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Government regulatory policies for digital transformation in small and medium-sized manufacturing enterprises: an evolutionary game analysis

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In recent years, digital transformation (DT) has become an inevitable choice for manufacturing enterprises to achieve sustainable development. As a large number of enterprise groups, small and medium-sized manufacturing enterprises (SMMEs) play an important role in the industrial development of China. However, due to insufficient resource investment, high transformation costs, lack of talents, and unclear transformation pathways, how the government can help SMMEs carry out DT has become an important research topic. Based on this background, this study considers the strategies of government, third-party demonstration enterprises (TDEs) and SMMEs, develops and builds a three-party evolutionary game model, and puts forward a governance mechanism for effective DT strategies (TDEs guide DT and SMMEs conduct DT). This study has drawn many interesting conclusions. (1) If the government chooses not to regulate, when SMMEs are risk-neutral, the government only needs to increase the rewards for SMMEs to effectively promote DT. When SMMEs are risk-averse, the government needs to increase the penalties for SMMEs and increase the rewards for TDEs to effectively promote DT. (2) If the government chooses to regulate, when SMMEs are risk-neutral, the government needs to increase the penalties for both TDEs and SMMEs to effectively promote DT. When SMMEs are risk-averse, the government only needs to increase penalties on SMMEs or TDEs to effectively promote DT. (3) When SMMEs are risk-averse, the government's best choice is regulation. Because when the government does not regulate, DT may fail even if the government increases the penalties for SMMEs and increases the incentives for TDEs.

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Introduction

Digital transformation (DT), one of the sought-after development modes all over the world, is profoundly altering all the interrelated value-added links within the product life cycle in manufacturing industry, such as research and development, production, and marketing (Lee et al. 2021; Zeng et al. 2022; Liu and Zhao 2022). DT can endow manufacturing enterprises with enormous benefits, including powerful innovation ability, increased revenue, high customer stickiness, lower cost, and better operating efficiency (Tuukkanen et al. 2022; Zhai et al. 2022). DT is a crucial guideline at the national level, and its successful landing and promotion require enterprises and governments to join hands.

Government regulatory policies are indispensable elements in the DT of manufacturing enterprises, especially small and medium-sized manufacturing enterprises (SMMEs) (Henderson 2020; Zhang et al. 2021). The rewards or punishments provided by governments can commendably guide the DT-related behaviors of SMMEs and other participants. In general, governments would implement subsidy schemes to promote DT. Two kinds of subsidy schemes frequently used by governments are subsidizing SMMEs and subsidizing third-party demonstration enterprises (TDEs) (Yu et al. 2023; Mai et al. 2023). The subsidies for SMMEs are used to partially compensate for the cost incurred in the DT processes of SMMEs. Such subsidies can drive SMMEs to be involved in DT more actively and produce more high-value-added products (Zhao et al. 2023). The subsidies for TDEs are paid by governments when TDEs provide DT support to SMMEs, which helps TDEs to increase the motivation to guide SMMEs (Font-Cot et al. 2023). When TDEs receive governmental subsidies, they would reduce guiding expense, making SMMEs acquire DT supports at lower cost and take part in DT with more enthusiasm. Similarly, governmental punishments are classified into two categories, that is, the punishments for SMMEs and the punishments for TDEs (Li et al. 2022; Zhang et al. 2021). Punishing SMMEs evading DT and TDEs refusing to provide DT guidance can actuate them to participate in DT (Zhang et al. 2023a; Liu et al. 2022).

In conclusion, SMMEs, TDEs and governments are indispensable DT participants and play significant roles in propelling DT despite their starting points and specific functions being disparate. The existing literature mainly discusses the cases that DT is advanced by a single participant (e.g., a SMME) and proposes static measures in terms of the participant without considering the internal rationality of the participant. For example, to help small, medium, and micro manufacturing enterprises to assess and adopt information and digital technologies under the background of Industry 4.0, Yang et al. (2023) proposed a decision-making framework neglecting the internal rationality of manufacturing enterprises and the dynamic nature of their decisions. Especially, few studies have explored the regulatory role and the corresponding regulatory policies of governments (Dubey et al. 2023; Kunkel and Matthess 2020). Motivated by the practical requirement to conduct DT by multiple participants and the research gap, through constructing two tripartite evolutionary game models among governments, SMMEs and TDEs, this paper attempts to research how SMMEs and TDEs together propel DT when different regulatory decisions and polices of governments are considered. Although different regulatory decisions and polices could impact SMMEs or TDEs in develop DT, but their concrete effects may differ. Particularly, it is necessary to dissect how various rewarding and punishing schemes affect different DT participants from a policy perspective, which would help to determine which kind of rewarding or punishing scheme is the surest way to the sustainable DT development in SMMEs. Thus, this paper aims to determine the evolutionary stable strategies of SMMEs, TDEs and governments and to explain the effect that governmental policies exert on enterprises' behaviors under different cases by answering the following questions:

(1) Under what conditions can relevant factors (e.g., the expenses of SMMEs and TDEs, and the subsidized degree of governments) positively affect the development of DT in SMMEs? And how do these factors exert an effect?
(2) From the angle of governments, it is better to subsidize SMMEs and TDEs or subsidize SMMEs and punish TDEs?
(3) If governments transform their targets from optimizing the DT results in SMMEs to optimizing subsidy efficiency, would the optimal rewarding or punishing scheme change?

