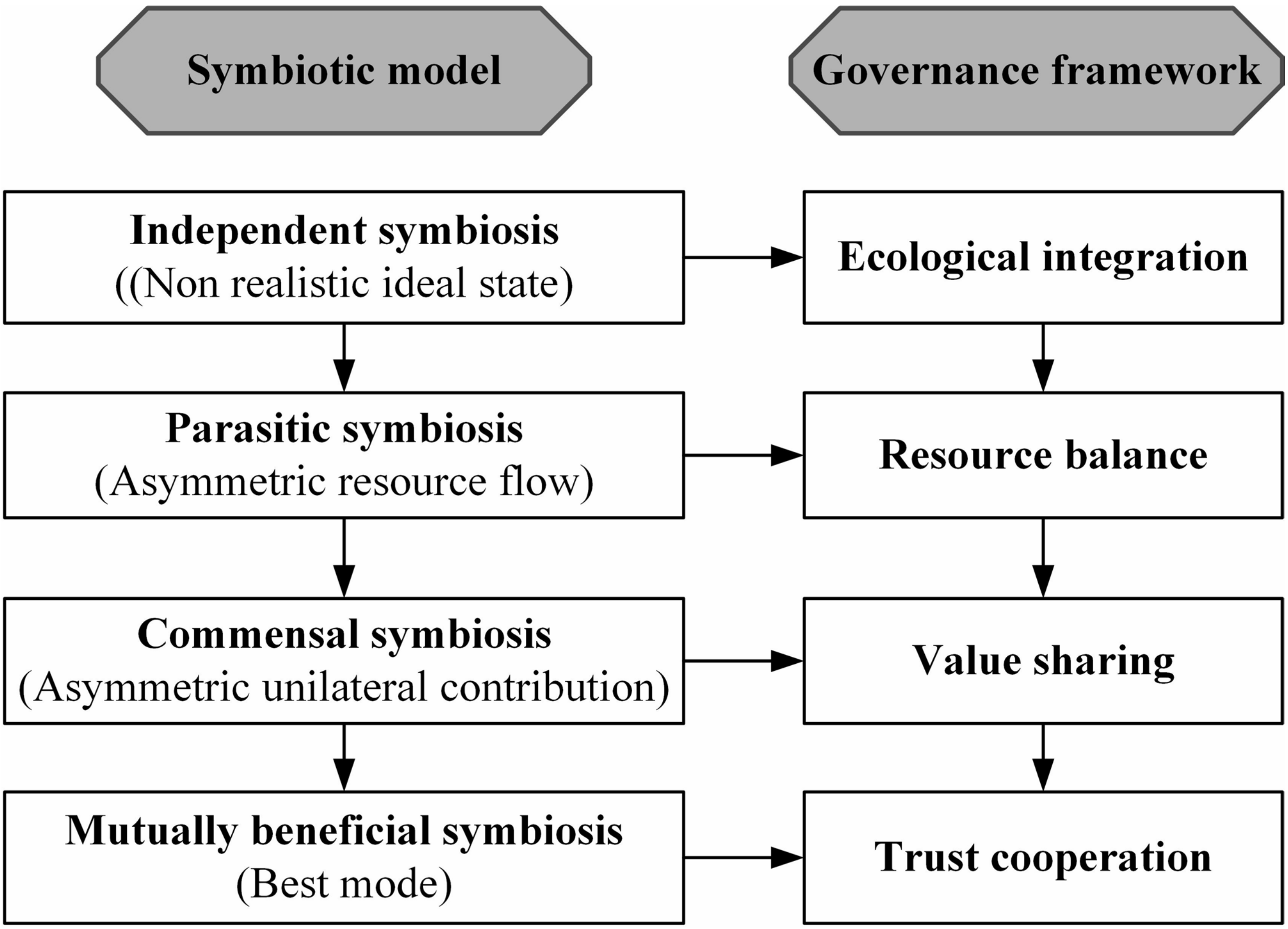


Fig. 2. Mapping framework of symbiotic patterns to governance mechanisms in DIES.

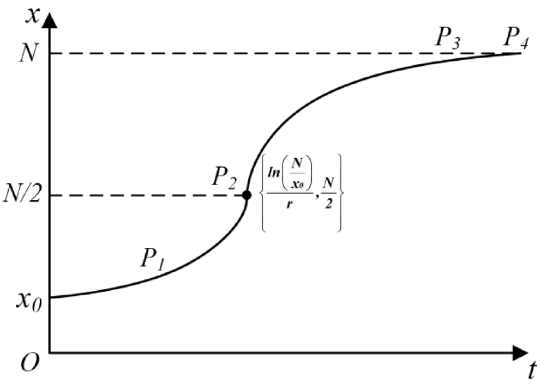


Fig. 3. Logistic growth curve of symbiotic populations in DIES.

$$\frac{dx(t)}{dt} = kx(1 - \frac{x}{N}) \tag{1}$$

In the equation $x(t)$ denotes the population size at time t, k represents the growth rate of the symbiotic actor, N is the maximum population capacity, and $1\text{-}x/N$ is the system's resource limitation term, indicating the relative distance of the population from the ecosystem's maximum carrying capacity.

Research hypothesis

To simulate the complex competition and cooperation among multiple actors within a DIES, this study extends the Lotka-Volterra model with a set of hypotheses intended to quantify resource constraints, intrinsic growth rates and collaborative innovation interactions. We denote the population densities of core digital enterprises, innovation partners, digital product users and digital platforms by x_1, x_2, x_3 and x_4; their natural growth rates by k_1, k_2, k_3 and k_4; and their maximum carrying capacities by N_1, N_2, N_3 and N_4。 .

We propose the following assumptions.

Assumption 1 Within a DIES, core digital enterprises, innovation partners, digital product users and digital platforms constitute the key actors driving digital innovation. The growth of each population is limited by resources, environmental conditions and institutional arrangements. Their growth follows the logistic law, ceasing once marginal output equals marginal input.

Assumption 2 According to symbiosis theory, interactions among populations are represented by symbiotic coefficients that capture cooperative, competitive or parasitic symbiosis[50]. A positive coefficient indicates a beneficial impact of population j on population i, while a negative coefficient signifies a detrimental effect.

Assumption 3 Each actor has an inherent growth capacity determined by its intrinsic attributes under ideal conditions, such as research efficiency for core enterprises or network effects for platforms. We therefore adopt a static equilibrium perspective, keeping natural growth rates constant and represented by the term $k_i x_i$ in the model.

Assumption 4 In line with the ecological principle of competitive exclusion[51]resource competition intensifies as population densities rise. We introduce the factor $(1\text{-}x_i/N_i)$ to model resource limitation[52]. This factor, together with the symbiotic coefficient α_{ij}, constitutes the core moderating term of the model, reflecting the dual impact of "resource constraints + subject interaction".

Different symbiotic patterns arise from the values of the symbiotic coefficients, as summarized in Table 1. In this notation, α_{ij} denotes the effect of population j on population i. To focus on the essential impacts of each pattern and the corresponding governance responses, we simplify the model by assuming constant growth rates and carrying capacities. Future work may incorporate more complex parameter dynamics.

Range of values	Symbiotic patterns	Feature analysis
$\alpha_{ab} = \alpha_{ba} = 0$	Independent symbiosis	The four digital innovation groups develop independently without mutual interference.
$\alpha_{ab}\alpha_{ba} < 0$	Parasitic symbiosis	A positive symbiotic coefficient indicates a beneficiary actor, while a negative coefficient indicates a disadvantaged actor.
$\alpha_{ab} > 0,\ \alpha_{ba} = 0$	Commensal symbiosis	A positive symbiotic coefficient indicates a beneficiary actor, whereas a coefficient of zero denotes a neutral actor.
$\alpha_{ab} > 0, \alpha_{ba} > 0$	Mutualistic symbiosis	All four digital innovation groups benefit.

Table 1. Symbiotic evolution patterns among populations in DIES.Note: Among them, a, $b \in [1,2,3,4]$, $a \neq b$.

Model construction

Construction of the three-actor symbiotic evolution model for the DIES

This section focuses on the populations of core digital enterprises, innovation partners and digital users within the DIES, examining how their interactive behaviors during the digital innovation process affect population scale and the symbiotic environment. Based on the Lotka-Volterra competitive symbiosis model, the symbiotic evolution of the DIES can be expressed as follows:

$$\begin{cases} \frac{dx_1(t)}{dt} = k_1x_1\left(1-\frac{x_1}{N_1}+\alpha_{12}\frac{x_2}{N_2}+\alpha_{13}\frac{x_3}{N_3}\right), & x_1(0)=x_{10} \\ \frac{dx_2(t)}{dt} = k_2x_2\left(1-\frac{x_2}{N_2}+\alpha_{21}\frac{x_1}{N_1}+\alpha_{23}\frac{x_3}{N_3}\right), & x_2(0)=x_{20} \\ \frac{dx_3(t)}{dt} = k_3x_3\left(1-\frac{x_3}{N_3}+\alpha_{31}\frac{x_1}{N_1}+\alpha_{32}\frac{x_2}{N_2}\right), & x_3(0)=x_{30} \end{cases} \tag{2}$$

In this formulation, k_1x_1, k_2x_2 and k_3x_3 represent the intrinsic growth trends of the core digital enterprise population, the innovation partner population and the digital user population, respectively. The ratios x_1/N_1, x_2/N_2 and x_3/N_3 denote each population's size relative to its maximum capacity. The terms (1-x_1/N_1), (1-x_2/N_2) and (1-x_3/N_3) capture inhibitory effects arising from environmental constraints, which act to suppress natural growth rates. The parameter α_{ij} is the symbiotic coefficient quantifying the impact of actor *j* on actor *i*. At equilibrium, the conditions $dx_1(t)/dt=0$, $dx_2(t)/dt=0$ and $dx_3(t)/dt=0$, must be satisfied, yielding eight equilibrium points: $E_1(0,0,0)$, $E_2(0,0,N_3)$, $E_3(0,N_2,0)$, $E_4(N_1,0,0)$, $E_5=\left(0,\ \frac{N_2(1+\alpha_{23})}{1-\alpha_{23}\alpha_{32}},\ \frac{N_3(1+\alpha_{32})}{1-\alpha_{23}\alpha_{32}}\right)$, $E_6=\left(\frac{N_1(1+\alpha_{13})}{1-\alpha_{13}\alpha_{31}},0,\frac{N_3(1+\alpha_{31})}{1-\alpha_{13}\alpha_{31}}\right)$, $E_7=\left(\frac{N_1(1+\alpha_{12})}{1-\alpha_{12}\alpha_{21}},\ \frac{N_2(1+\alpha_{21})}{1-\alpha_{12}\alpha_{21}},\ 0\right)$, $E_8(x_1^*,x_2^*,x_3^*)$, where the expressions for x_1^*,x_2^* and x_3^* are given in Eq. (3).

