Current Science
CS 5 (3), 2429-2448 (2025)
Received 22 Feb 2025 | **Revised 19 March** 2025 | **Accepted 16 April**. 2025 | **Online Available 18 May** 2025
https://doi.org/ 10.52845/CS/2025-5-3-30

Current Science

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OPEN ACCESS

ISSN (O) 2795-8639

Original Article

Decision-Making for the Digital Transformation and Sustainable Development of Artworks: A Game Theory Perspective

Yubin Zhu[1], Yongkang Dong[1], Xiaoqing Fu[1,*]

[1]Shandong Youth Political College, Jinan City 250103, China

[*]Corresponding Author: Xiaoqing Fu

Abstract:
This paper explores the interaction mechanisms underlying the complex behaviors of participants involved in the digital transformation of artworks and provides recommendations for prioritizing the key factors influencing the sustainable development of such transformations. First, an evolutionary game model involving artists, local governments, and art cooperation platforms is constructed to analyze the benefits and costs for each party and to identify the evolutionary stable strategy. Second, the evolutionary game model and preliminary conclusions are validated through empirical analysis. Finally, the impact of critical factors on the evolutionary trajectory is discussed in detail. The results indicate that: (1) Initial willingness affects the speed at which equilibrium is reached, but does not alter participants' strategic choices. (2) Artists, as key executors in the digital transformation process, not only influence their own choices but also regulate the strategic choices of the government and art cooperation platforms. (3) Artists' strategic choices are influenced by the perceived loss of purity and originality of their works in supporting digital transformation, but not by incentives from art cooperation platforms. Meanwhile, the government's strategic choices are related to the amount of financial and human resources invested, as well as the penalties imposed on art cooperation platforms, which in turn base their strategic choices on the penalties imposed by the government.

Keywords : Artworks; digital transformation; evolutionary game theory; sustainable development

Introduction

With the rapid advancement of digital technology, the art world is undergoing a profound transformation. Traditional art forms such as painting, sculpture, and photography are no longer confined to canvas, paper, or physical exhibition spaces, but are finding new expression on digital platforms [1]. Digitization has transformed not only the creation of art but also its dissemination and preservation, allowing artworks to reach a broader audience in ways previously unimaginable [2].

Artists are leveraging digitization to expand artistic boundaries through virtual reality (VR) art, interactive installations, and algorithm-based generative art. [3]. In addition, traditional artworks are being more widely distributed and preserved through digitization, as museums and galleries use high-resolution scanning, virtual exhibitions, and digital reproductions to overcome geographic limitations and allow a global audience to experience every detail of a masterpiece online [4].

This digital transformation goes beyond mere technological advancement; it has prompted a reevaluation of the nature of art itself. The ways in which art exists in virtual space, the possibilities introduced by digital creation tools, and emerging concerns such as copyright and digital ownership are challenging traditional theoretical and cultural frameworks of art [5]. The rise of technologies such as NFTs (non-fungible tokens) has also brought about significant changes in the market structure and economic value of art, forcing artists, collectors, and audiences to rethink notions of ownership and scarcity [6]. This transformation is not only driving the proliferation and

innovation of artworks, but also reshaping how art is created, collected, appreciated, and traded, signaling a new direction for art in the digital age [7].

However, the digital transformation of art also presents several challenges. First, copyright protection for digital works of art has become increasingly complex. Although blockchain technologies such as NFTs offer new ways to own and track works, the ease of reproduction and rapid distribution of digital works continue to facilitate piracy and unauthorized use [8]. Second, the preservation of digital works faces technical and financial hurdles, as evolving storage formats, aging storage media, and potential data loss threaten the long-term survival of these works [9].

Another major challenge is the digital divide and access to the arts. Although digitization has broadened access for global audiences, disparities in technology and equipment still prevent certain regions and populations from fully benefiting from these digital advances [10]. Moreover, the digital art market is still in its infancy, with market speculation, price volatility, and the standardization of artistic values raising concerns about its sustainability and development [11].

Addressing issues of copyright, preservation, and market standardization while encouraging continued innovation remains a critical topic for further exploration in the digital transformation of art. The remainder of this paper is organized as follows: Section 2 reviews the relevant literature and highlights distinctions in previous research. Section 3 outlines the basic assumptions of the study and develops an evolutionary game modeling framework. Section 4 presents numerical simulations of different evolutionarily stable strategies (ESSs). Section 5 conducts a sensitivity analysis to examine the key parameters influencing the game equilibrium. Finally, Section 6 provides a summary of the findings and offers recommendations for stakeholders, while also discussing the limitations of this research and suggesting avenues for future investigation.

Literature Review

The issues discussed in this paper are inextricably linked to the digital transformation of artworks and the evolutionary game model. Accordingly, we divide the summary into two subsections, each addressing one of these issues separately. This approach helps to clarify the distinctions between this paper and the existing literature in these areas.

Digital Transformation

In recent years, the evolution of artworks has received increasing attention from scholars. The research most relevant to this paper includes digitizing art creation, digital preservation and dissemination, digital markets and copyright issues, and art accessibility and the digital divide.

First, concerning the digitization of art production, AI art platforms can greatly enhance the convenience of artistic production and streamline the creative process through generative techniques. However, AI-generated art also poses certain risks and challenges, particularly concerning creators' creativity and copyright [12]. Regarding the digitization of art creation, Kim et al. highlighted that VR technology is transforming the presentation of art creation, allowing artists to transcend the limitations of physical space and create more immersive artistic experiences [13]. Furthermore, the use of artificial intelligence (AI) for algorithmic art generation is becoming mainstream in contemporary art, with automated processes offering new possibilities for artistic creation [14]. Second, in terms of digital preservation and dissemination, advances in digital technology have introduced new solutions for preserving artworks, particularly through high-resolution scanning, three-dimensional modeling, and digital restoration. Georgopoulos explored the role of digitization in preserving fragile artworks, arguing that digital archiving can effectively mitigate physical damage caused by time and environmental factors while providing valuable digital resources for future scholarly research [15]. However, challenges to the long-term preservation of digital works remain. Rothenberg noted in the late 20th century that the perishability of digital media and the need for format updates could threaten the longevity of digitized works[9]. These concerns are still relevant today, and ongoing research explores how to ensure sustainable access to digital artworks in the face of future technological change [16]. Third, the NFT market price began to gradually increase in 2019, experienced a rapid increase in 2021, and entered a relatively stable growth phase in 2022 [17]. Concerning digital markets and copyright issues, Colella examined the impact of NFT technology on the art market, arguing that NFTs

provide a unique mechanism for authenticating and verifying ownership of digital artworks via blockchain, significantly increasing the market value of digital art. However, copyright protection remains a significant challenge in the digital transformation of art[18]. The ease of reproduction and global distribution of digital works makes it difficult to completely prevent copyright infringement. Ullah et al. noted that although blockchain technology provides some copyright protection, the international digital copyright management system still needs significant improvement [19]. Finally, concerning art accessibility and the digital divide, while digitization has expanded access to art for global audiences, disparities in technological resources continue to exacerbate the digital divide. Mihelj showed that virtual exhibitions and digitized artworks offer new cultural experiences to audiences far from major art centers, but limitations in Internet access and digital devices limit access for certain regions and groups [20].

Overall, while numerous studies have examined the digital transformation of artworks, they have focused primarily on technical aspects such as digitization processes, market dynamics, and copyright issues. Few studies have explored the interaction and collaborative decision-making among stakeholders involved in the digital transformation of art, and even fewer have analyzed this process using evolutionary game theory.

Evolutionary Game Theory (EGT)

Originally developed as a mathematical tool for analyzing strategic choices in biological contexts, evolutionary game theory has since been applied to fields such as economics, sociology, and culture [21–23].