The contributions of this study are summarized as follows. (1) Considering integrality, dynamics and rationality, this study establishes two tripartite evolutionary game models to help SMMEs, TDEs and governments determine behavioral strategies at evolutionarily stable levels to together promote DT when subsidies, rewards and punishments constitute regulatory policies. (2) The conclusions deduced from evolutionary game models suggest that SMMEs and TDEs can select proper behavioral strategies to synergistically propel DT depending on whether governments supervise DT-related activities in SMMEs and TDEs with subsidies, rewards, and punishments or not, which benefits enterprises to determine dynamic DT decisions and plans that meet their own situations and governmental demands. (3) Our findings also show that different risk preferences of SMMEs requires different regulatory decisions and policies, which can provide scientific guidance for governments to form targeted supervising measures based on enterprises' risk appetite. The proposed models and the consequent conclusions synthesize previous literature to offer scientific and practical management insights for enterprises and governments to jointly drive DT to a better state.

The remainder of this paper is organized as follows. The "Literature review" section reviews the relevant literature. The "Problem description and assumptions" section describes the problems and presents the basic model assumptions. The "Tripartite evolutionary game models" section establishes two tripartite evolutionary game models to depict the relationships among governments, SMMEs and TDEs in different scenarios. In "Numerical simulations" section, a series of numerical simulations are conducted to verify our models, propositions, and inferences intuitively. The "Contributions and managerial implications" section sums up the contributions and managerial implications, and the "Conclusions" section concludes the paper.

Literature review

Digital transformation. The existing research often fails to fully distinguish between digitization, digitalization, and DT, and treats them as interchangeable terms. In fact, the three interconnected terms are different, and can be kept distinct at temporal, conceptual, and domanial levels (Verhoef et al. 2021; Bloomberg 2018; Vial 2019). At the temporal levels, digital continuum evolves from digitization to DT over digitalization, with each phase having its own targets, processes, scopes, growth means, business strategies, expected outcomes, etc. (Verhoef et al. 2021). At the conceptual level, digitization refers to the technical process that takes analog data into digital data in order that computers can handle such data (Bloomberg 2018; Legner et al. 2017). Digitalization is the sociotechnical process of utilizing digitized techniques to expand organizational contexts in terms of business models, business processes, commercial offerings, etc. (Tilson et al. 2010; Brynjolfsson and McAfee 2014). DT refers to the sociocultural process that aims to trigger significant changes to the properties of an entity by integrating information, computing, communication, and connectivity technologies (Saarikko et al. 2020). At the domanial level, DT is a superset of digitalization which, in turn, acts as a superset of digitization (Vial 2019). Briefly, digitization, digitalization and DT are discrepant. Compared with other digital phases within the digital continuum, DT possesses many unbeatable advantages in term of contents, adaptability, coverage, and value-creating potentials (Saarikko et al. 2020; Gong and Ribiere 2021), just to name a few. Therefore, this digital phase attracts extensive attention of manufacturing enterprises with different scales and digital foundations.

DT is a complicated system engineering that needs to be accomplished together by multiple participants (Poláková-Kersten et al. 2023), such as service providers and manufacturers. Nonetheless, previous works focus primarily on studying the cases involving a single kind of participants in DT. For instance, Zapata et al. (2020) assessed several DT maturities models to assist small and medium manufacturers in transforming their products into smart products. Mazumder and Garg (2021) conceptualized and identified six dynamic capabilities of service providers in the context of digital transformational outsourcing. Zhang et al. (2023b) divided DT into two ways and studied the impact of the two ways on corporate performance. Skare et al. (2023) explored how digital technology affected the specific business activities of small and medium enterprises. Dubey et al. (2023) examined the interaction effect of government support on dynamic digital capabilities by using qualitative and survey-based data. Considering the complexity of DT, exploring DT involving one kind of participants is not all-inclusive, and discussing the cases that DT is jointly promoted by multiple participants is necessary. Manufacturing enterprises, service providers and governments are main participants engaging in DT (Zhang et al. 2021). Manufacturing enterprises is the real DT executor. Service providers is the third parties that provide managerial tools and means, knowledge resources, technical supports, etc. for manufacturing enterprises to perform better DT. Governments are the regulators guiding the behaviors of the former two participants. This paper attempts to explore the case that DT is driven by SMMEs, TDEs and governments.