$$\begin{cases} x_1^* = \frac{N_1(-1+\alpha_{23}\alpha_{32}-\alpha_{12}-\alpha_{13}\alpha_{32}-\alpha_{13}-\alpha_{12}\alpha_{23})}{-1+\alpha_{13}\alpha_{21}\alpha_{32}+\alpha_{12}\alpha_{23}\alpha_{31}+\alpha_{13}\alpha_{31}+\alpha_{23}\alpha_{32}+\alpha_{12}\alpha_{21}} \\ x_2^* = \frac{N_2(-1+\alpha_{13}\alpha_{31}-\alpha_{21}-\alpha_{21}\alpha_{13}-\alpha_{23}-\alpha_{23}\alpha_{31})}{-1+\alpha_{13}\alpha_{21}\alpha_{32}+\alpha_{12}\alpha_{23}\alpha_{31}+\alpha_{13}\alpha_{31}+\alpha_{23}\alpha_{32}+\alpha_{12}\alpha_{21}} \\ x_3^* = \frac{N_3(-1+\alpha_{12}\alpha_{21}-\alpha_{31}-\alpha_{31}\alpha_{12}-\alpha_{32}-\alpha_{32}\alpha_{21})}{-1+\alpha_{13}\alpha_{21}\alpha_{32}+\alpha_{12}\alpha_{23}\alpha_{31}+\alpha_{13}\alpha_{31}+\alpha_{23}\alpha_{32}+\alpha_{12}\alpha_{21}} \end{cases} \tag{3}$$

To analyze model stability, we derive the Jacobian matrix of the three actor symbiotic evolution model as follows:

$$J=\begin{bmatrix} k_1\left(1-\frac{2x_1}{N_1}+\alpha_{12}\frac{x_2}{N_2}+\alpha_{13}\frac{x_3}{N_3}\right) & k_1\alpha_{12}\frac{x_1}{N_2} & k_1\alpha_{13}\frac{x_1}{N_3} \\ k_2\alpha_{21}\frac{x_2}{N_1} & k_2\left(1-\frac{2x_2}{N_2}+\alpha_{21}\frac{x_1}{N_1}+\alpha_{23}\frac{x_3}{N_3}\right) & k_2\alpha_{23}\frac{x_2}{N_3} \\ k_3\alpha_{31}\frac{x_3}{N_1} & k_3\alpha_{32}\frac{x_3}{N_2} & k_3\left(1-\frac{2x_3}{N_3}+\alpha_{31}\frac{x_1}{N_1}+\alpha_{32}\frac{x_2}{N_2}\right) \end{bmatrix} \tag{4}$$

The Jacobian matrix is a fundamental tool for evaluating the stability of equilibrium points. If the Jacobian matrix satisfies both the conditions of $|J|>0$ and $Tr(J)<0$, it serves as the asymptotic stability equilibrium point.

Construction of the four-actor symbiotic evolution model for the DIES

Digital platforms represent an emerging force among diverse innovators in the digital-economy era, offering expansive network space and abundant resources that support innovation activities. These platforms integrate innovation resources from multiple parties, transcend geographical and organizational boundaries, and facilitate communication and collaboration among ecosystem actors. To investigate how the introduction of the digital platform affects the innovation partner and digital user populations and to enrich our understanding of symbiotic relationships within the ecosystem, we extend the three-actor model by incorporating the digital platform. The resulting four-actor Lotka-Volterra model is presented in Eq. (5). The modeling and solution approach parallels that of the three-actor case; therefore, we focus here on the core extensions.

$$\begin{cases} \frac{dx_1}{dt} = k_1x_1\left(1-\frac{x_1}{N_1}+\alpha_{12}\frac{x_2}{N_2}+\alpha_{13}\frac{x_3}{N_3}+\alpha_{14}\frac{x_4}{N_4}\right), & x_1(0)=x_{10} \\ \frac{dx_2}{dt} = k_2x_2\left(1-\frac{x_2}{N_2}+\alpha_{21}\frac{x_1}{N_1}+\alpha_{23}\frac{x_3}{N_3}+\alpha_{24}\frac{x_4}{N_4}\right), & x_2(0)=x_{20} \\ \frac{dx_3}{dt} = k_3x_3\left(1-\frac{x_3}{N_3}+\alpha_{31}\frac{x_1}{N_1}+\alpha_{32}\frac{x_2}{N_2}+\alpha_{34}\frac{x_4}{N_4}\right), & x_3(0)=x_{30} \\ \frac{dx_4}{dt} = k_4x_4\left(1-\frac{x_4}{N_4}+\alpha_{41}\frac{x_1}{N_1}+\alpha_{42}\frac{x_2}{N_2}+\alpha_{43}\frac{x_3}{N_3}\right), & x_4(0)=x_{40} \end{cases} \tag{5}$$

Here, $k_4\times_4$ represents the intrinsic growth trend of the digital platform; x_4/N_4 denotes the population size as a proportion of its maximum capacity; and (1-x_4/N_4) is the logistic coefficient, reflecting the inhibitory effect of the platform's resource consumption on the growth of the other actors. Solving Eq. (5) yields sixteen equilibrium points, as detailed in Table 2. The Jacobian matrix of the system coefficients is given in Eq. (6), where $A=k_1\left(1-\frac{2x_1}{N_1}+\alpha_{12}\frac{x_2}{N_2}+\alpha_{13}\frac{x_3}{N_3}+\alpha_{14}\frac{x_4}{N_4}\right)$, $B=k_2\left(1-\frac{2x_2}{N_2}+\alpha_{21}\frac{x_1}{N_1}+\alpha_{23}\frac{x_3}{N_3}+\alpha_{24}\frac{x_4}{N_4}\right)$, $C=k_3\left(1-\frac{2x_3}{N_3}+\alpha_{31}\frac{x_1}{N_1}+\alpha_{32}\frac{x_2}{N_2}+\alpha_{34}\frac{x_4}{N_4}\right)$,$D=k_4\left(1-\frac{2x_4}{N_4}+\alpha_{41}\frac{x_1}{N_1}+\alpha_{42}\frac{x_2}{N_2}+\alpha_{43}\frac{x_3}{N_3}\right)$.

$$J=\begin{bmatrix} A & k_1\alpha_{12}\frac{x_1}{N_2} & k_1\alpha_{13}\frac{x_1}{N_3} & k_1\alpha_{14}\frac{x_1}{N_4} \\ k_2\alpha_{21}\frac{x_2}{N_1} & B & k_2\alpha_{23}\frac{x_2}{N_3} & k_2\alpha_{24}\frac{x_2}{N_4} \\ k_3\alpha_{31}\frac{x_3}{N_1} & k_3\alpha_{32}\frac{x_3}{N_2} & C & k_3\alpha_{34}\frac{x_3}{N_4} \\ k_4\alpha_{41}\frac{x_4}{N_1} & k_4\alpha_{42}\frac{x_4}{N_2} & k_4\alpha_{43}\frac{x_4}{N_3} & D \end{bmatrix} \tag{6}$$