In recent years, evolutionary game models have been widely used to explore the complexities of the digital transformation of artworks, particularly in the areas of art creation, market behavior, and copyright protection. These models reveal the strategic evolution of stakeholders within the digital ecosystem [24]. Researcher analyzed innovation and imitation behavior in art creation, noting that during the digital transformation, innovative artists can achieve higher returns through technological advantages, while imitators can gain market share by replicating successful works at low cost [25]. The evolutionary game model reveals the dynamic equilibrium between innovation and imitation under varying technological and market conditions, providing a theoretical framework for understanding how artists choose between innovation and imitation in a rapidly evolving digital environment. Khare applied game theory to examine copyright protection mechanisms for digital artworks and found that stronger copyright regulation and technological protection can significantly reduce infringement [26]. By analyzing strategic evolution within the game, their study showed that as the cost of infringement increases and copyright protection technologies advance, the incidence of infringement decreases, leading to an overall improvement in the effectiveness of copyright protection. Li used a game model to analyze the dynamic game in the market, showing how market participants' strategic decisions regarding pricing, scarcity, and market trust are shaped by blockchain technology, platform reputation, and market regulations [27]. Prinz investigated the game dynamics between artists and digital platforms, analyzing the evolution of artists' platform selection strategies [28]. Fudenberg and Levine pointed out that the creation, distribution, and consumption of art in the digital context form a complex ecosystem [29]. The evolutionary game model can simulate the strategic interactions and evolutionary processes among various stakeholders, revealing the dynamic equilibrium of this ecosystem. This approach provides a macro-level theoretical framework to support the digital transformation of artworks.

Methodology

Problem Description

In the context of the digital transformation of artworks, this paper identifies three main players: artists, local governments, and art cooperation platforms, each of which faces different challenges.

The primary challenge for artists is how to protect and display their creative works in a digital environment. While digitization offers greater opportunities for the dissemination and commercialization of artworks, it also poses challenges for copyright protection. Artists must navigate the tension between maximizing the

exposure of their work on digital platforms and protecting their intellectual property rights against illegal copying and misuse [30]. In addition, the shift to digital art forms requires artists to develop technical expertise in emerging digital tools and platforms in order to remain competitive in an increasingly crowded marketplace.

For local governments, the challenge is to formulate effective policies that support the digital transformation of artworks while ensuring the preservation of cultural heritage [31]. Governments must establish a robust legal framework that protects artists' rights and encourages the growth of the digital cultural industry. In addition, they must consider how to encourage broader participation of artists and cultural institutions in the digital transformation process through policy incentives that ensure both the diversity and sustainability of digital culture.

The challenge for art cooperation platforms, as a critical intermediary between artists and the public, is to strike an optimal balance between technology and art. These platforms must provide a digital space that protects artists' originality and intellectual property rights, while also providing artists with the means to effectively display and promote their work [32]. In addition, platforms face the constant pressure of technological advances that require them to continually optimize the user experience in order to attract and retain both artists and users. Furthermore, art cooperation platforms must skillfully manage their relationships with local governments and other commercial organizations within the complex digital ecosystem to maintain their legitimacy and competitiveness. The theoretical framework for the game model involving the three parties-artists, local governments, and art cooperation platforms-is depicted in Figure 1.

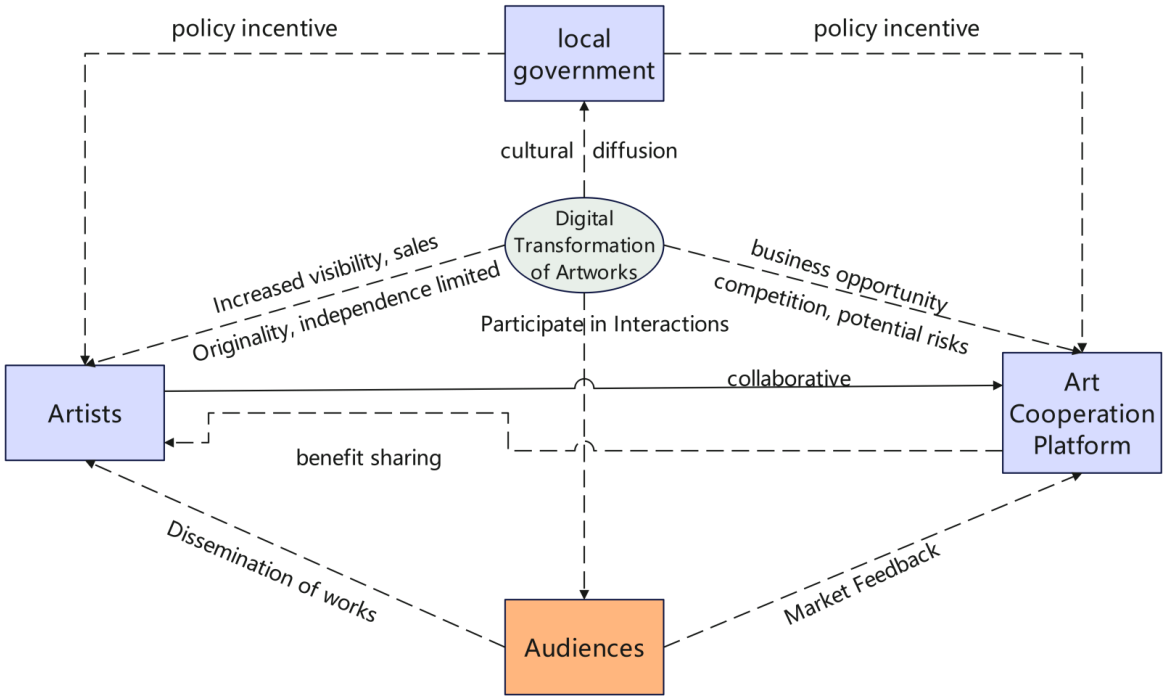

Figure 1 Diagram of the theoretical framework of the game model

Model assumptions

Assumption 1: In the evolutionary game model, artists, local governments, and art cooperation platforms are considered finitely rational actors. They learn from and imitate each other throughout the game in order to maximize their interests.

Assumption 2: The artist's strategy space is $S_A = \{support, not\ support\}$, where x represents the probability of supporting the digital transformation of artworks, and $1-x$ represents the probability of not supporting it. The local government's strategy space is $S_G = \{support, not\ support\}$, where y is the probability of supporting and $1-y$ is the probability of not supporting. Similarly, the art collaboration platform's strategy space is $S_P = \{support, not\ support\}$, where z is the probability of supporting digital transformation and $1-z$ is the probability of not supporting.

Assumption 3: Artists who support digital transformation experience increased visibility and sales, generating an immediate gain denoted as R_{A1}. Digital platforms enable effective audience engagement, improve work distribution, and provide real-time feedback, leading to cumulative benefits R_{A2}. However, platform commercialization risks compromising the purity and originality of artwork, resulting in potential losses C_{A1}. Artists incur Ldecision costs when platforms resist transformation.

If the artist does not support the digital transformation of their artwork, they can focus on the creative process and the presentation of artistic values, preserving the purity and independence of their work, resulting in enhanced reputation and word-of-mouth benefits, referred to as R_{A3}. However, the artist loses the opportunity for closer audience interaction and broader promotion of their work, resulting in a significant decline in popularity and sales. This direct loss is recorded as C_{A2}.

Hypothesis 4: Local government support for digital transformation fosters new cultural industries. This support modernizes and internationalizes the cultural sector, while introducing innovative methods of cultural protection, increasing urban visibility and development vitality. The cumulative benefit is recorded as R_{G1}. However, supporting the digital transformation of artworks requires financial and human resource investment in the art cooperation platform, denoted as Q.

While higher-level governments are aligning their policies with digital trends to improve cultural quality, some local governments remain inactive. Inactive governments risk F_G penalties from higher authorities.

Assumption 5: Platforms supporting transformation capitalize on digital opportunities to increase brand awareness and market share. The direct benefit from this is captured as R_{P1}. Digital platforms also expand opportunities for collaboration, strengthen relationships between artists and audiences, and offer potential benefits R_{P2}. However, transformation involves originality risks C_{P1}. Platforms must handle technological updates and optimize user experience, incurring input costs C_{P2}. In addition, the platform must implement incentives to encourage artists to support the digital transformation, and the cost of these incentives is recorded as E.

Platforms avoiding transformation face reduced brand exposure and commercial influence C_{P3}. Local governments provide platform support but enforce monitoring, with penalties F_P for non-compliance.