SMME-specific challenges for DT. SMMEs often fall behind larger manufacturing enterprises when it comes to DT (Eller et al. 2020). This phenomenon results from the fact that SMMEs face different DT-related challenges (Horváth and Szabó 2019). Such challenges can be roughly concluded into six classes, involving financial/economic (Canhoto et al. 2021), cultural (Vial 2019), legal/regulatory (Lammers et al. 2019), technical/infrastructural (Bai et al. 2021), resource/competency (Chen and Tian 2022), and management process (Fischer et al. 2020), these challenges can also intersect and then form new issues.

Four inherent flaws of SMMEs have been mentioned frequently in the literature, that is, financial resource constraint, knowledge resource constraint, management competency constraint, and technology dependence constraint (Schönfuß et al. 2021; Stentoft et al. 2021). SMMEs generally have limited financial resources, confined investment and financing channels, and weak bargaining power, hindering the absorption of external nutrition (Canhoto et al. 2021; Masood and Sonntag 2020). Manufacturing DT processes are incredibly knowledge-intensive, requiring systematic knowledge reserve and continual knowledge reserve update. SMMEs lacking knowledge resources are easily trapped in comprehensively understanding the DT phenomena and its influences on manufacturing industries, finally impeding the integration of DT and manufacturing domain knowledge (Lee et al. 2021). Often, SMMEs are marked by poorly developed DT best practices, because SMMEs lack the management competency to implement proper DT strategies, allocate necessary resources, define effective decision-making processes, address DT skill gaps, motivate employees and attract external support (Moeuf et al. 2020; Ghobakhloo and Iranmanesh 2021). Moreover, SMMEs need to integrate the new digital solutions with legacy technical systems in their DT processes, during which external technology dependence exists (Horváth and Szabó 2019; Jones et al. 2021).

Current measures to facilitate DT in SMMEs. Various methods dealing with the above SMME-specific challenges appear in literature, and they are mainly proposed from the angles of manufacturing enterprises, service providers and governments.

For manufacturing enterprises, alternative methods distribute in the different stages of DT lifecycle, including developing DT maturity models (Dutta et al. 2020), designing enterprise architecture and strategies for DT (Saarikko et al. 2020; Gökalp and Martinez 2021), assessing DT solutions and their risks (Yang et al. 2021a; Liu 2022), presenting implementation paths, procedures and instruments of DT (Jing et al. 2021; Stich et al. 2020; Matarazzo et al. 2021), improving existing information systems (Ku et al. 2020) and etc. For example, Kıyıklık et al. (2022) developed a static maturity model to aid airline firms to assess their DT maturity levels. These methods are believed to optimize DT processes based on restricted resources, capabilities, or surroundings. For service providers, configuration frameworks of capabilities and resources (Mazumder and Garg 2021; Rahnama et al. 2021), service-providing mechanisms (Niu and Qin 2021), business expansion processes and strategies (Ojala et al. 2018; Kuula et al. 2019), and market stability mechanisms (Wang 2021) are concerned preferentially. For instance, Rahnama et al. (2021) proposed a collaboration framework in terms of service providers, to provide solutions to handle certain DT issues in manufacturing enterprises. Manufacturing enterprises and service providers are profit organizations with asymmetric information, leading to the risks of adverse selection and moral hazard. If governments do not leave these risks alone, successful DT may be more likely to appear. For governments, the regulatory means can be classified as opinions, guidebooks, planning, notices, plans, programs, and action programs (Henderson 2020; Zhang et al. 2021; Wang 2021). Among these means, subsidies, rewards, or punishments can be useful measures for governments to regulate the behaviors of manufacturing enterprises and service providers in DT. However, regulating the enterprise behaviors in DT with subsidies, rewards and punishments is scarcely explored in literature and is desperately needed in practice. For example, Skare et al. (2023) found that government regulations were necessary but insufficient for small and medium enterprises undergoing DT.

The above achievements benefit the corresponding participants to propel DT, but three aspects need attention when integrality, dynamics and rationality are considered. First, all roles involved in DT are interconnected, yet most of existing methods are directed at isolated participants. In particular, the regulatory role of government using subsidies, rewards and punishments is rarely discussed. Second, digital continuum reveals that DT is dynamic, but many methods are static. Finally, there is information asymmetry among DT participants of bounded rationality, which is overlooked by many studies assuming that a stable equilibrium can be achieved in a single decision. Taking the above three research gaps into consideration, more suitable methods are thus needed.

Evolutionary game theory. Evolutionary game theory, a main branch of game theory, supposes that participants with bounded rationality and persistent learning ability can dynamically adjust their own strategies and behaviors according to internal and external environments (Smith 1982). The core that participants reach equilibrium is an evolutionarily stable strategy (ESS) (Smith and Price 1973), which provides valid decision-making guidelines for the participants.