Local equilibrium points	Eigenvalues	Stability conditions
$E_1(0,0,0,0)$	All positive	Not a stable point
$E_2(N_1, 0,0,0)$	All negative	$(1+\alpha_{21})(1+\alpha_{31})(1+\alpha_{41})<0$
$E_3(0, N_2,0,0)$	All negative	$(1+\alpha_{12})(1+\alpha_{32})(1+\alpha_{42})<0$
$E_4(0,0, N_3,0)$	All negative	$(1+\alpha_{13})(1+\alpha_{23})(1+\alpha_{43})<0$
$E_5(0,0,0, N_4)$	All negative	$(1+\alpha_{14})(1+\alpha_{24})(1+\alpha_{34})<0$
$E_6=(\frac{N_1(1-\alpha_{12})}{1-\alpha_{12}\alpha_{21}}, \frac{N_2(1-\alpha_{21})}{1-\alpha_{12}\alpha_{21}}, 0, 0)$	There is a positive	Not a stable point
$E_7=(\frac{N_1(1-\alpha_{13})}{1-\alpha 13\alpha 31}, 0, \frac{N_3(1-\alpha_{31})}{1-\alpha_{13}\alpha_{31}}, 0)$	There is a positive	Not a stable point
$E_8=(\frac{N_1(1+\alpha_{14})}{1-\alpha_{14}\alpha_{41}}, 0, 0, \frac{N_4(1+\alpha_{41})}{1-\alpha_{14}\alpha_{41}})$	There is a positive	Not a stable point
$E_9=(0, \frac{N_2(1+\alpha_{23})}{1-\alpha_{23}\alpha_{32}}, \frac{N_3(1+\alpha_{32})}{1-\alpha_{23}\alpha_{32}}, 0)$	There is a positive	Not a stable point
$E_{10}=(0, \frac{N_2(1+\alpha_{24})}{1-\alpha_{24}\alpha_{42}}, 0, \frac{N_4(1+\alpha_{42})}{1-\alpha_{24}\alpha_{42}})$	There is a positive	Not a stable point
$E_{11}=(0, 0, \frac{N_3(1+\alpha_{34})}{1-\alpha_{34}\alpha_{43}}, \frac{N_4(1+\alpha_{43})}{1-\alpha_{34}\alpha_{43}})$	There is a positive	Not a stable point
E_{12}	All negative	$\frac{\alpha_{23}\alpha_{34}+\alpha_{23}+\alpha_{24}\alpha_{43}+\alpha_{24}-\alpha_{34}\alpha_{43}+1}{\alpha_{23}\alpha_{32}+\alpha_{23}\alpha_{34}\alpha_{42}+\alpha_{24}\alpha_{32}\alpha_{43}+\alpha_{24}\alpha_{42}+\alpha_{34}\alpha_{43}-1}<0$ $\frac{\alpha_{24}\alpha_{32}-\alpha_{24}\alpha_{42}+\alpha_{32}+\alpha_{34}\alpha_{42}+\alpha_{34}+1}{\alpha_{23}\alpha_{32}+\alpha_{23}\alpha_{34}\alpha_{42}+\alpha_{24}\alpha_{32}\alpha_{43}+\alpha_{24}\alpha_{42}+\alpha_{34}\alpha_{43}-1}<0$ $\frac{\alpha_{23}\alpha_{32}-\alpha_{23}\alpha_{42}-\alpha_{23}\alpha_{43}-\alpha_{42}-\alpha_{43}-1}{\alpha_{23}\alpha_{32}+\alpha_{23}\alpha_{34}\alpha_{42}+\alpha_{24}\alpha_{32}\alpha_{43}+\alpha_{24}\alpha_{42}+\alpha_{34}\alpha_{43}-1}>0$
E_{13}	All negative	$\frac{\alpha_{13}\alpha_{34}+\alpha_{13}+\alpha_{14}\alpha_{43}+\alpha_{14}-\alpha_{34}\alpha_{43}+1}{\alpha_{13}\alpha_{31}+\alpha_{13}\alpha_{34}\alpha_{41}+\alpha_{14}\alpha_{31}\alpha_{43}+\alpha_{14}\alpha_{41}+\alpha_{34}\alpha_{43}-1}<0$ $\frac{\alpha_{14}\alpha_{31}-\alpha_{14}\alpha_{41}+\alpha_{31}+\alpha_{34}\alpha_{41}+\alpha_{34}+1}{\alpha_{13}\alpha_{31}+\alpha_{13}\alpha_{34}\alpha_{41}+\alpha_{14}\alpha_{31}\alpha_{43}+\alpha_{14}\alpha_{41}+\alpha_{34}\alpha_{43}-1}<0$ $\frac{\alpha_{13}\alpha_{31}-\alpha_{13}\alpha_{41}-\alpha_{31}\alpha_{43}-\alpha_{41}-\alpha_{43}-1}{\alpha_{13}\alpha_{31}+\alpha_{13}\alpha_{34}\alpha_{41}+\alpha_{14}\alpha_{31}\alpha_{43}+\alpha_{14}\alpha_{41}+\alpha_{34}\alpha_{43}-1}>0$
E_{14}	All negative	$\frac{\alpha_{12}\alpha_{24}+\alpha_{12}+\alpha_{14}\alpha_{42}+\alpha_{14}-\alpha_{24}\alpha_{42}+1}{\alpha_{12}\alpha_{21}+\alpha_{12}\alpha_{24}\alpha_{41}+\alpha_{14}\alpha_{21}\alpha_{42}+\alpha_{14}\alpha_{41}+\alpha_{24}\alpha_{42}-1}<0$ $\frac{\alpha_{14}\alpha_{21}-\alpha_{14}\alpha_{41}+\alpha_{21}+\alpha_{24}\alpha_{41}+\alpha_{24}+1}{\alpha_{12}\alpha_{21}+\alpha_{12}\alpha_{24}\alpha_{41}+\alpha_{14}\alpha_{21}\alpha_{42}+\alpha_{14}\alpha_{41}+\alpha_{24}\alpha_{42}-1}<0$ $\frac{\alpha_{12}\alpha_{21}-\alpha_{12}\alpha_{41}-\alpha_{21}\alpha_{42}-\alpha_{41}-\alpha_{42}-1}{\alpha_{12}\alpha_{21}+\alpha_{12}\alpha_{24}\alpha_{41}+\alpha_{14}\alpha_{21}\alpha_{42}+\alpha_{14}\alpha_{41}+\alpha_{24}\alpha_{42}-1}>0$
E_{16}	All negative	–

Table 2. Equilibrium points and stability conditions for the four-actor symbiotic evolution model in DIES.

When the DIES attains stability, it exhibits multiple equilibrium points. Each of the four symbiotic modes corresponds to a distinct equilibrium configuration. By computing the eigenvalues of all sixteen points, we determine the local stability conditions of the system. The ecosystem is evolutionarily stable when every eigenvalue is negative. Ultimately, nine stable equilibrium points emerge; these define the boundary of the four-actor symbiotic evolution model and are listed in Table 2. Because the solution procedure is identical for each equilibrium point and the parameter set is extensive, points E_{12} through E_{16} are omitted for brevity.

Simulation analysis of three-actor symbiotic evolution in DIES

To uncover the macro-level dynamics of DIES, we conduct numerical simulations of the evolution equations using MATLAB R2020b. Drawing on established literature for parameter selection[53,54]and aligning with observed growth rates of ecosystem actors, we set the intrinsic growth rates of core digital enterprises, innovation partners and digital product users to $k_1=0.2$, $k_2=0.15$ and $k_3=0.1$, respectively. The maximum carrying capacity N_i is normalized to 1000 (representing units such as thousands of production lines or billions in market size), and all populations share the initial condition $x_i(0)=100$. The simulation horizon is $t=400$. The parameter range refers to the commonly used empirical settings of Modis[55] we systematically vary the symbiotic coefficients α according to Table 1 to generate the four symbiotic patterns: independent, parasitic symbiosis, commensal symbiosis and mutually beneficial symbiosis, and observe their evolution trajectories. Equilibrium points and the overall stability structure remain consistent under typical parameter fluctuations, shifting only under extreme perturbations.

Three-actor symbiotic evolution simulation analysis

Three-actor independent symbiosis pattern

When the symbiotic coefficients among core digital enterprises, innovation partners and digital product users are all zero, the three actors evolve independently, forming an ideal independent symbiosis pattern as shown in Fig. 4. In this scenario, each population develops in isolation, unaffected by the others. The size of each

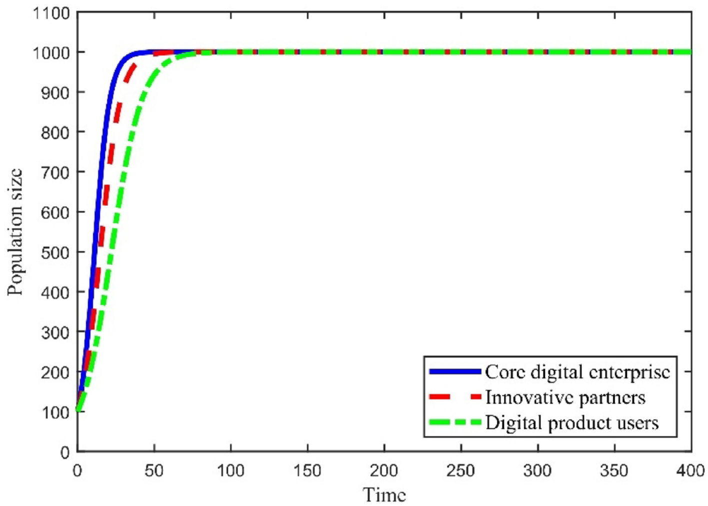


Fig. 4. Simulation of the independent symbiosis pattern in the three-actor DIES.

population depends solely on its intrinsic growth rate and environmental constraints, and at equilibrium each population reaches its maximum capacity.

Three-actor parasitic symbiosis pattern
When a pair of symbiotic coefficients $\alpha_{ab}\alpha_{ba}<0$, the three-actor system exhibits a parasitic symbiosis pattern. Figure 5 illustrates this dynamic. In Fig. 5a, with $\alpha_{12}=0.25$, $\alpha_{13}=0.1$, $\alpha_{21}=-0.1$, $\alpha_{23}=-0.2$, $\alpha_{31}=-0.05$ and $\alpha_{32}=-0.1$, the core digital enterprise population parasitizes both the innovation partner and the digital product user populations. As a result, the core population extracts resources from its partners and users and grows well beyond its independent carrying capacity. Using the same parameter-setting rules, Fig. 5b shows the inverse scenario in which the core digital enterprise is parasitized by the other two populations, causing its population size to collapse and forfeiting its growth advantage. Figure 5c illustrates the scenario where innovative partners parasitize on other populations, the innovation partner population can rapidly expand by drawing on resources from the core enterprise and users, achieving a carrying capacity that exceeds that of the core enterprise. Figure 5d shows the scenario where digital product users parasitize on other populations, depicts a case in which both the core enterprise and the innovation partner are exploited, allowing the digital product user population to dominate the ecosystem and capture most resources and benefits. Under parasitic symbiosis, innovation and R&D incentives weaken as populations free-ride and seek short-term gains. Prolonged parasitism destabilizes the ecosystem, producing unsustainable divergence between over-prosperous and over-declining populations that ultimately threatens the system's viability.

Three-actor commensal symbiosis pattern
When a symbiotic coefficient satisfies the condition that $\alpha_{ab}>0$, $\alpha_{ba}=0$, the system enters a commensal symbiosis pattern. In this configuration one actor benefits from the interaction while the other experiences neither gain nor loss. Figure 6 illustrates four representative cases. In Fig. 6a, with $\alpha_{12}=0.25$, $\alpha_{13}=0.1$,$\alpha_{21}=0$, $\alpha_{23}=0$, $\alpha_{31}=0$, $\alpha_{32}=0$, both the innovation partner and the digital product user significantly enhance the growth of the core digital enterprise population through technology collaboration or resource provision. The core enterprise, however, exerts no reciprocal influence on these two populations. This one-way enhancement highlights the imbalance of resource flows within the ecosystem. Figure 6b presents the inverse scenario: the core digital enterprise drives the expansion of the innovation partner and user populations, yet it derives no benefit from these interactions. This asymmetry illustrates how a dominant actor may become a "single-sided contributor" when technology lock-in or unidirectional resource transfers occur. Figure 6c,d show analogous situations in which the innovation partner or the digital product user population alone reaps the benefits. Each case underscores the complexity of nonreciprocal relationships and the diverse dynamics between individual actors and the ecosystem as a whole. Although commensal symbiosis can enhance local performance in the short term, sustained asymmetry creates hidden vulnerabilities. Should the beneficiary's growth stall, the contributor faces both resource misallocation and restricted development. These findings demonstrate the critical need to balance actor interactions and promote equitable benefit distribution if the ecosystem's long-term stability and sustainability are to be secured.