Table 1 shows a description of the parameters, variables and their meanings in this section.

Table 1. Parameter and Variable Settings

Stakeholders	Parameters	Meanings
Artists	R_{A1}	Increase visibility and sales by supporting the digital transformation of artwork
	R_{A2}	Real-time feedback and support to support the digital transformation of artwork
	R_{A3}	The word-of-mouth and reputational benefits of not supporting the digital transformation of artwork
	L	Additional costs to the artist when not supported by an art collaboration platform
	C_{A1}	The loss of purity and originality of artworks when supporting digital transformation of artworks
	C_{A2}	Direct costs of not supporting the digital transformation of artwork
Local government	R_{G1}	Improved city image and visibility when supporting digital transformation of artwork
	Q	Financial and human resources invested to support the digital transformation of artwork
	F_G	Penalties for failing to support the digital transformation of artwork

Artistic Cooperation Platform	R_{P1}	Increase brand awareness and market share by supporting the digital transformation of artwork
	R_{P2}	The benefits of building strong relationships with artists when supporting the digital transformation of artwork
	C_{P1}	Risk of loss of originality of works when supporting digital transformation of artwork
	C_{P2}	Technology costs invested to support the digital transformation of artwork
	C_{P3}	Opportunity cost of not supporting the digital transformation of artwork
	E	Incentive costs invested in artists when supporting digital transformation of artwork
	F_P	Penalized by local governments if not supported in digital transformation of artwork
	Variables	Meanings
	x	Probability that the artist supports the digital transformation of the artwork
	y	Probability that local government supports the digital transformation of artwork
	z	Probability that the art collaboration platform chooses to support the digital transformation of the artwork

Model Building

Combining the above assumptions, the payoff matrix of the tripartite game model is constructed as shown in Table 2.

Table 2. Payoff Matrix of the Three-Party Game Subjects

Artists	Local government	Artistic Cooperation Platform	
		Support (z)	Not Support (1-z)
Support(x)	Support(y)	$R_{A1}+R_{A2}+E-C_{A1}$ $R_{G1}-Q$ $R_{P1}+R_{P2}+Q-E-C_{P1}-C_{P2}$	$R_{A1}+R_{A2}-L-C_{A1}$ F_P-Q $Q-C_{P3}-F_P$
	Not Support (1-y)	$R_{A1}+R_{A2}+E-C_{A1}$ $-F_G$ $R_{P1}+R_{P2}-E-C_{P1}-C_{P2}$	$R_{A1}+R_{A2}-L-C_{A1}$ $-F_G$ $-C_{P3}$
Not Support (1-x)	Support (y)	$R_{A3}+E-C_{A2}$ $-Q$ $Q-E-C_{P2}$	$R_{A3}-C_{A2}$ F_P-Q $Q-C_{P3}-F_P$
	Not Support (1-y)	$R_{A3}+E-C_{A2}$ $-F_G$ $-E-C_{P2}$	$R_{A3}-C_{A2}$ $-F_G$ $-C_{P3}$

Model Analysis

Based on the assumptions of the evolutionary game for the digital transformation of artworks and the pure strategy payoff matrices of the various participants, the payoff functions and dynamic replicator equations for the artist, the local government, and the art cooperation platform can be derived. The expected returns for artists adopting the "support" and "not support" strategies are denoted as U_{11} and U_{12}, respectively. The average expected return, $\overline{U_1}$, is calculated as follows:

$$U_{11} = yz(R_{A1} + R_{A2} + E - C_{A1}) + y(1-z)(R_{A1} + R_{A2} - L - C_{A1}) + (1-y)z(R_{A1} + R_{A2} + E - C_{A1}) + (1-y)(1-z)(R_{A1} + R_{A2} - L - C_{A1}) \quad (1)$$

$$U_{12} = yz(R_{A3} + E - C_{A2}) + y(1-z)(R_{A3} - C_{A2}) + (1-y)z(R_{A3} + E - C_{A2}) + (1-y)(1-z)(R_{A3} - C_{A2}) \quad (2)$$

$$\overline{U_1} = xU_{11} + (1-x)U_{12} \quad (3)$$

Building dynamic equations for artist's replication:

$$F(x) = \frac{dx}{dt} = x\left(U_{11} - \overline{U_1}\right) = x(1-x)(C_{A2} - C_{A1} - L + R_{A1} + R_{A2} - R_{A3} + zL) \quad (4)$$

Take the first-order derivative of $F(x)$:

$$F'(x) = (1-2x)(C_{A2} - C_{A1} - L + R_{A1} + R_{A2} - R_{A3} + zL) \quad (5)$$

According to the evolutionary stability theorem, if $F(x) = 0$, $F'(x) < 0$, then x is an evolutionarily stable point. Since $F(x) = 0$, x can be either 0, 1, or $z = \frac{-C_{A2}+C_{A1}+L-R_{A1}-R_{A2}+R_{A3}}{L}$. If $z = \frac{-C_{A2}+C_{A1}+L-R_{A1}-R_{A2}+R_{A3}}{L}$, then for any x there exists $F(x) = 0$ and $F'(x) = 0$, meaning that x is in a stable state, and any strategy chosen by the artist at that point becomes a stabilizing strategy. When $z \neq \frac{-C_{A2}+C_{A1}+L-R_{A1}-R_{A2}+R_{A3}}{L}$, the following discussion is divided into cases:

If $z > \frac{-C_{A2}+C_{A1}+L-R_{A1}-R_{A2}+R_{A3}}{L}$, and according to the model assumption $L > 0$, substituting $x = 0$ and $x = 1$ into $F'(x)$ yields $F'(0) > 0$ and $F'(1) < 0$. This indicates that $x = 1$ is the evolutionarily stable point. At this point, the finitely rational artist will choose to support the digital transformation of artwork.

If $z < \frac{-C_{A2}+C_{A1}+L-R_{A1}-R_{A2}+R_{A3}}{L}$, substituting $x = 0$ and $x = 1$ into $F'(x)$ yields $F'(0) < 0$ and $F'(1) > 0$. This indicates that $x = 0$ is the evolutionarily stable point. At this point, the finitely rational artist will not choose to support the digital transformation of artwork.

The expected benefits of the government's "support" and "not support" strategies are denoted as U_{21} and U_{22}, respectively, and the average expected benefit, $\overline{U_2}$, is calculated using the following formula:

$$U_{21} = xz(R_{G1} - Q) + x(1-z)(F_P - Q) + (1-x)z(-Q) + (1-x)(1-z)(F_P - Q) \quad (6)$$

$$U_{22} = xz(-F_G) + x(1-z)(-F_G) + (1-x)z(-F_G) + (1-x)(1-z)(-F_G) \quad (7)$$

$$\overline{U_2} = yU_{21} + (1-y)U_{22} \quad (8)$$

Building a replicated dynamic equation for government:

$$F(y) = \frac{dy}{dt} = y\left(U_{21} - \overline{U_2}\right) = y(1-y)(F_G + F_P - Q - zF_P + xzR_{G1}) \quad (9)$$

Take the first-order derivative of $F(y)$:

$$F'(y) = (1-2y)(F_G + F_P - Q - zF_P + xzR_{G1}) \quad (10)$$

The expected gains for the "support" and "non-support" strategies are shown as U_{31} and U_{32}, respectively, and the average expected gain, $\overline{U_3}$, is calculated using the following formula:

$$U_{31} = xy(R_{P1} + R_{P2} + Q - E - C_{P1} - C_{P2}) + x(1-y)(R_{P1} + R_{P2} - E - C_{P1} - C_{P2}) + (1-x)y(Q - E - C_{P2}) + (1-x)(1-y)(-E - C_{P2}) \quad (11)$$

$$U_{32} = xy(Q - C_{P3} - F_P) + x(1-y)(-C_{P3}) + (1-x)y(Q - C_{P3} - F_P) + (1-x)(1-y)(-C_{P3}) \quad (12)$$

$$\overline{U_3} = zU_{31} + (1-z)U_{32} \quad (13)$$

Building replicated dynamic equation for art cooperation platforms:

$$F(z) = \frac{dz}{dt} = z\left(U_{31} - \overline{U_3}\right) = z(1-z)(C_{P3} - C_{P2} - E - xC_{P1} + yF_P + xR_{P1} + xR_{P2}) \quad (14)$$