Evolutionary game theory has been broadly employed to study the dynamic interactions among all the players in a game and analyze individual behavior strategies (Yang et al. 2021b; Brunetti et al. 2018; Hosseini-Motlagh et al. 2021). Many robust applications and related achievements have been made. Wang et al. (2019) constructed an evolutionary game model in terms of population to observe the allocation tendency of diverse cloud computing services among users. He and Sun (2022) developed a tripartite evolutionary game model including new energy vehicle manufacturers, governments, and customers, and analyzed their behavioral strategies to explore the ERP mechanism of power battery recycling from a supply-side view. Zhang et al. (2021) established a tripartite differential game model to survey the coordination mechanism and dynamic decision-making processes among industrial enterprises, governments, and digital technology providers. Hammoud et al. (2021) believed that the instability of the fog federations formed by different fog providers negatively affected the performance of the provided service and quantified the issue as an evolutionary game model. Cui et al. (2020) formulated multi-user computation offloading as an evolutionary game model to tackle multiple Internet of Things (IoT) devices computation offloading problem under dynamic environments. These studies indicate that evolutionary game theory is very suited to solve the game problem among different stakeholders in DT.

It can be concluded that evolutionary game theory is an effective method to overcome the drawbacks of the above-mentioned methods of studying DT. Therefore, by building an evolutionary game model among SMMEs, governments and TDEs, this paper can better explore the behavior and decision-making of each participant and provide pertinent governance suggestions to propel DT.

Problem description and assumptions

Problem description. Over the past decade, DT has accelerated the fusion of information technology and the activities within product life cycle. According to the data released by digital transformation service platform, the number of the enterprises involved in DT by the beginning 2019 had reached 1,419,571, of which 5% were seeking innovative breakthrough and 17.4% were in the stage of integration and upgrading (Zhu and Sun 2020). Besides, of the enterprises engaged in DT, the enterprises realizing digital research and development, the digitization of key processes networked collaborative manufacturing and smart manufacturing represent 68.9%, 49.2%, 35.2%, and 7.7%, respectively.

The statistical results above reveal that the overall situation of DT is not optimistic. The primary reason for this is that the vast majority of Chinese businesses are SMMEs, and due to their limited resources, they are frequently concerned about the investment required for DT and the return on that investment. Consequently, it is sometimes challenging for managers to make judgments regarding the implementation of DT. In addition, their own IT capabilities are frequently inadequate, so they essentially implement a completely outsourced model for the design of digital systems, which poses a potential barrier for SMMEs during DT.

Currently, three key issues are frequently encountered in DT: (1) SMMEs sparsely exchange DT-related experiences and ideas with each other and lack scientific guidance during their DT processes; (2) SMMEs mainly rely on governmental supports (e.g., capital) to impel DT, while such supports are finite. (3) Scale economy. It is essential to note, however, that the benefits of economies of scale are not absolute and can be overcome through a variety of strategies. SMMEs can collaborate with larger enterprises, technology partners, and digital service providers, for instance, to leverage their expertise and resources for implementing DT initiatives. In addition, they can adopt a phased approach to DT, beginning with smaller-scale initiatives that can yield fast wins and progressively scaling up over time.

Consequently, based on the preceding explanation, in order to promote DT, SMMEs must maximize their use of large enterprises and government public service platforms and reduce their investment in non-core business connections. Compared to SMMEs, large enterprises typically have a longer operating history, a larger scale, a greater accumulation of technology, capital, talent, and other resources, a relatively robust IT department, and a wealth of internal financial and human resources to support the DT of enterprises. Therefore, digitalization will not utilize outsourcing, and the DT process will typically be completed by the enterprise's internal IT department. Therefore, the DT of large enterprises is generally spontaneous and does not necessitate the intervention of TDEs. In this paper, to reflect the characteristics of SMMEs, we examine the influence of TDEs and governments on the DT of SMMEs using this model. Incorporating scale economy considerations into DT strategies may also necessitate a thorough evaluation of the costs and benefits of various approaches. Considerations for SMMEs may include the cost of acquiring technology and personnel, the potential return on investment, and the risk of disruption to their current business models. In our model, we therefore consider the impact of risk factors.

In this paper, the government primarily uses subsidies and taxes to encourage SMMEs to endure DT. Using tax policies and other fiscal measures, for instance, the U.S. government encourages SMMEs to undertake DT and rewards excellence in digital solutions in specific areas. In addition, large enterprises are incentivized to SMMEs with their efforts to DT. For instance, the Chinese government has supported the Internet Plus action plan and provided a variety of policy and financial incentives to large manufacturing enterprises that actively participate in the plan to encourage them to assist SMMEs with their DT. This policy has promoted DT and fostered the growth of SMMEs. In this paper, TDEs refer large enterprises with DT expertise and capabilities. China advocates for large enterprises to assume their corporate social responsibility to promote and support SMMEs DT upstream and downstream in the industry chain. For instance, Lenovo offers SMMEs a one-stop integrated delivery of "software+hardware+service" to facilitate DT. Amazon has launched the Small Business Accelerator programme to assist SMMEs in making better use of digital technology and the Internet in order to increase production and sales efficiency, enhance customer experience, and boost competitiveness. Nike uses digital technology to help suppliers standardize production, monitor production processes, and manage inventory, thereby increasing supply chain efficiency and transparency. Walmart assists small retailers in achieving digital transformation by utilizing digital technology to improve supply chain administration, enhance customer experience, expand sales channels, etc. Alibaba offers a variety of digital services, such as online store creation, online payments, and data analytics, to assist SMMEs in expanding their market reach and maximizing their efficiency. By providing digital tools, solutions, and services, these large enterprises aid SMMEs in undergoing DT, thereby fostering their development and market competitiveness.