Three-actor mutualistic symbiosis pattern
When the symbiotic coefficients among core digital enterprises, innovation partners and digital product users are all positive, a mutualistic symbiosis pattern emerges among the three actors, as shown in Fig. 7. Under this pattern, the maximum population sizes of each actor far exceed those seen in parasitic symbiosis and commensal symbiosis scenarios. This outcome demonstrates that synergistic interaction not only overcomes individual growth limits but also harnesses complementary strengths to achieve greater scale and improved

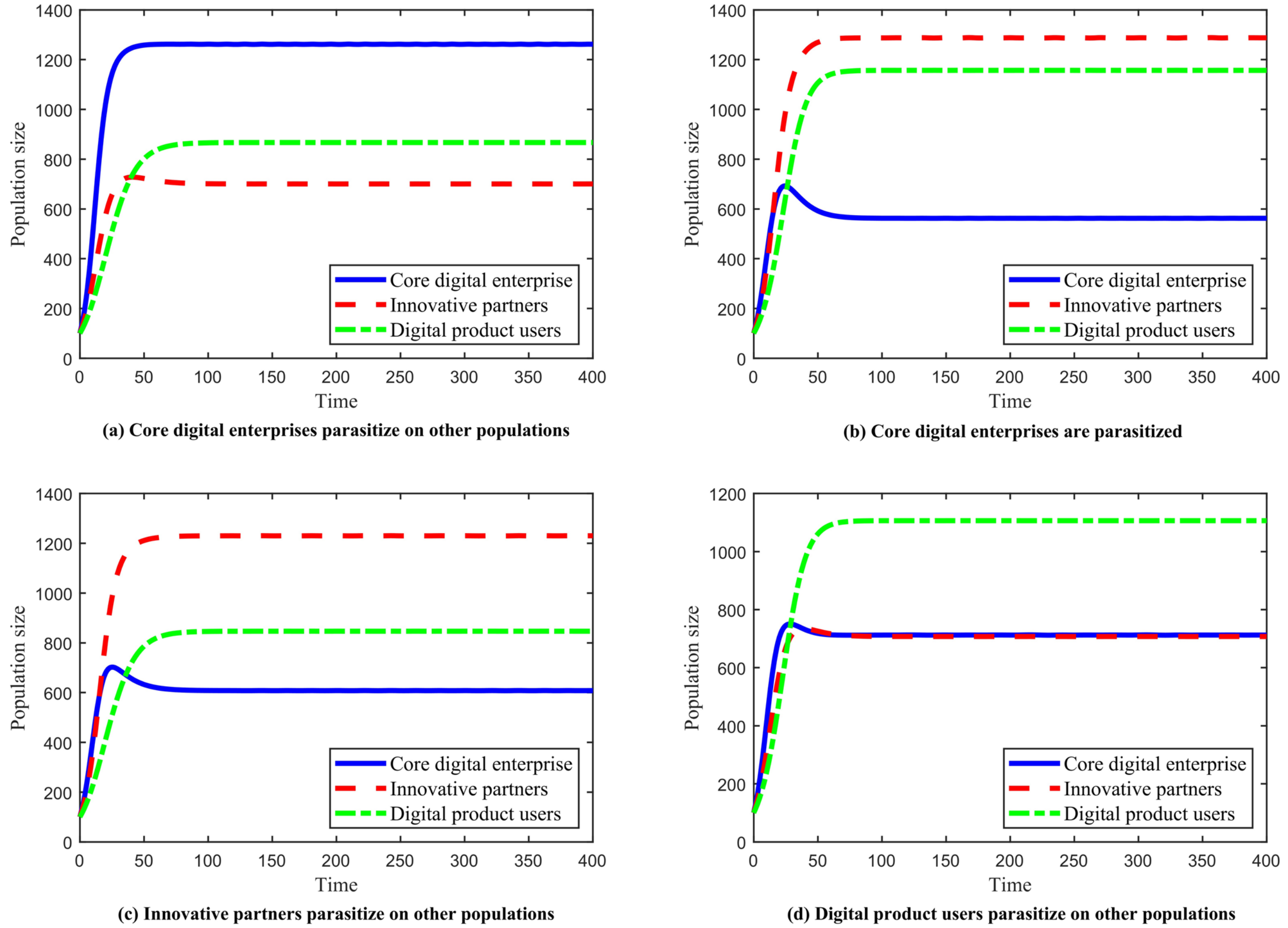


Fig. 5. Simulation of the parasitic symbiosis pattern in the three-actor DIES.

efficiency. Specifically, core digital enterprises leverage their technological expertise and market channels to support innovation partners and users; innovation partners accelerate the innovation process for enterprises and users through high quality inputs and specialized research services; and users drive product iteration and service enhancement by providing demand feedback and application insights. These multi directional positive exchanges optimize the allocation of resources and capabilities within the ecosystem, fostering a virtuous cycle of digital innovation.

The analysis above indicates that the evolutionary trajectories of core digital enterprises, innovation partners and digital product users are profoundly shaped by their symbiotic relationships. In a parasitic symbiosis pattern, one actor extracts resources unilaterally, leading to excessive dependence. In a commensal symbiosis pattern, resource allocation becomes skewed because one actor benefits while the other remains unaffected. By contrast, mutualistic symbiosis, founded on reciprocal empowerment and joint progress, enables efficient resource allocation and drives collective advancement among all three actors. To foster this mutualistic symbiosis, future efforts should prioritize collaborative research and development, establish joint-benefit mechanisms and reinforce the stability and resilience of DIES, thereby ensuring optimal resource deployment and sustainable growth.

Simulation analysis of four-actor symbiotic evolution in DIES

The three-actor symbiotic evolution analysis reveals that under parasitic symbiosis and commensal symbiosis patterns, DIES suffer from structural imbalances such as uneven resource distribution and excessive dependency. Although mutually beneficial symbiosis offers a promising route for optimizing resource allocation, its full potential remains underexplored. In the wave of digitalization, the digital platform's powerful integration and connectivity capabilities not only dismantle information barriers and collaboration boundaries among traditional actors but also inject fresh vitality into the ecosystem through advanced data processing and resource coordination. Motivated by this insight, we introduce the digital platform as a fourth actor in our model. Retaining the original parameter settings for the three existing actors, we assign the platform a natural growth rate of $k_4=0.05$,an initial population of $x_4(0)=100$ and a maximum carrying capacity of $N_4=1000$. The simulation horizon remains 400. We then systematically examine the dynamic characteristics of the four-actor symbiotic evolution model to uncover how platform empowerment shapes the ecosystem's evolution and identify directions for its optimization.

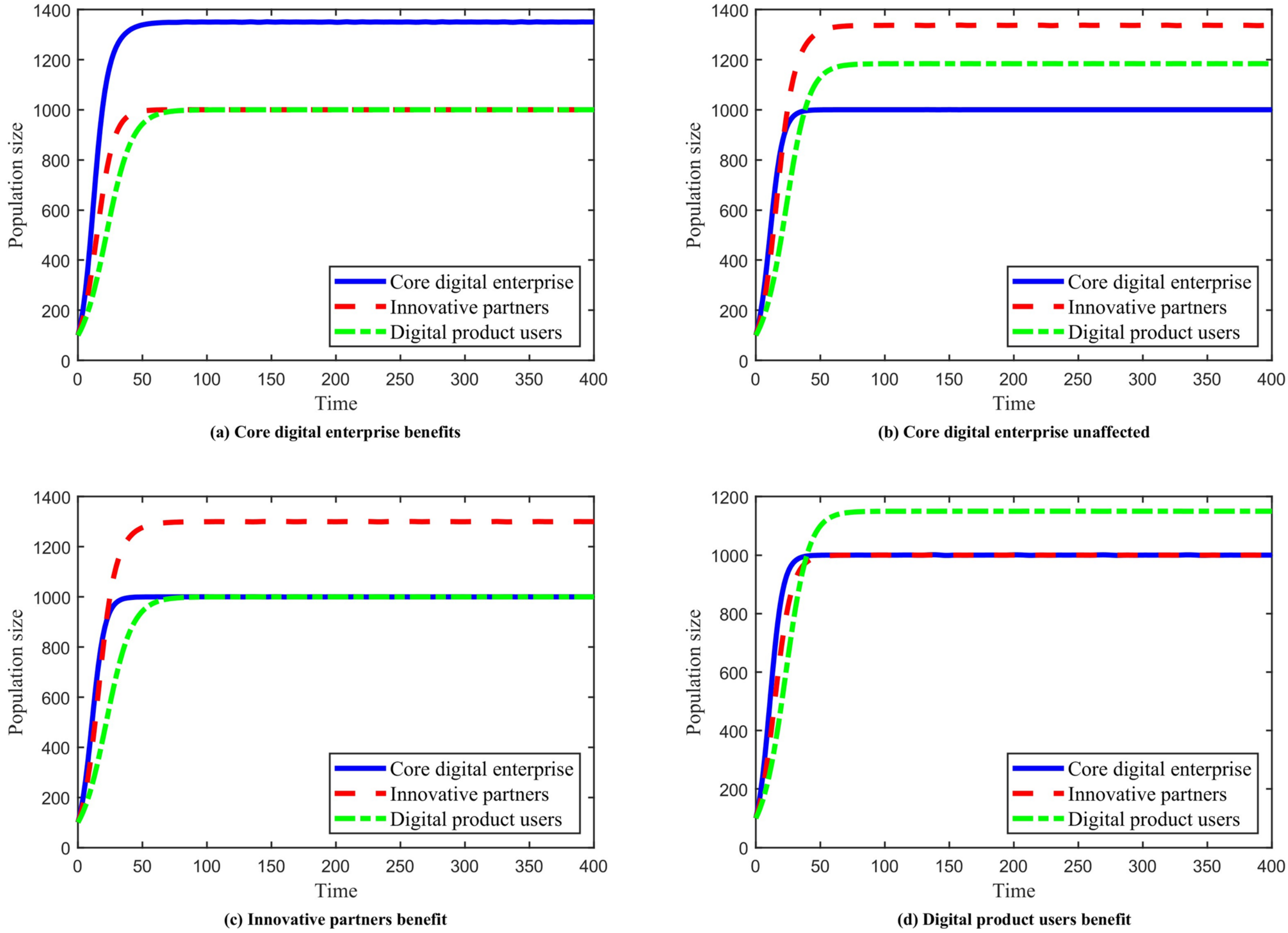


Fig. 6. Simulation of the commensal symbiosis pattern in the three-actor DIES.