Take the first-order derivative of $F(z)$:

$$F'(z) = (1-2z)(C_{P3} - C_{P2} - E - xC_{P1} + yF_P + xR_{P1} + xR_{P2}) \quad (15)$$

The three equations $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$ from the replicator dynamics equations yield eight local equilibrium points: $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,0,1)$, $E_7(1,1,0)$ and $E_8(1,1,1)$. The Evolutionary Stable Strategy (ESS) of the system of differential equations is determined by analyzing the local stability of the Jacobian matrix. This stability is determined by evaluating its eigenvalues [33]. The Jacobian matrix is derived from the replicator dynamics equations as follows:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

By substituting each of the eight equilibrium points into the Jacobian matrix, the corresponding eigenvalues can be computed, as shown in Table 3. According to Lyapunov's stability theory, an equilibrium point is an Evolutionarily Stable Strategy (ESS) if and only if all eigenvalues of the Jacobian matrix are negative [34]. Conversely, the equilibrium point is unstable if the signs of all eigenvalues can be determined and at least one eigenvalue is positive [35].

Table 3. Eigenvalues of the Jacobi Matrix

Equilibrium point	Eigenvalue 1	Eigenvalue 2	Eigenvalue 3
$E_1(0,0,0)$	$C_{A2} - C_{A1} - L + R_{A1} + R_{A2} - R_{A3}$	$F_G + F_P - Q$	$C_{P3} - C_{P2} - E$
$E_2(0,0,1)$	$C_{A2} - C_{A1} + R_{A1} + R_{A2} - R_{A3}$	$F_G - Q$	$-C_{P3} + C_{P2} + E$
$E_3(0,1,0)$	$C_{A2} - C_{A1} - L + R_{A1} + R_{A2} - R_{A3}$	$-F_G - F_P + Q$	$C_{P3} - C_{P2} - E + F_P$
$E_4(0,1,1)$	$C_{A2} - C_{A1} + R_{A1} + R_{A2} - R_{A3}$	$-F_G + Q$	$-C_{P3} + C_{P2} + E - F_P$
$E_5(1,0,0)$	$C_{A1} - C_{A2} + L - R_{A1} - R_{A2} + R_{A3}$	$F_G + F_P - Q$	$C_{P3} - C_{P2} - C_{P1} - E + R_{P1} + R_{P2}$
$E_6(1,0,1)$	$C_{A1} - C_{A2} - R_{A1} - R_{A2} + R_{A3}$	$F_G + R_{G1} - Q$	$-C_{P3} + C_{P2} + C_{P1} + E - R_{P1} - R_{P2}$
$E_7(1,1,0)$	$C_{A1} - C_{A2} + L - R_{A1} - R_{A2} + R_{A3}$	$-F_G - F_P + Q$	$C_{P3} - C_{P2} - C_{P1} - E + F_P + R_{P1} + R_{P2}$
$E_8(1,1,1)$	$C_{A1} - C_{A2} - R_{A1} - R_{A2} + R_{A3}$	$-F_G - R_{G1} + Q$	$C_{P1} + C_{P2} - C_{P3} + E - F_P - R_{P1} - R_{P2}$

For the sake of generality, it is assumed that the benefits when all three parties of the game choose to support the digital transformation strategy of the artwork are greater than the benefits when they do not and that the benefits are all positive [36]. So that, $R_{A1} + R_{A2} + E - C_{A1} > 0$ 、$R_{G1} - Q > 0$、$R_{P1} + R_{P2} + Q - E - C_{P1} - C_{P2} > 0$. Similarly, if all three parties choose not to support the digital transformation strategy for artwork, their utility functions are all less than 0. Therefore, the $R_{A3} - C_{A2} < 0$ 、$-F_G < 0$、$-C_{P3} < 0$. It follows that, $C_{A2} - C_{A1} - L + R_{A1} + R_{A2} - R_{A3} < 0$. The stability analysis results of the tripartite evolutionary results of the artwork digital transformation strategy game obtained by analyzing the eigenvalues in the Jacobi matrix are shown in Table 4.

Table 4. Equilibrium and Stability

Equilibrium point	Eigenvalue	Stability
E_1(0,0,0)	(-,-,+)	non-stable point
E_2(0,0,1)	(+,-,-)	non-stable point
E_3(0,1,0)	(-,+,+)	non-stable point
E_4(0,1,1)	(+,+,-)	non-stable point
E_5(1,0,0)	(+,-,+)	non-stable point
E_6(1,0,1)	(+,+,-)	non-stable point
E_7(1,1,0)	(+,+,+)	saddle
E_8(1,1,1)	(-,-,-)	ESS

In the real world, political, cultural, and other external environmental factors influence decisions related to the digital transformation and sustainable development of artworks. These influences are accompanied by speculative behavior, irrational decision-making, and moral hazard, which interact to create random perturbations that affect the tripartite evolutionary game process. This introduces uncertainty and causes random mutations in the game dynamics [37]. To account for this uncertainty, [38] pioneered the integration of randomness into replicator dynamics equations and proposed a stochastic differential equation model, commonly referred to as a stochastic evolutionary game model. Scholars primarily represent stochastic interference in decision-making strategies by incorporating the Itô process, the Moran process, the Wright-Fisher process, and the pairwise comparison process into evolutionary game models. Among these, the Itô process is a generalized form of the Wiener process, which extends Brownian motion by introducing a random interference term. It characterizes the stochastic nature of random variables through stochastic differential equations, effectively capturing their time series properties [39]. Based on the above analysis, by introducing Gaussian white noise $d\omega(t)$ as well as a random disturbance term σ to represent the random disturbance factor, the replication dynamic equation with disturbance term is constructed by introducing the disturbance factor into the replication dynamic equation as follows:

$$dx(t) = (C_{A2} - C_{A1} - L + R_{A1} + R_{A2} - R_{A3} + zL)x(t)dt + \sigma x(t)d\omega(t) \quad (16)$$

$$dy(t) = (F_G + F_P - Q - zF_P + xzR_{G1})y(t)dt + \sigma y(t)d\omega(t) \quad (17)$$

$$dz(t) = (C_{P3} - C_{P2} - E - xC_{P1} + yF_P + xR_{P1} + xR_{P2})z(t)dt + \sigma z(t)d\omega(t) \quad (18)$$

Empirical Analysis

To further validate and test the proposed model, this paper conducts an empirical analysis of the "City of Light" light and shadow art project [40]. The successful implementation and operation of this project, a milestone in the digital transformation of artworks, exemplifies the deep integration of art and technology. In the initial phase, an investment of approximately RMB 7.4 million was made, which included customized LED screen installations, advanced control

systems, creative design and content production by the design team, and cooperation costs with the art cooperation platform. During the operational phase, the project will require approximately RMB 800,000 annually for electricity, maintenance and system upgrades. These investments have generated significant financial returns, with the project expected to generate over RMB 3.5 million annually through visitor attraction, exhibitions, and advertising sponsorships. However, success is not without risk. The project faces challenges such as technical failures and delayed content updates, with estimated losses of approximately RMB 100,000 per year due to technical issues and an additional RMB 200,000 per year for content updates. To incentivize the project team, the government has offered tax breaks of RMB 300,000 and a capital grant of RMB 500,000. However, if the project encounters major failures or quality issues, it risks penalties such as the withdrawal of government subsidies, public criticism, or fines of up to RMB 1 million.

Based on the above information, we set the parameter to $C_{A2} = 1$, $C_{A1} = 1.6$, $L = 1.5$, $R_{A1} = 0.8$, $R_{A2} = 0.6$, $R_{A3} = 0.5$, $F_G = 2$, $F_P = 1$, $Q = 7.4$, $R_{G1} = 6$, $C_{P3} = 1.5$, $C_{P2} = 0.8$, $E = 0.2$, $C_{P1} = 0.3$, $R_{P1} = 3.5$, $R_{P2} = 0.5$, in millions of RMB Yuan.