Therefore, SMMEs should perform DT based on the regulatory policies of governments and the guidelines of TDEs. The interactions between the three players are described as follows. On one hand, TDEs can choose to help SMMEs reasonably reform sociocultural processes and allocate resources. On the other hand, governments can use subsidies or rewards to stimulate enterprises to conduct DT and punish the ones doing nothing about DT by penalties. This paper examines the competitive and cooperative behavior of TDEs and SMMEs under the supervision of the government and then presents the optimal strategy options for the government, TDEs, and SMMEs. In contrast to simple three player game, participants' strategies in evolutionary games can evolve over time. Typically, evolutionary games consist of a succession of repeated games in which players can modify their strategies based on their experience and the outcomes of the games. Typically, random factors, such as participants' learning effects, risk aversion, etc., influence such strategy adjustments. Consequently, evolutionary games place a greater emphasis on dynamic changes and adaptability of strategies. Moreover, evolutionary games typically emphasize long-term evolutionary outcomes over short-term triumphs and losses. In evolutionary games, participants may need to undergo multiple cycles of adaptation and adjustment to achieve improved long-term results. This paper uses evolutionary games to examine the behavior and strategy selection of competition and cooperation. Through the construction and analysis of evolutionary game models, we can gain insight into the mechanism of behavior and strategy selection during DT of SMMEs and predict the interaction and impact of different strategies.

Model assumptions. In repetitive games, players with limited information continuously replace unsatisfactory strategies with satisfactory ones depending on their own vested interests until they reach an ESS. Thus, discussing the dynamic stability of an asymmetric game must investigate the dynamic evolutionary processes of the game. This paper assumes that governments, SMMEs and TDEs are "economic man" with bounded rationality. When the three kinds of DT participants are faced with incomplete data, the behavioral strategies at the start are not optimal. As time goes on, they keep learning and obtain the desired behavioral strategies by trial and error. Governments, SMMEs and TDEs are disparate groups, and this paper makes the following assumptions for simplicity:

(1) To governments, preferential policies would be provided to SMMEs, and random supervision aiming at the DT processes of the enterprises is needed, to make SMMEs implement DT. Let X $(0 \leq X \leq 1)$ represent the probability of random regulation performed by governments. Government regulation on DT requires human, material, and financial resources which form the regulatory cost denoted as C_G. When governments do not regulate, national resources are wasted if SMMEs conduct DT without using government-assigned resources. At this juncture, SMMEs convert government-provided resources to their own private gain, resulting in the loss of public resources. In this case, the loss of social welfare is L_G. When governments regulate, the cases for SMMEs and TDEs are as follows: (1) if SMMEs do not utilize government-assigned resources to perform DT, enterprises would receive punishments quantified as P_E, otherwise enterprises would receive rewards quantified as R_E from governments; (2) if governments find that TDEs do not guide SMMEs to conduct DT, TDEs would receive punishments denoted as P_T, and the DT in SMMEs can bring social benefits indicated as R_G for governments; otherwise, TDEs would receive rewards denoted as R_T, and the social benefits governments obtained is R_{NG}.

(2) To TDEs, the probability that they guide SMMEs to conduct DT is expressed as Y $(0 \leq Y \leq 1)$. The directive cost that TDEs spend on the DT of manufacturing enterprises is assumed as C_T. When TDEs provide guidance to SMMEs to implement DT, the revenue of TDEs received from manufacturing enterprises is R_{ZT}. When TDEs do not provide DT-related guidance to SMMEs, TDEs could suffer loss denoted as L_T if SMMEs carry out DT indeed.

(3) To SMMEs, the probability that they employ government-assigned resources to conduct DT is denoted as Z $(0 \leq Z \leq 1)$. Government subsidies provided to SMMEs that implement DT can be quantified as R_S, and the resource inputs in DT of SMMEs can be set as C_E. If SMMEs conduct DT under the guidance of TDEs, the real revenue that SMMEs obtain is R_{GE}; otherwise, the real revenue obtained by SMMEs is R_{NGE}.

To facilitate understanding, the parameter and variable notations and their definitions are further described in Table 1.

Tripartite evolutionary game models

The reason for choosing evolutionary game theory in this article is because for the government, SMMEs and TDEs, they have bounded rationality and incomplete information. Therefore, they cannot achieve the optimal equilibrium for all three parties in a single instance, but rather, decision-makers obtain the optimal three-party equilibrium through a process of repeated iterations, continuously trying and making mistakes (each decision carries a certain inertia). Therefore, when analyzing their optimal decisions, we must combine game theory analysis with dynamic evolutionary processes to obtain a dynamic and robust equilibrium. Traditional game theory assumes that participants are fully rational, and the focus of research is on static equilibrium and comparative static equilibrium. Therefore, this article chooses to use evolutionary game theory to analyze the optimal decisions in the three-party game.