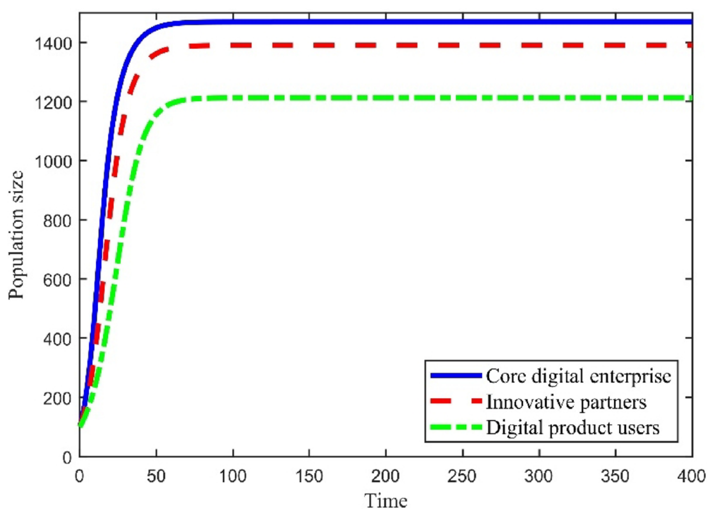


Fig. 7. Simulation of the mutualistic symbiosis pattern in the three-actor DIES.

Four-actor symbiotic evolution simulation analysis

When all symbiotic coefficients among the four actors are set to zero, the system exhibits an idealized independent symbiosis pattern, as shown in Fig. 8. This pattern extends the core logic of the three-actor model: the populations of core digital enterprises, innovation partners, digital product users and the digital platform develop independently, governed solely by their intrinsic growth rates and carrying capacities. Although this

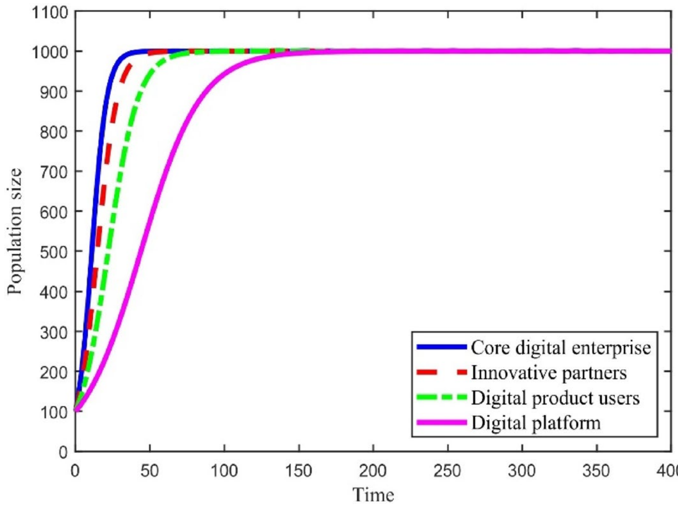


Fig. 8. Simulation of the independent symbiosis pattern in the four-actor DIES.

Inter-population dynamics	Value of symbiosis coefficient	Equilibrium value	Improvement ratio
Core digital enterprises parasitize on other populations	$\alpha_{12}=0.25$; $\alpha_{13}=0.1$; $\alpha_{14}=0.2$	$x_1=1460$	$x_1=13.60\%$
	$\alpha_{21}=-0.1$; $\alpha_{23}=-0.2$; $\alpha_{24}=-0.1$	$x_2=537$	$x_2=4.73\%$
	$\alpha_{31}=-0.05$; $\alpha_{32}=-0.1$; $\alpha_{34}=-0.05$	$x_3=807$	$x_3=7.07\%$
	$\alpha_{41}=0.05$; $\alpha_{42}=0.1$; $\alpha_{43}=0.1$	$x_4=1195$	$x_4=10.95\%$
Core digital enterprises are parasitized by other populations	$\alpha_{12}=-0.25$; $\alpha_{13}=-0.1$; $\alpha_{14}=-0.2$	$x_1=279$	$x_1=1.79\%$
	$\alpha_{21}=0.1$; $\alpha_{23}=0.2$; $\alpha_{24}=0.1$	$x_2=1391$	$x_2=12.91\%$
	$\alpha_{31}=0.05$; $\alpha_{32}=0.1$; $\alpha_{34}=0.05$	$x_3=1208$	$x_3=11.08\%$
	$\alpha_{41}=0.05$; $\alpha_{42}=0.1$; $\alpha_{43}=0.1$	$x_4=1259$	$x_4=11.59\%$
Innovative partners parasitize other populations	$\alpha_{12}=-0.25$; $\alpha_{13}=-0.1$; $\alpha_{14}=-0.2$	$x_1=351$	$x_1=2.51\%$
	$\alpha_{21}=0.1$; $\alpha_{23}=0.2$; $\alpha_{24}=0.1$	$x_2=1309$	$x_2=12.09\%$
	$\alpha_{31}=-0.05$; $\alpha_{32}=-0.1$; $\alpha_{34}=-0.05$	$x_3=789$	$x_3=6.89\%$
	$\alpha_{41}=0.05$; $\alpha_{42}=0.1$; $\alpha_{43}=0.1$	$x_4=1211$	$x_4=11.11\%$
Digital product users parasitize other populations	$\alpha_{12}=-0.25$; $\alpha_{13}=-0.1$; $\alpha_{14}=-0.2$	$x_1=498$	$x_1=3.98\%$
	$\alpha_{21}=-0.1$; $\alpha_{23}=-0.2$; $\alpha_{24}=-0.1$	$x_2=604$	$x_2=5.04\%$
	$\alpha_{31}=0.05$; $\alpha_{32}=0.1$; $\alpha_{34}=0.05$	$x_3=1136$	$x_3=10.36\%$
	$\alpha_{41}=0.05$; $\alpha_{42}=0.1$; $\alpha_{43}=0.1$	$x_4=1183$	$x_4=10.83\%$

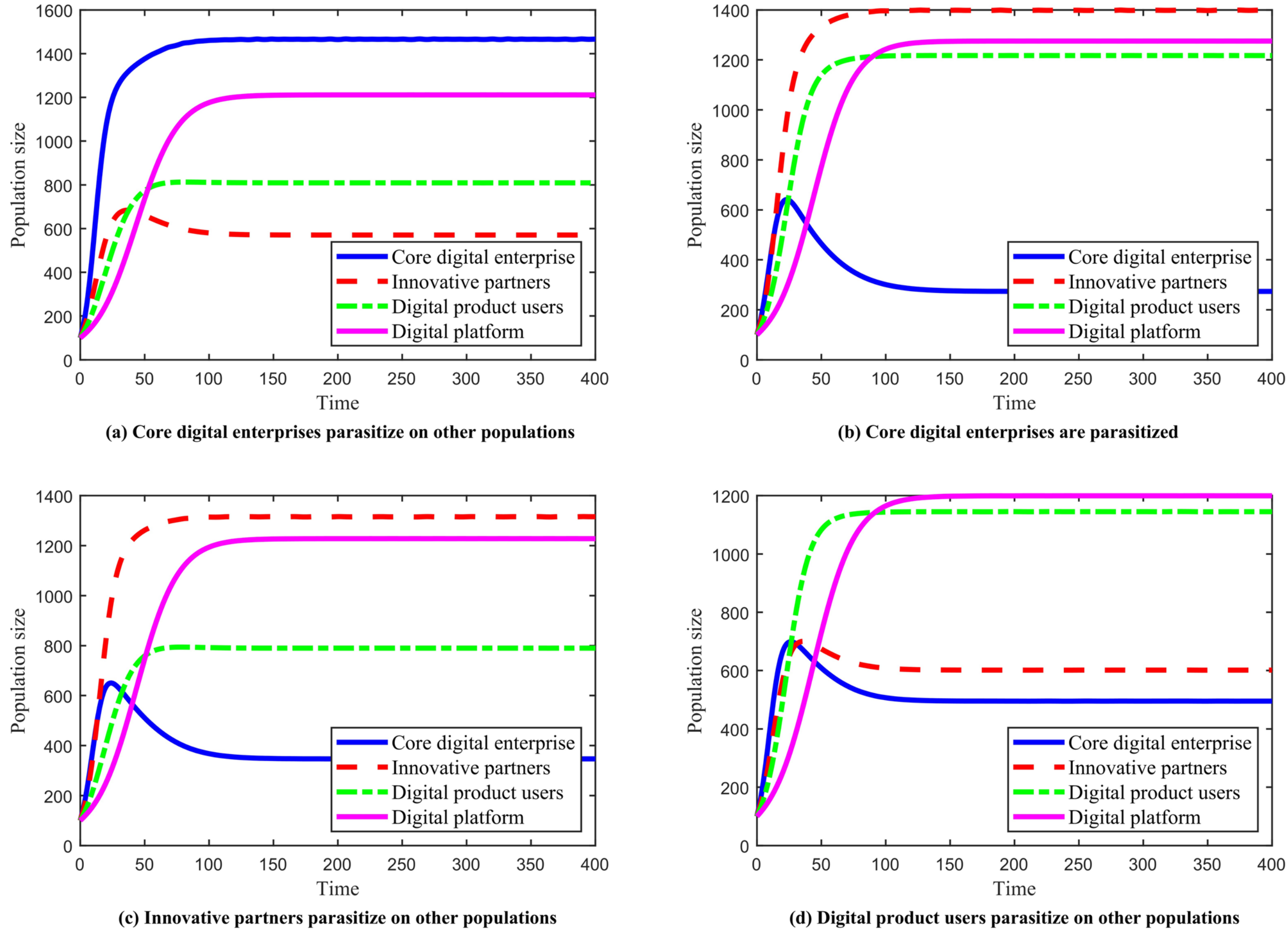
Table 3. Four-actor symbiosis pattern under the parasitic symbiosis between the digital platform and three-actor.

ideal scenario rarely occurs in practice, it provides a logical baseline for analyzing more complex symbiotic patterns and helps identify the genuine interactive effects that emerge once the platform is introduced.