Simulation and Analysis

Evolutionary Stability Strategy Tests

Under the above assignment conditions, the initial evolutionary trajectory of the three-party game subject replicating the dynamic equation for 100 iterations is obtained, as shown in Figure 2.

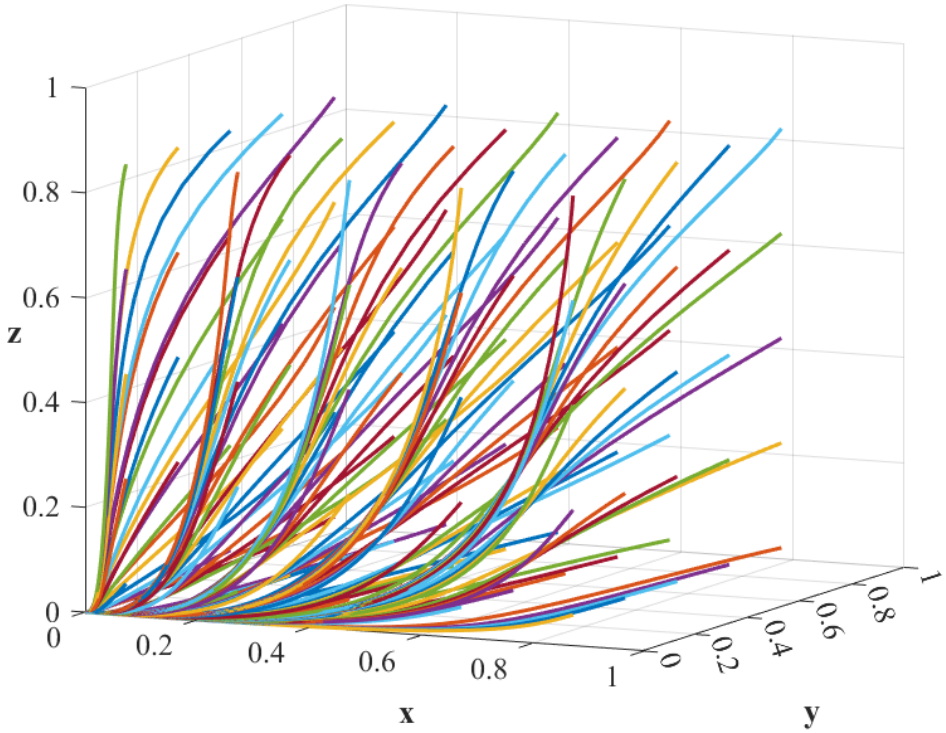

Figure 2 Initial evolutionary trajectory

Under the initial conditions, the evolutionary stable strategy of the three-dimensional game tends to $E_1(0,0,0)$. This indicates that the equilibrium point is the asymptotically evolutionary stable strategy of the three-dimensional game system. At this point, the corresponding strategies for each party are: the artist adopts the "no support" strategy, the government adopts the "no support" strategy, and the art cooperation platform also adopts the "no support" strategy. Thus, all three parties - the artist, the government, and the art cooperation platform - converge on the "no support" strategy.

The effect of initial willingness on evolutionary results

Initial willingness refers to the degree to which

artists, governments, and art cooperation platforms are inclined to support the digital transformation of artworks. In order to analyze how this initial readiness affects the evolutionary trajectory of these three groups, this section sets the initial readiness levels of artists, governments, and art cooperation platforms - denoted A, B, C - at low, medium, and high levels, corresponding to values of 0.2, 0.5, and 0.8, respectively. Meanwhile, all other parameters remain unchanged in order to study how the different levels of initial willingness of the three parties affect the equilibrium of the system, as shown in Figure 3.

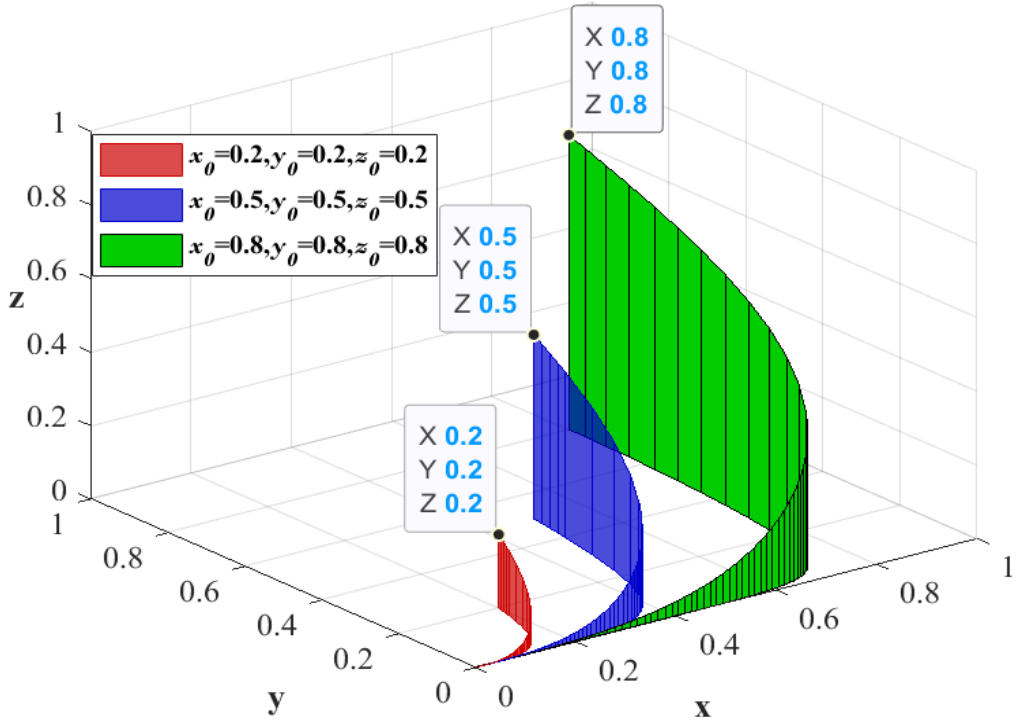

Figure 3. The effect of initial willingness on evolutionary results

As shown in Figure 3, changes in initial willingness do not affect the strategic choices of game participants. Artists, regardless of initial willingness, consistently choose not to support the digital transformation of artworks. This suggests that artists weigh the potential value-added gains against the associated costs and other negative impacts, and ultimately decide that the benefits of not supporting digital transformation outweigh those of supporting it. Similarly, both the government and the art cooperation platforms, while changing their initial willingness to support digital transformation, maintain their strategy of "not supporting" when the initial conditions are fixed.

Influence of C_{A1} on evolutionary results

As key actors in the digital transformation of artworks, artists' actions not only affect their own decisions but also shape the strategic choices of governments and art cooperation platforms. This section analyzes the impact of C_{A1}, which represents the loss of purity and originality of artworks when artists support digital transformation. Specifically, the effects of C_{A1} values of 0.2, 0.9, and 1.6 on the equilibrium of the system are examined when artists support the digital transformation of artworks. According to the previous analysis, changes in initial willingness do not affect the strategic choices of game participants. Therefore, for simplicity, the initial willingness of all three parties is set uniformly to 0.5, while other parameters remain unchanged. The influence of C_{A1} on the evolutionary results is shown in Figure 4, and its influence on the artists' strategies is shown in Figure 5.