Based on the above assumptions, this paper lists the payoff matrices of the tripartite game. The payoff matrices of TDEs, governments and SMMEs are separately shown in Tables 2 and 3, where the functions in each table indicate the proceeds of governments, SMMEs and TDEs.

Model 1: the tripartite evolutionary game model considering SMMEs' randomly shocked revenue. When manufacturing enterprises conduct DT, their revenue can fluctuate with the internal and external environment. This paper assumes that the revenue of SMMEs fluctuate randomly. Let random variable ξ denote this fluctuation, and ξ obey normal distribution N $(0, \delta^2)$. Thus, $R_{NGE} = R_{GE} - \xi$, $R_{NG} = R_G - \xi$, $L_T = L_T - \xi$. Based on the above payoff matrices, the replicator dynamic equations considering the randomly shocked revenue of SMMEs can be given as follows:

$$F(X) = \frac{dX}{dt} = X(1-X)\left[P_E + P_T - R_S - C_G - Z(R_E + P_E + L_G)\right] \quad (1)$$

$$F(Y) = \frac{dY}{dt} = Y(1-Y)\left[X(R_T + P_T) + Z(R_{ZT} + L_T) - C_T\right] \quad (2)$$

$$F(Z) = \frac{dZ}{dt} = Z(1-Z)\left[X(P_E + R_E) + R_{GE} - C_E\right] \quad (3)$$

The specific construction processes of Eqs. (1)–(3) are presented in Appendix A. Let $a = P_E + P_T - R_S - C_G$, $b = P_E + R_E + L_G$, $c = P_T + R_T$, $d = R_{ZT} + L_T$, $e = R_E + P_E$, $f = R_{GE} - R_{NGE}$ and $g = R_{NGE} - C_E$, and $b > 0$, $c > 0$, $d > 0$, $e > 0$ and $f > 0$ are satisfied. After simplification, the following equation can be obtained:

$$\begin{cases} \frac{dX}{dt} = X(1-X)(a-bZ) \\ \frac{dY}{dt} = Y(1-Y)(cX+dZ-C_T) \\ \frac{dZ}{dt} = Z(1-Z)(eX+f+g) \end{cases} \tag{4}$$

Table 1 Parameters and variables symbol descriptions.

Parameters	Descriptions
C_G	Governmental regulation cost
L_G	The loss of social welfare
P_E	Governmental punishments for SMMEs
R_E	Governmental rewards for SMMEs
P_T	Governmental punishments for TDEs
R_T	Governmental rewards for TDEs
C_E	The DT cost in SMMEs
R_G	The social benefits that governments obtained from DT if TDE guide SMMEs
R_{NG}	The social benefits governments obtained if SMMEs conduct DT independently
R_S	Government subsidies provided to SMMEs implementing DT
R_{GE}	The revenue that SMMEs obtain from the DT if TDEs guide them
R_{NGE}	The revenue that SMMEs obtain from the DT if TDEs do not guide them
C_T	The directive cost of TDEs
R_{ZT}	The revenue that TDEs obtain from SMMEs if TDEs guide SMMEs to conduct DT
L_T	The loss that TDEs suffer if TDEs do not guide SMMEs to conduct DT
Variables	**Descriptions**
X	The probability that governments implement random regulation
Y	The probability that TDEs guide SMMEs to conduct DT
Z	The probability that SMMEs use government-assigned resources to conduct DT

By solving $\frac{dX}{dt}=0$, $\frac{dY}{dt}=0$ and $\frac{dZ}{dt}=0$, ten equilibrium points of Eq. (4) can be obtained. Of these equilibrium points, E_1 (1,1,1), E_2(1,1,0), E_3(1,0,1), E_4(1,0,0), E_5(0,1,1), E_6(0,1,0), E_7(0,0,1) and E_8(0,0,0) are pure equilibrium points, and $E_9(-\frac{f+g}{e},1,\frac{a}{b})$ and $E_{10}(-\frac{f+g}{e},0,\frac{a}{b})$ are mixed equilibrium points. The Jacobian matrix of Eq. (4) is as below:

$$J=\begin{bmatrix} \frac{\partial F(X)}{\partial X} & \frac{\partial F(X)}{\partial Y} & \frac{\partial F(X)}{\partial Z} \\ \frac{\partial F(Y)}{\partial X} & \frac{\partial F(Y)}{\partial Y} & \frac{\partial F(Y)}{\partial Z} \\ \frac{\partial F(Z)}{\partial X} & \frac{\partial F(Z)}{\partial Y} & \frac{\partial F(Z)}{\partial Z} \end{bmatrix} = \begin{bmatrix} (1-2X)(a-bZ) & 0 & -X(1-X)b \\ cY(1-Y) & (1-2Y)(cX+dZ-C_T) & Y(1-Y)d \\ eZ(1-Z) & 0 & (1-2Z)(eX+f+g) \end{bmatrix}$$

The eigenvalues of Jacobian matrix J with different equilibrium points are shown in Table 4.