Four-actor parasitic symbiosis pattern

Under the assumption of parasitic symbiosis, we examine how the entry of a digital platform affects the scale evolution of the original DIES. Using the Lotka-Volterra model equations and parameters, we employ Python 3.9 to compute each actor's equilibrium population size and the relative improvement ratios. The results show that the platform's introduction significantly increases the population scales of core digital enterprises, innovation partners and digital product users. Specific symbiotic coefficient values and improvement ratios are provided in Table 3.

Figure 9 illustrates four parasitic symbiosis scenarios. In Fig. 9a, with the core digital enterprise acting as the parasite, the platform amplifies its resource extraction, driving exponential growth and rapid emergence of a single dominant actor. Figure 9b shows the inverse situation, where the core enterprise is parasitized and its population collapses sharply, demonstrating the strong inhibitory effect of parasitism. Figure 9c,d depict scenarios in which the innovation partner or the digital product user serves as the parasite. In these cases the platform optimizes resource flow paths and lowers access barriers, enabling these actors to exceed traditional growth limits and undergo leapfrog niche reconstruction, thus illustrating the platform's empowerment of parasitic actors. However, this asymmetric empowerment introduces significant fragility. Over time parasitized actors suffer continuous resource outflow that severely diminishes their innovative vitality, trapping them in a



(a) Core digital enterprises parasitize on other populations

(b) Core digital enterprises are parasitized

(c) Innovative partners parasitize on other populations

(d) Digital product users parasitize on other populations

Fig. 9. Simulation of the parasitic symbiosis pattern in the four-actor DIES.

downward spiral. Parasites, in turn, face technology path dependency risks due to excessive reliance on platform resources, which hinders the development of their own innovation capabilities. Although the platform's entry boosts local performance in the short term, persistent imbalances among actors may eventually fracture the ecosystem. These findings underscore the need to design governance mechanisms that maintain dynamic equilibrium among symbiotic actors.

Four-actor commensal symbiosis pattern

In the commensal symbiosis pattern between the digital platform and the core digital enterprise, innovation partners and digital product users, all symbiotic coefficients from the platform to the other actors are zero, indicating that the platform does not directly affect their growth but provides implicit support. Figure 10 shows that in each commensal scenario, whether the core enterprise, the innovation partners or the user community benefits, the platform's entry substantially raises each actor's maximum scale, with improvements far exceeding those observed under parasitic symbiosis. The specific values appear in Table 4.

Further analysis shows that the digital platform, through its strong capacity for resource integration and information exchange, creates a more favorable external environment for all actors. Core digital enterprises can use the platform to expand market reach and access innovation inputs more efficiently; innovation partners benefit from platform technical support that reduces research and development costs and accelerates technology transfer; and digital product users receive more convenient services via the platform, driving their own growth. However, this pattern has notable limitations. First, reliance on the platform in one direction may become entrenched, weakening actors' ability to develop independently and making the ecosystem vulnerable to platform disruptions. Second, the platform's neutral support model, which provides benefits without feedback, prevents deeper collaboration and resource sharing among actors, constraining overall system performance. While this commensal symbiosis pattern promotes scale growth, it also underscores the necessity of establishing mechanisms for bidirectional interaction and strengthening actor autonomy to ensure the ecosystem's long-term stability and efficient development.

Four-actor mutualistic symbiosis pattern

In the mutually beneficial symbiosis pattern among the digital platform, core digital enterprises, innovation partners and digital product users, all actors engage in two-way positive interactions that remove traditional

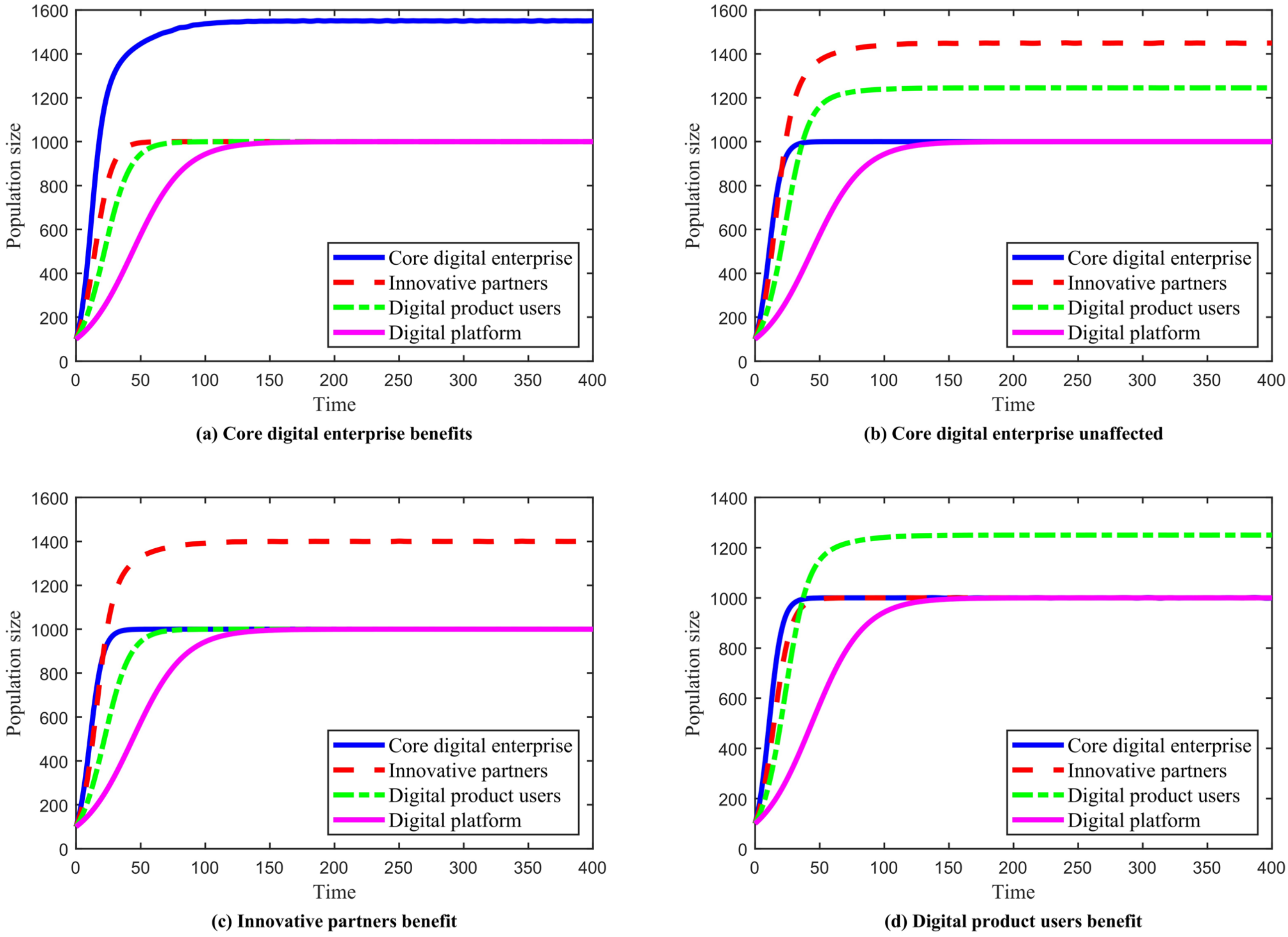


Fig. 10. Simulation of the commensal symbiosis pattern in the four-actor DIES.

Inter-population dynamics	Value of symbiosis coefficient	Equilibrium value	Improvement ratio
Core digital enterprises benefit	$\alpha_{12}=0.25$; $\alpha_{13}=0.1$; $\alpha_{14}=0.2$	$x_1=1541$	$x_1=14.41\%$
	$\alpha_{21}=0$; $\alpha_{23}=0$; $\alpha_{24}=0$	$x_2=994$	$x_2=8.94\%$
	$\alpha_{31}=0$; $\alpha_{32}=0$; $\alpha_{34}=0$	$x_3=990$	$x_3=8.90\%$
	$\alpha_{41}=0$; $\alpha_{42}=0$; $\alpha_{43}=0$	$x_4=980$	$x_4=8.80\%$
Core digital enterprises unaffected	$\alpha_{12}=0$; $\alpha_{13}=0$; $\alpha_{14}=0$	$x_1=995$	$x_1=8.95\%$
	$\alpha_{21}=0.1$; $\alpha_{23}=0.2$; $\alpha_{24}=0.1$	$x_2=1440$	$x_2=13.40\%$
	$\alpha_{31}=0.05$; $\alpha_{32}=0.1$; $\alpha_{34}=0.05$	$x_3=1235$	$x_3=11.35\%$
	$\alpha_{41}=0$; $\alpha_{42}=0$; $\alpha_{43}=0$	$x_4=980$	$x_4=8.80\%$
Innovative partners benefit	$\alpha_{12}=0$; $\alpha_{13}=0$; $\alpha_{14}=0$	$x_1=995$	$x_1=8.95\%$
	$\alpha_{21}=0.1$; $\alpha_{23}=0.2$; $\alpha_{24}=0.1$	$x_2=1391$	$x_2=12.91\%$
	$\alpha_{31}=0$; $\alpha_{32}=0$; $\alpha_{34}=0$	$x_3=990$	$x_3=8.90\%$
	$\alpha_{41}=0$; $\alpha_{42}=0$; $\alpha_{43}=0$	$x_4=980$	$x_4=8.80\%$
Digital product users benefit	$\alpha_{12}=0$; $\alpha_{13}=0$; $\alpha_{14}=0$	$x_1=995$	$x_1=8.95\%$
	$\alpha_{21}=0$; $\alpha_{23}=0$; $\alpha_{24}=0$	$x_2=994$	$x_2=8.94\%$
	$\alpha_{31}=0.05$; $\alpha_{32}=0.1$; $\alpha_{34}=0.1$	$x_3=1240$	$x_3=11.04\%$
	$\alpha_{41}=0$; $\alpha_{42}=0$; $\alpha_{43}=0$	$x_4=980$	$x_4=8.80\%$

Table 4. Four-actor symbiosis pattern under the commensal symbiosis between the digital platform and three-actor.