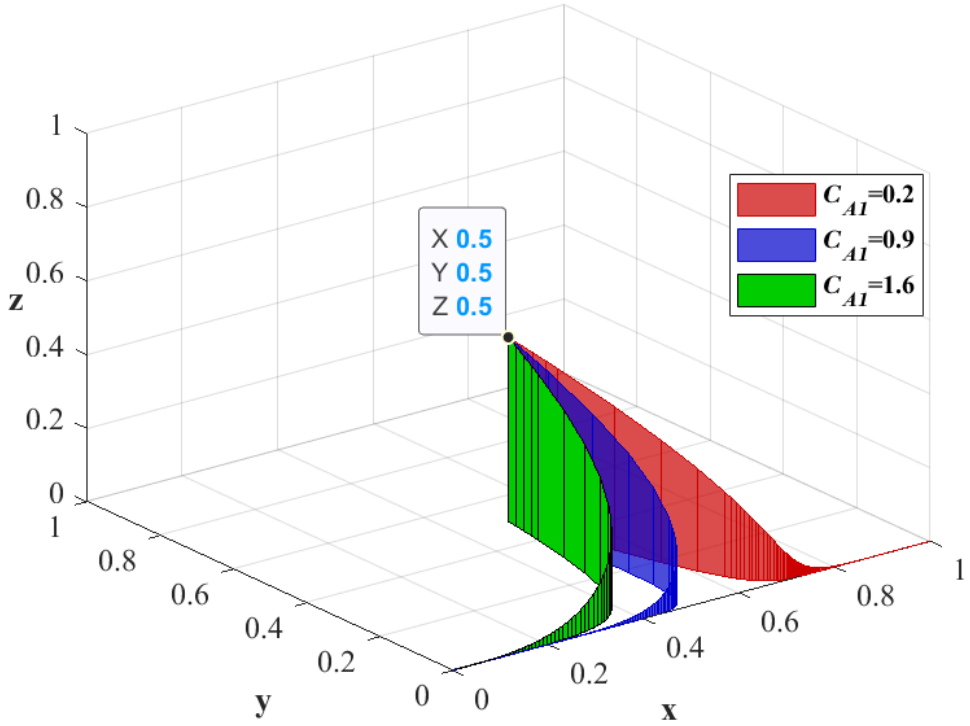

Figure 4 Influence of C_{A1} on evolutionary results

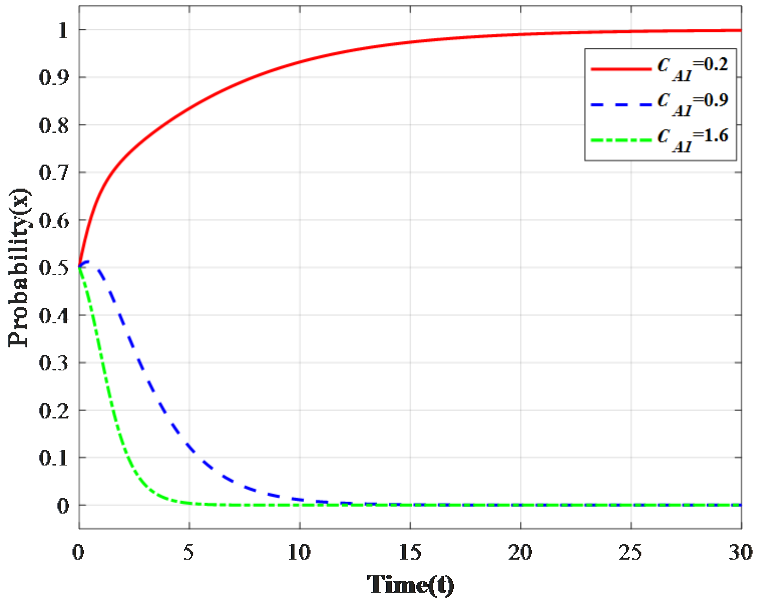

Figure 5 Influence of C_{A1} on artists' strategies

According to Figure 4, the evolutionary stabilization strategy of the three-party game changes as the loss of purity and originality of the artwork increases when the artist supports its digital transformation. This suggests that as the loss of purity and originality increases, the artist's potential risk in supporting the digital transformation increases, leading to progressively lower relative returns. Consequently, due to the limited rationality of game participants, they tend to choose strategies that maximize their interests at the outset.

As shown in Figure 5, the change in the strategy threshold regarding the loss of purity and originality occurs between C_{A1} values of 0.2 and 0.9. When $C_{A1} = 0.2$, x tends to 1, which means that the artist adopts a supportive strategy.

However, when $C_{A1} \geq 0.9$, x tends toward 0, indicating that the artist is adopting a non-support strategy. Additionally, the higher the value of C_{A1}, the shorter the time it takes for the system to reach equilibrium. Higher potential risks lead the artist to abandon support for the digital transformation project more quickly.

Influence of Q on Evolutionary Results

Q represents the financial and human resources invested by the government to support the digital transformation of artworks. Let Q take the values 2.4, 4.4, and 6.4, while the initial willingness of the three parties is uniformly set to 0.5. With all other parameters held constant, the influence of Q on the evolutionary outcomes is shown in Figure 6, while the influence of Q on the government's strategy is shown in Figure 7.

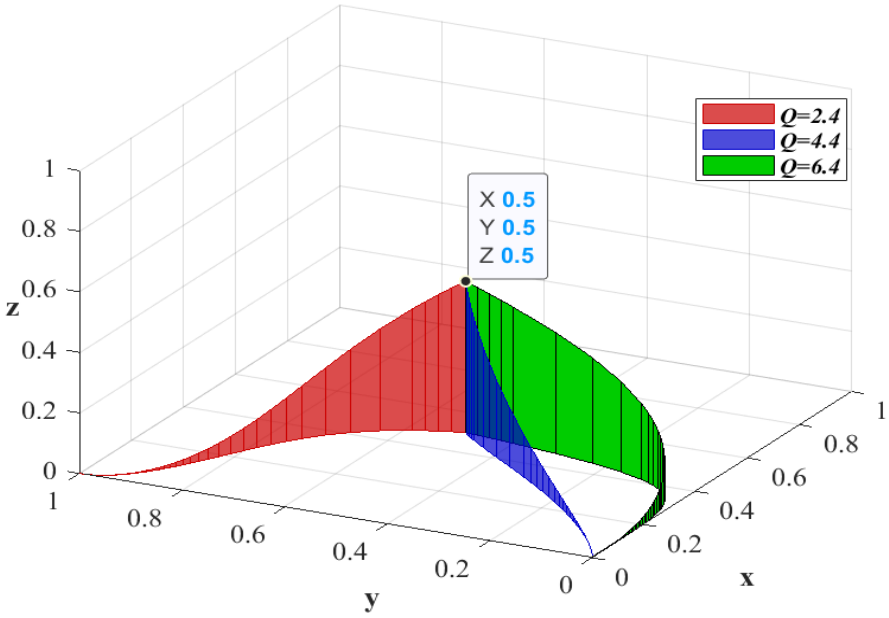

Figure 6 Influence of Q on evolutionary results

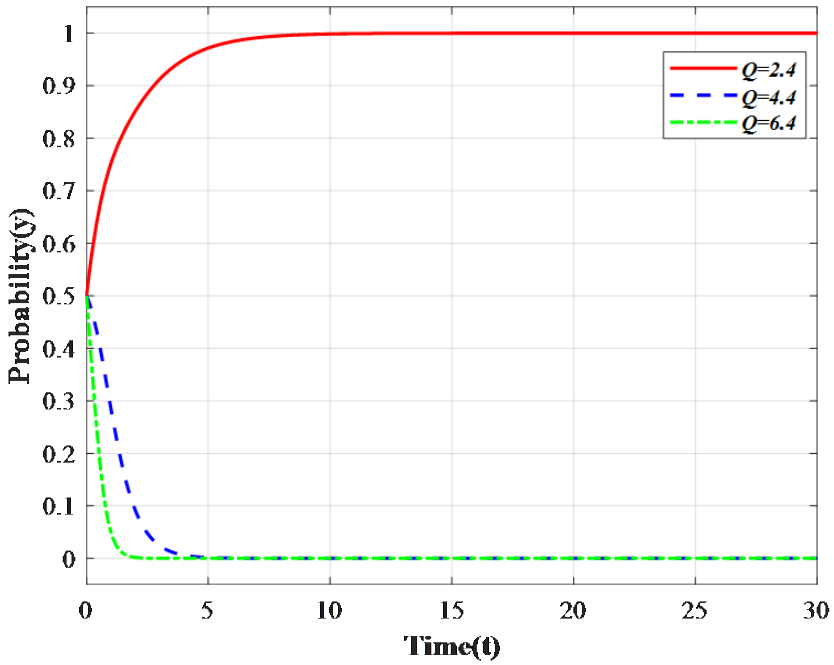

Figure 7 Q influence on government strategy.