According to Lyapunov stability theorem, if and only if all the eigenvalues are less than zero, the corresponding equilibrium point is a stable point. Among the ten eigenvalues of Eq. (4), equilibrium points E_4, E_9 and E_{10} all have at least one eigenvalue that is greater than zero and are saddle points. The remaining equilibrium points can possess three eigenvalues that are all less than zero under certain conditions and are thus the potential ESS points. When E_1, E_2, E_3, E_5, E_6, E_7 and E_8 are stable respectively, there exists only one stable equilibrium point, that is, the EES point is unique, as Table 5a, b shows.

Ideally, governments would adjust their own strategies to equilibrium states, where any SMMEs would not escape from performing DT, and any TDEs would not avoid guiding SMMEs to perform DT. Such an ideal case means that $Y=1$ and $Z=1$ are satisfied in an equilibrium point, which reveals that E_3 and E_8 are ideal ESS points. The dissections of the two ideal ESS points are summarized in Table 6a, b, Propositions 1 and 2 are then put forward.

Proposition 1. When $P_T<C_G+R_E+L_G+R_S$, $C_T<R_{ZT}+L_T$ and $R_{GE}>C_E$, $E_3(0, 1, 1)$ is the unique ESS, that is, governments do not regulate, and SMMEs propel DT under the guidance of TDEs.

Table 2 The payoff matrix of governments, SMMEs and TDEs when TDEs guide.

Governments					
		Regulate (*X*)	**Not regulate (1 − *X*)**		
SMMEs	Conduct DT (Z)	$\begin{bmatrix} -C_G-R_E-R_T+R_G-R_S \\ R_E-C_E+R_S+R_{GE} \\ -C_T+R_T+R_{ZT} \end{bmatrix}$	$\begin{bmatrix} R_G-R_S \\ -C_E+R_S+R_{GE} \\ -C_T+R_{ZT} \end{bmatrix}$	Guide (Y)	TDEs
	Not conduct DT ($1-Z$)	$\begin{bmatrix} -C_G-R_T-R_S+P_E \\ -P_E+R_S \\ -C_T+R_T \end{bmatrix}$	$\begin{bmatrix} -L_G-R_S \\ R_S \\ -C_T \end{bmatrix}$		

Table 3 The payoff matrix of governments, SMMEs and TDEs when TDEs do not guide.

Governments					
		Regulate (*X*)	**Not regulate (1 − *X*)**		
SMMEs	Conduct DT (Z)	$\begin{bmatrix} -C_G-R_E+P_T+R_{NG}-R_S \\ R_E-C_E+R_S+R_{NGE} \\ -P_T-L_T \end{bmatrix}$	$\begin{bmatrix} R_{NG}-R_S \\ R_S+R_{NGE}-C_E \\ -L_T \end{bmatrix}$	Not guide ($1-Y$)	TDEs
	Not Conduct DT ($1-Z$)	$\begin{bmatrix} -C_G-R_S+P_E+P_T \\ -P_E+R_S \\ -P_T \end{bmatrix}$	$\begin{bmatrix} -L_G-R_S \\ R_S \\ 0 \end{bmatrix}$		

Proposition 1 indicates that when the revenue of governments earned by punishing TDEs is not enough to pay for governmental regulation cost, governmental rewards and subsidies for SMMEs, and the loss of social welfare, when the difference that the directive cost of TDEs subtracts the revenue that they obtain from SMMEs due to guiding DT is less than the loss that they suffer due to avoiding guiding DT, and when the revenue that SMMEs obtain from guiding TDEs to implement DT is more than the DT cost in SMMEs, the ESS is (0, 1, 1). In other words, when $X = 0$, governments do not regulate; when $Y = 1$, TDEs guide SMMEs to implement DT; when $Z = 1$, SMMEs perform DT. R_E, P_T and R_S are endogenous variables that governments can control, and governments can force SMMEs to choose DT by enhancing governmental rewards.

To TDEs, the loss of providing no guidance exceeds the loss of providing guidance. Thus, TDEs would select to provide DT guidance to SMMEs when governmental rewards increase. The first conclusion of our research is: if governments are not motivated to continuously supervise SMMEs and TDEs, they can increase governmental rewards for SMMEs (i.e., R_E) and keep governmental punishments for SMMEs unchanged, with the purpose to ensure that SMMEs implement DT under the guidance of TDEs.

Table 6b indicates that governments can prompt SMMEs and TDEs to implement DT and provide DT guidance respectively by decreasing P_T or increasing one of R_E and R_S, if governments lack the impetuses to supervise. Further, as there is no government supervision, increasing R_E does not add governmental cost, which in turn works as an incentive. Besides, decreasing P_T or enhancing R_S can bring governments additional cost. Therefore, the optimal strategy for governments is giving rewards to enterprise DT.