Inter-population dynamics	Value of symbiosis coefficient	Equilibrium value	Improvement ratio
Mutualistic symbiosis	$\alpha_{12}=0.25$; $\alpha_{13}=0.1$; $\alpha_{14}=0.2$	$x_1=1795$	$x_1=16.95\%$
	$\alpha_{21}=0.1$; $\alpha_{23}=0.2$; $\alpha_{24}=0.1$	$x_2=1574$	$x_2=14.74\%$
	$\alpha_{31}=0.05$; $\alpha_{32}=0.1$; $\alpha_{34}=0.05$	$x_3=1308$	$x_3=12.08\%$
	$\alpha_{41}=0.05$; $\alpha_{42}=0.1$; $\alpha_{43}=0.1$	$x_4=1364$	$x_4=12.64\%$

Table 5. Four-actor symbiosis pattern under the mutualistic symbiosis between the digital platform and three-actor.

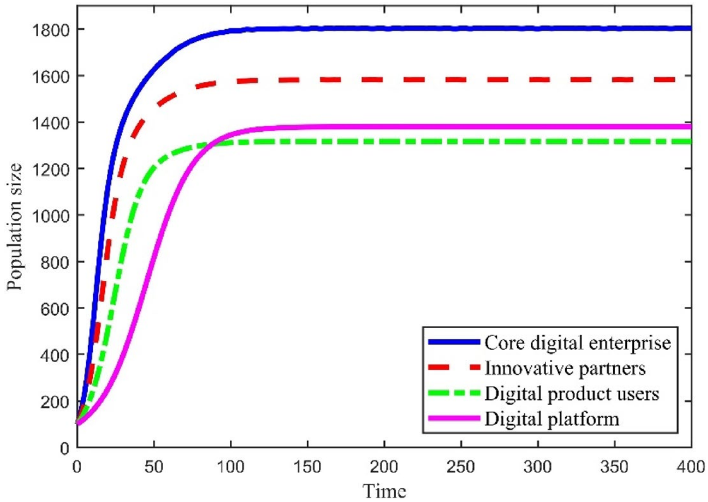


Fig. 11. Simulation of the mutualistic symbiosis pattern in the four-actor DIES.

collaboration barriers. Under this four-actor configuration, each population's equilibrium scale and improvement ratio exceed those seen in parasitic symbiosis and commensal symbiosis, as detailed in Table 5. The maximum improvement ratio reached 16.95%, indicating that the ecosystem can support nearly 17% additional activity under the same resource constraints. It can thus accommodate more users and partners, run additional concurrent innovation projects or handle greater request volumes without performance degradation. This expansion directly increases the potential market size and revenue ceiling, offering substantial growth opportunities for platforms and enterprises.

Figure 11 shows a substantial increase in the ecosystem's upper bound when the platform is present. Serving as the central hub, the digital platform enhances the efficient flow and sharing of critical resources such as technology, data and capital. Core digital enterprises leverage the platform's integration capabilities and market reach to accelerate innovation cycles. Innovation partners gain access to abundant R&D resources and collaboration opportunities, boosting their technology transfer efficiency. Digital product users enjoy enriched service experiences that support steady growth. Conversely, the development of these three actor groups supplies the platform with vast data resources and diverse application scenarios, driving continual platform improvements and service upgrades. Overall, compared with other patterns, mutually beneficial symbiosis avoids excessive concentration of resources or one-sided dependencies. By advancing together, all actors strengthen their competitiveness and foster a healthy, sustainable DIES. It is important to recognize that even under mutualistic symbiosis, the optimal pattern, care must be taken to prevent misaligned incentives or opportunistic behavior from eroding trust and undermining the system's sustainability.

The foregoing numerical simulations validate the evolutionary dynamics of DIES under both three-actor and four-actor symbiotic patterns. They demonstrate how parasitic symbiosis, commensal symbiosis and mutualistic symbiosis each differentially affect system scale and stability, and they quantify the significant enhancements in actor scales and carrying capacity achieved by introducing a digital platform. Building on these insights, the next step is to translate the symbiotic logic embodied in the theoretical model into practical governance strategies that will steer the ecosystem toward healthier and more sustainable evolution. Accordingly, we now develop a governance framework tailored to the core tensions of each symbiotic pattern, laying the theoretical groundwork for the subsequent case analysis.

Governance mechanism for symbiotic patterns in DIES

Having identified the symbiotic evolution patterns through numerical simulations and the enabling effects of the digital platform, this chapter turns to the design of a matching governance model. Conventional platform governance tends to focus on rule-making and benefit allocation led by dominant firms, emphasizing operational efficiency and short-term gains through centralized controls such as behavior constraints and trafficbased resource allocation. However, in DIES these measures prove increasingly inadequate given the complex interdependencies among diverse actors. In contrast, our proposed governance approach builds on symbiosis theory to diagnose the core tensions of parasitic symbiosis, commensal symbiosis and mutualistic symbiosis, then remedies each through a three-dimensional framework of resource balancing, value sharing and trust cooperation. This novel mechanism moves beyond uniform, center-edge paradigms to guide the ecosystem from chaotic, low-order states to organized, high order equilibrium and from transient imbalances to lasting stability, offering a fresh pathway for the sustainable development of DIES.

The ideal outcome of symbiotic evolution in DIES is a continuous cycle of mutual benefit that sustains the dynamic equilibrium of the digital value network. Although ecosystem evolution seeks to improve overall innovation performance, practical implementations often face barriers such as asymmetric resource drain, one way benefit transfers and unsustainable virtuous cycles. These factors can divert the evolution path from its optimal direction. To address these challenges and maximise collective benefits, we propose a governance mechanism for symbiotic patterns in DIES as shown in Fig. 12. This governance mechanism is built on three interlinked dimensions: resource balancing, value sharing and trust cooperation. Each dimension is designed to resolve the core tension of its corresponding symbiotic pattern and to guide the ecosystem towards a higher order and sustainable state.

The resource balancing mechanism corrects the asymmetric flow of resources in parasitic symbiosis and prevents extreme imbalances. In parasitic symbiosis, resources become overly concentrated in the parasitic actor or are depleted from the host, causing ecosystem instability. For example, when the core digital enterprise acts as a parasite it may dominate the ecosystem, whereas being parasitized causes its scale to collapse. By deploying edge computing nodes and blockchain smart contracts, resource flows and volumes among actors are tracked in real time. An elastic quota system based on dynamic thresholds ensures that when an actor's resource use nears its limit, the smart contract automatically applies tiered pricing and flow control, and redirects any excess usage fees into a collective R&D fund. These hard constraints make the cost of resource exploitation explicit, while technical feedback clauses in supply agreements, such as revenue sharing from digitized services, serve as soft incentives. Together they break the cycle of resource siphoning and niche collapse by channeling a portion of the parasite's gains back to the host as innovation support.

The value sharing mechanism addresses the one-way benefit problem in commensal symbiosis. In this pattern one actor gains at the expense of balance, which undermines the ecosystem's sustainability. Digital innovation depends on integrating heterogeneous resources, yet commensal symbiosis concentrates innovation dividends in a single actor and disrupts system equilibrium. To counter this, we establish a tiered revenue sharing plan that requires beneficiaries to allocate agreed proportions back to contributors and to the platform. For instance, when the core digital enterprise benefits in a commensal scenario, it must invest part of its gains in the innovation partner's R&D or in user experience improvements. This ensures that contributors receive tangible rewards. We also build a resource and capability exchange platform. In cases where innovation partners benefit, they establish a technology for market access channel with core enterprises, sharing cutting-edge algorithms in exchange for

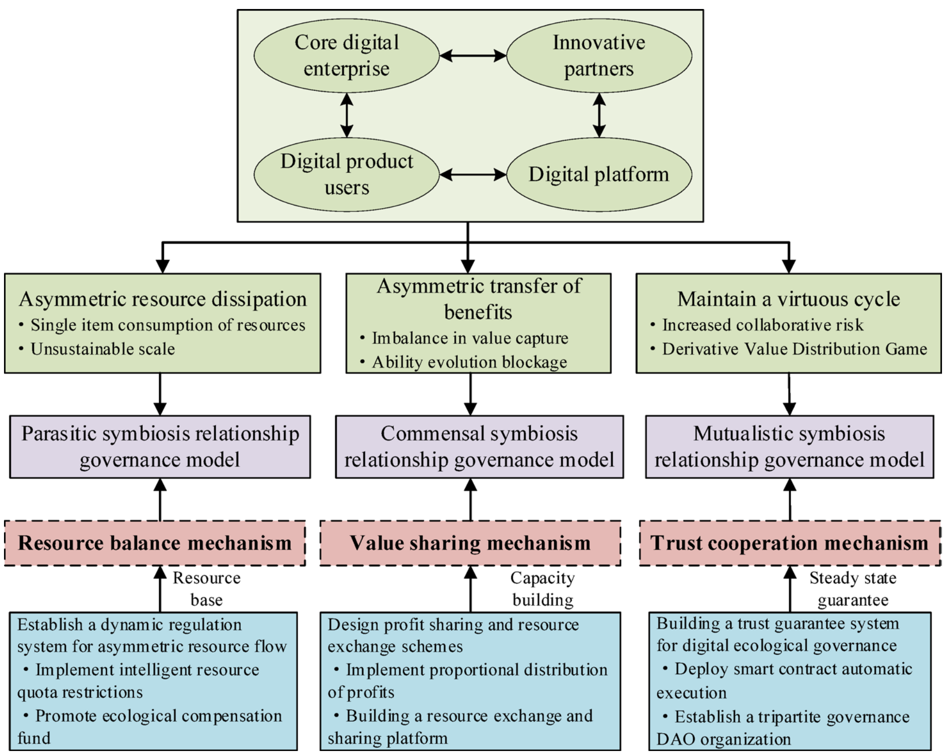


Fig. 12. Implementation architecture diagram of three-dimensional governance mechanism for DIES.