According to Figures 6 and 7, the evolutionarily stable strategy of the three-party game shifts from $E_3(0,1,0)$ to $E_1(0,0,0)$ as the financial and human resources invested by the government to support the digital transformation of artworks increase. Specifically, the threshold for additional investment that influences the government's strategy change is between 2.4 and 4.4. When Q=2.4, y tends to 1, which means that the government supports the digital transformation of artworks. However, when $Q \geq 4.4$, y tends to 0, indicating that the government does not support the digital transformation of artworks. To optimize the process, the government should focus on effective financial planning, proactively acquire relevant information, and establish efficient workflows to reduce costs and ensure the sustainable development of the digital transformation of artworks.

Influence of F_P on evolutionary results

Local governments not only provide financial incentives to art cooperation platforms but also establish monitoring mechanisms. If these platforms fail to fulfill their responsibilities in the digital transformation of artworks, they will be punished by the government. The likelihood that an art cooperation platform, as an implementer of government policy, will choose the "support" strategy may be influenced by the severity of the penalties imposed by the government. Based on this, with F_P set at 2, 6, and 10, and the initial willingness of all three parties uniformly set at 0.5, while holding other parameters constant, the influence of F_P on the evolutionary outcomes is illustrated in Figure 8. The effects of F_P on the strategies of the government and the art cooperation platform are shown in Figures 9 and 10.

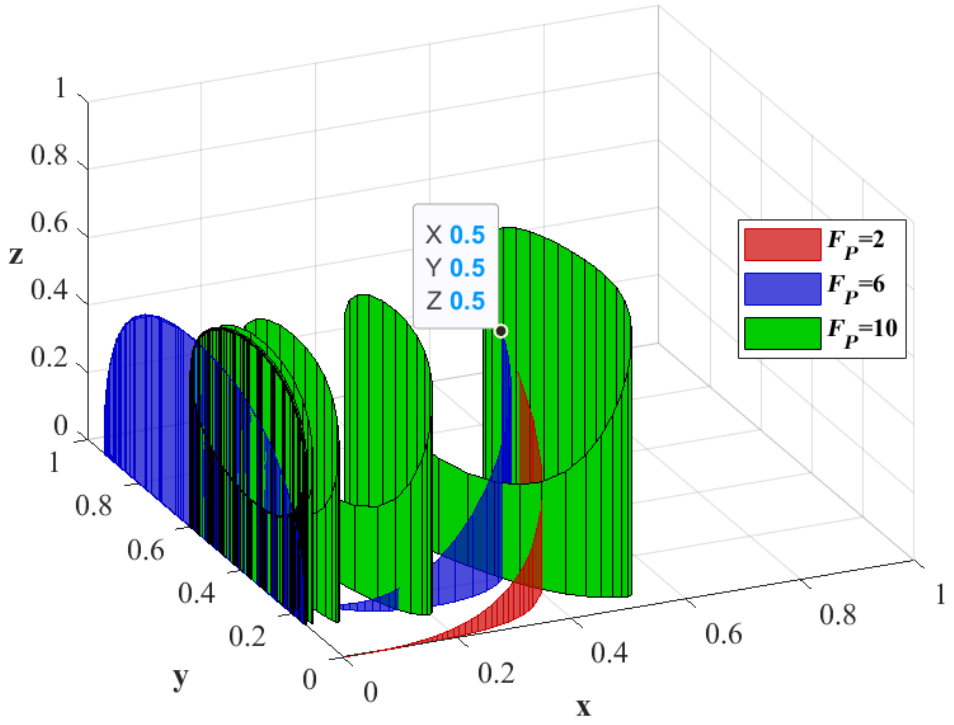

Figure 8 Influence of F_P on evolutionary results

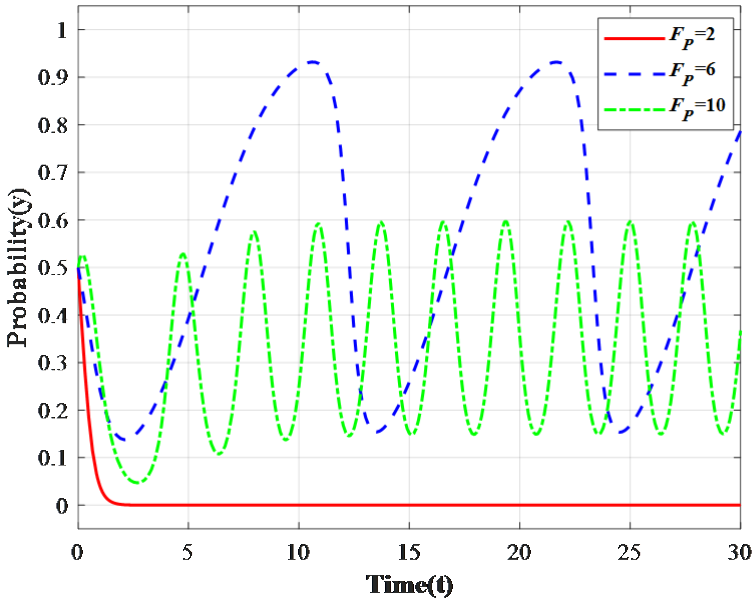

Figure 9 Influence of F_P on Government Strategies

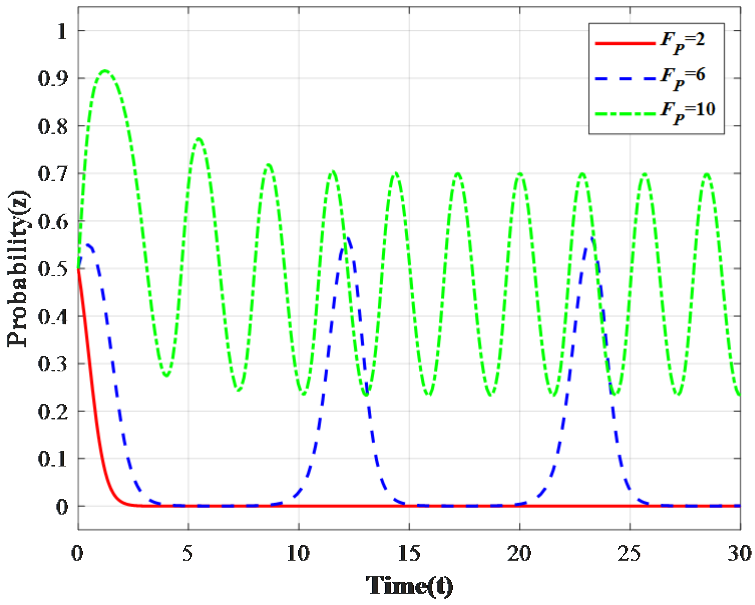

Figure 10 The Influence of F_P on Artistic Collaboration Platform Strategies

According to Figure 8, the evolutionarily stable strategy of the three-party game subjects changes when art cooperation platforms are penalized by the local government for not supporting the digital transformation of artworks. This indicates that as the penalty amount increases, the profitability of the "not support" strategy for the art cooperation platform decreases, forcing the platform to adjust its strategy. At the same time, fluctuations in the platform's strategy will influence the government's decision. However, the artists' strategy remains unaffected due to the uniqueness of the effect of the penalty, and they continue to maintain the "no support" strategy under the current conditions.

As shown in Figures 9 and 10, the penalty threshold that causes both the art cooperation platform and the government to change their strategy lies between $F_P = 2$ and $F_P = 6$. When $F_P = 2$, the stable strategy of the three-party game converges to $E_{1(0,0,0)}$. When $F_P \geq 6$, the strategy choices of both the art cooperation platform and the government fluctuate, making the subjects highly sensitive to any external changes that might affect their decision-making.

In this regard, the government can implement

measures such as (1) establishing certification standards for digital art, (2) setting specific thresholds for platform fines, and (3) creating a special fund for digital transformation projects to encourage game companies to support the digitization of artworks.