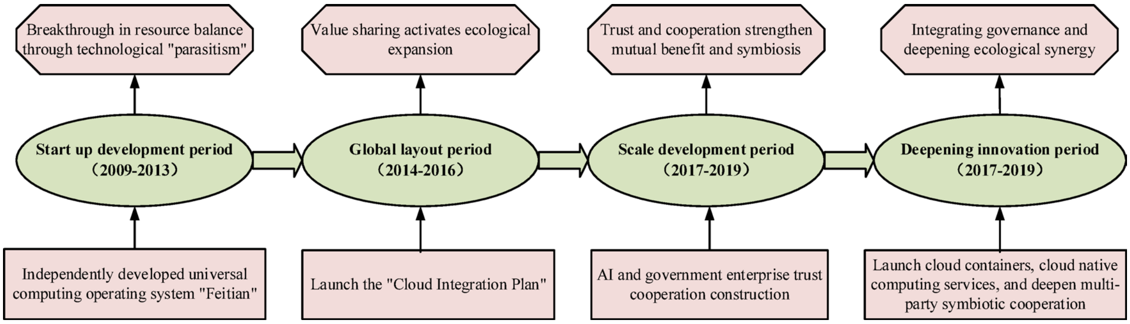


Fig. 13. Development history of Alibaba Cloud.

distribution support. Joint laboratories co-hosted by the platform facilitate regular training and workshops, bolstering contributors' technical reserves and reducing dependence on any single actor.

The trust cooperation mechanism resolves coordination risks within mutualistic symbiosis and consolidates collaborative foundations. Although mutualistic symbiosis fosters joint growth, opportunism can still undermine cooperation. We therefore implement a dynamic smart contract system that uses deep reinforcement learning to analyse each actor's resource inputs and innovation contributions. Based on indicators such as ecosystem health and technology conversion rates, the system adjusts benefit allocations in real time. If overall health declines, the system prioritises resource access for high-contribution actors. We also establish a decentralised autonomous organisation governed by permissioned blockchain, where voting weight is tied to data contribution and major decisions require multiple rounds of consensus voting to reach Nash equilibrium. A digital twin platform simulates collaboration pathways, modeling resource flows and innovation outputs to identify and resolve potential conflicts in advance. Using a federated learning framework, actors combine knowledge while maintaining data sovereignty, allowing models to be co-trained without sharing raw data.

Together these three mechanisms form an integrated governance loop. Resource balancing internalises the cost of parasitic exploitation to stabilise the system. Value sharing realigns incentives and resource exchanges to transform commensal relationships into mutualistic symbiosis and to activate innovation factors. Trust cooperation converts short-term mutual gains into stable long-term equilibrium through technological and institutional innovation. These sequential and adaptive mechanisms comprise a resilient governance architecture for DIES. They extend symbiosis theory into digital contexts and offer a practical institutional toolkit for avoiding the traps of one-sided digital transformation.

Case study: taking Alibaba cloud digital ecosystem as an example

The case analysis complements our numerical simulations by illustrating how a leading cloud provider has navigated symbiotic challenges in practice. As a global frontrunner, Alibaba Cloud combines deep technical expertise with extensive market reach to shape China's DIES. Domestically, it has focused on serving small and medium-sized enterprises, incubating numerous technology unicorns and building an open-ecosystem model. Alibaba Cloud's development can be divided into four stages, as shown in Fig. 13. We apply an explanatory case-study approach to dissect its evolutionary challenges and governance strategies at each stage, thereby providing empirical support for our governance framework.

In the initial phase of the cloud-computing industry, overseas giants dominated resource access with IOE technologies (IBM, Oracle, EMC), creating a "technological parasitic" risk for domestic firms. Alibaba Cloud overcame this hurdle by developing the "Feitian" operating system, a massively parallel computing platform that met the urgent need for large-scale processing in its retail operations. This breakthrough enabled Alibaba Cloud to become the first Chinese company offering global cloud services and freed it from external compute dependencies. During this critical period, Alibaba Cloud's resource-balancing efforts followed a dual strategy. First, it broke the overseas technology blockade through active substitution, greatly improving server utilization and optimizing resource allocation. Second, by providing free cloud storage quotas to small developers, it attracted a vibrant community of startups and laid the foundation for supply-and-demand alignment within its ecosystem. This combination of technological substitution and open access allowed Alibaba Cloud to transition from "technological parasitism" to "resource autonomy." As the "Feitian" system matured and stabilized, Alibaba Cloud pursued a globalization strategy, establishing data centers in Singapore, Australia, Germany and the United States and exporting standardized cloud offerings. In this phase, its value-sharing mechanism evolved through tiered pricing. Large enterprise customers received customized resource packages and negotiated discounts that addressed their scale and complexity. Small and medium enterprises benefited from pay-as-you-go plans that lowered entry barriers. The "Cloud Partner Program" leveraged open APIs and revenue-sharing to energize the developer community. For example, UFIDA reduced its enterprise-resource-planning deployment costs by building on Alibaba Cloud's platform. This stage highlighted the importance of a stepped benefit structure that balances returns for core contributors and incentives for long-tail innovators, thereby driving ecosystem revenue growth.

Upon entering the scale-expansion stage, deepening mutualistic collaboration brought data security and trust to the forefront as the ecosystem's bottlenecks. Alibaba Cloud addressed these issues by launching the PAI AI platform and the DataTrust privacy-computing system. These innovations established a "data usable but not visible" trust foundation. In the Hangzhou City Brain project, government agencies trained traffic-flow models via federated learning without exposing raw data. Complementary hardware innovation, the Shenlong cloud server, attracted AI firms such as SenseTime through compute-rental revenue sharing and significantly lowered their model-training costs. This phase's governance breakthrough lay in converting frontier technologies like privacy computing and hardware encryption into tight collaboration bonds, enabling ecosystem members to co-innovate efficiently while managing risk.

In response to continuous digital-transformation demands, Alibaba Cloud introduced cloud container services, cloud-native computing and other next-generation offerings, further lowering adoption barriers. At the resource-balancing level, its "Cloud-DingTalk integration" strategy unified enterprise and user resources and empowered development through a low-code platform. For value sharing, it created layered models that combined open-source operating systems with commercial databases, allowing developers to exchange code contributions for resource credits. In trust cooperation, integrating blockchain and smart contracts into its cross-border trade platform increased transaction efficiency and reduced counterparty risk. This stage's governance model exemplified the deep integration of technological tools and institutional design needed for dynamic, multi-dimensional coordination.

Overall, Alibaba Cloud's journey validates a "build the resource pool, reshape the value chain, fortify the trust network" governance pathway. From securing compute autonomy with "Feitian" to enabling global value flows through tiered pricing, then embedding trust via privacy computing and finally orchestrating multi-layered governance, Alibaba Cloud offers a home-grown blueprint for sustaining DIES.

Conclusion and discussion

Conclusion

This study develops a conceptual model of DIES and introduces a four-actor Lotka-Volterra framework to simulate symbiotic evolution from three to four actors, identify the optimal symbiotic pattern and uncover the dynamic characteristics and governance logic of each pattern. The main findings are as follows.

First, the key actors in a DIES are core digital enterprises, innovation partners, digital product users and digital platforms. Under parasitic symbiosis, asymmetric resource flows cause extreme concentration or depletion, polarizing actor performance. Under commensal symbiosis, one-way benefit transfers weaken contributors' innovation incentives. Both patterns hinder efficient resource allocation and healthy system dynamics.

Second, the four-actor symbiotic pattern achieves higher carrying capacity and equilibrium scale than the three-actor model. By integrating technology, data and market channels, the digital platform establishes multidimensional linkages that alleviate resource competition and dependency, making it the pivotal factor in restoring ecosystem balance.

Third, symbiotic relationships are governed by symbiotic coefficients. When all coefficients are positive, the four actors achieve mutualistic symbiosis. In this mode, scale improvements for core enterprises, innovation partners, users and the platform reach 16.95%, 14.74%, 12.08% and 12.64% respectively, significantly outperforming parasitic and commensal patterns.

Fourth, we propose a governance framework based on resource balancing, value sharing and trust cooperation, and validate its real-world applicability through the Alibaba Cloud case. This framework suggests a path of building the resource pool, reshaping the value chain and strengthening the trust network to support sustainable digital ecosystem development.

Discussion

In addition to theoretical and methodological contributions, this study further proposes the following practical and management insights for enterprise managers, platform operators, and policy makers.

Core digital enterprise managers should integrate resource balance and value sharing mechanisms throughout the entire product lifecycle. During demand analysis, technology development and market piloting phases they should deploy edge computing nodes and blockchain based smart contracts to quantify partner and user inputs and outputs in real time. If the system detects insufficient contribution or excessive resource consumption by any actor it should automatically reallocate quotas or draw from an ecosystem compensation fund. Surplus resources can then flow back to universities, suppliers and other innovation partners as joint research grants, technology licensing fees or targeted subsidies to prevent resource siphoning and energize collaborative innovation. At the same time enterprises should establish joint laboratories with leading research institutions and embed technical milestones and commercialization benchmarks in their agreements to ensure sustained returns for all parties and reinforce long term trust in the alliance.

Platform operators must pursue professional alignment of technology architecture and governance. Technically, they should enable seamless integration of enterprise, partner and user systems and offer real-time dashboards and analytics for monitoring data flows system performance and participation levels. In governance they should convene a council comprising firms, universities research institutes and user representatives. This body regularly reviews contributions in technology data and market impact and adjusts revenue-sharing arrangements and access rules to prevent benefit concentration. Contracts can include an ecosystem health trigger clause that boosts incentives for high-performing actors and initiates urgent council review when key health metrics decline ensuring stable ecosystem operation.

Policy makers can accelerate adoption by designing targeted incentives and delivering effective oversight. They should tie tax credits and subsidies to ecosystem performance metrics. Projects that achieve technical demonstration and commercialisation through third-party validation could receive phased R&D tax deductions. Actors that foster the growth of small innovators and generate significant synergies on the platform could receive innovation vouchers or risk compensation grants reducing their cost of experimentation and amplifying exemplar effects. For oversight they should authorise an independent agency to publish a "DIES Health Report" based on resource flow balance equitable value distribution and contract fulfilment efficiency and incorporate these findings into government and industry regulator performance reviews. Public disclosure of third-party evaluations will compel platforms and enterprises to refine collaboration rules and governance arrangements.

This study examines a DIES composed of four core actors: core digital enterprises, innovation partners, digital product users and digital platforms, with a focus on the mechanisms of their symbiotic evolution. In reality, external entities such as government agencies, regulators and industry associations also play a significant role in ecosystem development. Future research could expand this framework by exploring multi-tier symbiotic relationships in theory and by conducting empirical studies in specific sectors such as healthcare, logistics networks and cloud computing services, in order to understand how differences in resource types, regulatory environments and collaboration models influence the effectiveness of governance frameworks.

Data availability

Data is provided within the manuscript or supplementary information files.

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Declarations

Competing interests
The authors declare no competing interests.

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