The influence of Stochastic Disturbances on Evolutionary Results

Due to the volatility of external factors such as politics and culture, as well as the speculative mindset of decision-makers, the strategic decisions of artists, local governments, and art cooperation platforms to support the digital transformation of artworks remain unstable. Therefore, it is essential to consider the impact of random interference on decision-making. To investigate the impact of different levels of random interference on strategic choices, the random interference intensity σ is set to 0, 0.5, and 1, respectively. The corresponding evolutionary results are shown in Figure 11.

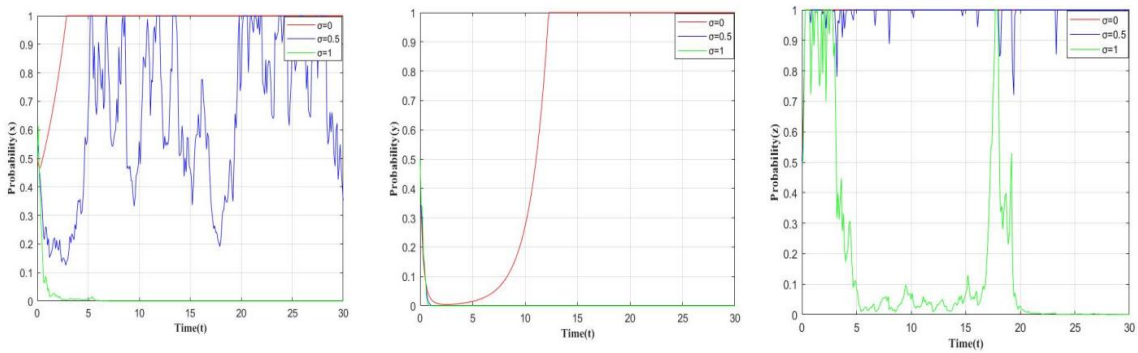

Figure 11. The influence of σ on evolutionary results

As shown in Figure 11, when the government, artists, and art cooperation platforms are not influenced by political, cultural, or other external factors, they quickly converge on an evolutionarily stable strategy and are more inclined to support the digital transformation of artworks. However, as external uncertainty increases, players tend to withdraw their support for digital transformation to protect their own interests. The evolutionary results suggest that the strategic choices of artists and art cooperation platforms exhibit greater volatility in response to changes in the external environment. To address this, it is necessary to: (1) improve policy formulation and strengthen policy supervision; (2) implement reasonable financial measures; and (3) establish diversified rights protection mechanisms for artists and art platforms to safeguard copyrights and other related rights.

Conclusion

The willingness of artists, governments, and art cooperation platforms to engage in digital transformation projects for artworks remains a contentious issue. Previous studies have not adequately considered the evolutionary stability of these stakeholders or the conditions necessary to reach equilibrium. In this paper, we use the evolutionary game model to analyze and identify potential Evolutionarily Stable Strategies (ESS) and their respective stability conditions. We then conduct numerical simulations, along with empirical and sensitivity analyses, to explore the dynamic evolution of the game participants as various parameters change. Our main conclusions are as follows:

First, the strategies of artists, governments, and art cooperation platforms remain unchanged under different initial values. However, appropriate regulation in the early stages can shorten the evolution time of the system, thereby reducing the overall time cost of digital transformation projects for artworks.

Second, the artist, as the primary executor in the digital transformation of artworks, influences not only his own decisions but also the strategic choices of the government and the art cooperation platform.

Third, artists' strategic choices are influenced by the perceived loss of purity and originality of their works during digital transformation, but not by the incentives provided by art cooperation platforms. In contrast, the government's strategic choices are

influenced by the amount of financial and human resources invested and the penalties imposed on art cooperation platforms. The strategic choices of the art cooperation platform are directly related to the severity of the penalties imposed by the government. These parameters can be further optimized, suggesting that local governments should focus on setting specific priorities.

Finally, local governments should adopt additional strategies to protect the purity and originality of artists' works while enhancing the motivation of both artists and art cooperation platforms. Balancing local protectionism with policy incentives will be a key challenge for local governments in the future.

Management Implications

Effective early-stage regulation and planning. Local governments should: 1) Establish digital art authentication standards through blockchain verification protocols. 2) Set specific thresholds for platform penalties (e.g., 5-10% of annual revenue for copyright violations). 3) Create dedicated funding pools allocating 15-20% of annual cultural budgets for digital transformation projects. 4) Legally mandate contracts to automate royalty distribution (e.g. 60% to artists, 30% to platforms, 10% to public art funds). 5) Develop tiered certification system (e.g. Basic/Pro/Enterprise levels) with corresponding technical requirements and tax incentives (15-25% reduction).

Emphasize the central role of artists. Governments and platforms must operationalize artist centrality through three measurable actions: 1) give artists 51% decision weight in content review panels, backed by mandatory disclosure of algorithmic training datasets; 2) implement encrypted digital watermarking systems that maintain ≥90% artwork integrity over 5-year archival cycles; 3) require platforms to allocate 40% of revenue to artist-jury panels that distribute funds based on originality indices (e.g., 70% for works that score >8/10 in peer-reviewed creativity assessments), while limiting commercial partnerships to 30% of total project budgets.

Optimizing Government Support and Penalty Mechanisms. It calls for quantifiable policy design: 1) Allocate 18-22% of regional cultural budgets to digital arts subsidies, prioritizing projects where artists retain ≥65% creative control. 2) Implement tiered, revenue-based penalties (e.g., 6% fines for royalty reporting delays of more than 30 days, escalating to 18% for repeated ethical violations). 3) Require 150 annual hours of copyright compliance training for platform operators, with certification tied to subsidy eligibility. 4) Implement real-time monitoring systems that track subsidy utilization rates (target ≥85%), penalty resolution timelines (≤72 hours), and stakeholder satisfaction scores (≥80/100). Annual reviews should adjust these thresholds by ±5% based on performance data.

Stakeholder collaboration requires institutionalized frameworks: 1) mandate quarterly cross-sector workshops with ≥60% artist participation and 30% agenda control. 2) allocate 25% of digital transformation funding to co-creation projects in which artists, technologists, and policymakers collaboratively design tools that meet interoperability standards. 3) implement a "collaboration index" scoring system (0-100) that combines project completion rates (40% weight), stakeholder satisfaction surveys (35%), and open source code contributions (25%), with grants increasing 5% for each 10-point score improvement.

Balancing local protectionism requires measurable policy tools: 1) Allocate 55-60% of cultural subsidies to local creators verified through residency databases, while reserving 40-45% for projects that demonstrate cross-regional user engagement (≥30% of participants from other provinces). 2) Provide 20% tax rebates to platforms that maintain ≥50% local artist representation, but impose 8% revenue penalties if cross-platform collaborations decline by >15% annually. 3) Mandate quarterly reporting on two key metrics: Local IP registrations per 100 artists (minimum 25 registrations) and adoption rates of externally developed digital tools (target ≥65%).

These policy implications provide a strategic framework for stakeholders involved in the digital transformation of artworks, ensuring that the interests of all parties are aligned and that the process is both efficient and effective.

Limitations and Future Research

Despite the valuable insights this study provides into the strategic evolution of stakeholders in the digital transformation of artworks, the inherent complexity of the digital art field presents

challenges that cannot be fully addressed in the short term by a single study. The digitization of artworks involves multidimensional interactions among artistic creation, technology, market, and policy, and the dynamics of these factors are often difficult to predict or control, making it difficult to ensure the long-term effectiveness of any strategy. In addition, as technology advances, new tools and platforms emerge, posing new challenges, such as how to continuously protect the originality and cultural value of artworks in a rapidly changing environment. Future research could explore the development of more flexible policy frameworks that integrate technology and art to respond to the evolving market landscape and demands for innovation.

Future research directions could include exploring how to coordinate art protection policies at the global level, particularly in promoting standardized intellectual property protection across transnational digital platforms. Moreover, with the advent of emerging technologies such as AI and blockchain, future studies could explore the applications and potential impacts of these technologies in the creation, dissemination, and protection of artworks, thereby providing broader theoretical and practical support for the digital transformation of the art industry.

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