The first conclusion is comprehensible in practice. When the revenue of implementing DT exceeds the corresponding cost in SMMEs, and when the loss of avoiding guiding DT is more than that of guiding DT in TDEs, SMMEs and TDEs are often motivated to execute DT and guide DT, respectively. Now, if governments increase incentives to SMMEs, manufacturing enterprises would be certain to continue DT. Under the condition, TDEs would also keep guiding DT, for the guiding income surpasses the corresponding cost. At this point, whether governments supervise or not makes no difference.

Table 4 The eigenvalues at each equilibrium point of Eq. (4).

Equilibrium point	Eigenvalues
$E_1(0, 0, 1)$	$\lambda_1^1 = a - b$, $\lambda_1^2 = d - C_T$, $\lambda_1^3 = -g - f$
$E_2(0, 0, 0)$	$\lambda_2^1 = a$, $\lambda_2^2 = -C_T$, $\lambda_2^3 = g + f$
$E_3(0, 1, 1)$	$\lambda_3^1 = a - b$, $\lambda_3^2 = C_T - d$, $\lambda_3^3 = -g - f$
$E_4(0, 1, 0)$	$\lambda_4^1 = a$, $\lambda_4^2 = C_T$, $\lambda_4^3 = f + g$
$E_5(1, 0, 1)$	$\lambda_5^1 = -(a - b)$, $\lambda_5^2 = c + d - C_T$, $\lambda_5^3 = -(e + f + g)$
$E_6(1, 0, 0)$	$\lambda_6^1 = -a$, $\lambda_6^2 = c - C_T$, $\lambda_6^3 = e + f + g$
$E_7(1, 1, 0)$	$\lambda_7^1 = -a$, $\lambda_7^2 = C_T - c$, $\lambda_7^3 = e + f + g$
$E_8(1, 1, 1)$	$\lambda_8^1 = -(a - b)$, $\lambda_8^2 = C_T - c - d$, $\lambda_8^3 = -(e + f + g)$
E_9, E_{10}	At least one eigenvalue is greater than zero.

Proposition 2. When $P_T > C_G + R_E + L_G + R_S$, $C_T < R_{ZT} + L_T + P_T + R_T$ and $C_E < R_{GE} + P_E + R_E$, $E_8(1, 1, 1)$ is the unique ESS, that is, governments regulate, and SMMEs propel DT under the guidance of TDEs.

Proposition 2 shows that when the revenue of governments earned by punishing TDEs is enough to pay for governmental regulation cost, governmental rewards and subsidies for SMMEs, and the loss of social welfare, when the difference that the directive cost of TDEs subtracts the revenue that they obtain from SMMEs due to guiding DT and the governmental rewards for TDEs is below the sum of the loss that they suffer due to avoiding guiding DT and the governmental punishments for TDEs, and when the difference that the DT cost in SMMEs subtracts the revenue obtained by the SMMEs conducting DT with the help of TDEs and the governmental

Table 5 Evolutionary stability analysis of each equilibrium point in model 1.

Conditions	The values of eigenvalues	Non-ESS points	ESS points
(a) Evolutionary stability analysis of each equilibrium point when $P_T \leq C_G + L_G$			
$P_T < C_G + R_E + L_G + R_S$, $R_{ZT} + L_T < C_T$, $R_{GE} > C_E$	$\lambda_1^i < 0 (i = 1, 2, 3)$; $\lambda_2^3 > 0$; $\lambda_3^2 > 0$; $\lambda_5^1 > 0$; $\lambda_6^3 > 0$; $\lambda_7^3 > 0$; $\lambda_8^1 > 0$	E_2, E_3, E_5, E_6, E_7, E_8	E_1
$P_E + P_T < R_S + C_G$, $R_{GE} < C_E$	$\lambda_1^3 > 0$; $\lambda_2^i < 0 (i = 1, 2, 3)$; $\lambda_3^3 > 0$; $\lambda_j^1 > 0 (j = 5, 6, 7, 8)$	E_1, E_3, E_5, E_6, E_7, E_8	E_2
$P_T < C_G + R_E + L_G + R_S$, $C_T < R_{ZT} + L_T$, $R_{GE} > C_E$	$\lambda_1^2 > 0$; $\lambda_2^3 > 0$; $\lambda_3^i < 0 (i = 1, 2, 3)$; $\lambda_6^3 > 0$; $\lambda_j^1 > 0 (j = 5, 7, 8)$	E_1, E_2, E_5, E_6, E_7, E_8	E_3
$P_E + P_T > R_S + C_G$, $P_T + R_T < C_T$, $R_E + P_E + R_{GE} < C_E$	$\lambda_1^3 > 0$; $\lambda_2^1 > 0$; $\lambda_3^3 > 0$; $\lambda_5^3 > 0$; $\lambda_6^i < 0 (i = 1, 2, 3)$; $\lambda_7^2 > 0$; $\lambda_8^3 > 0$	E_1, E_2, E_3, E_5, E_7, E_8	E_6
$P_E + P_T > R_S + C_G$, $P_T + R_T > C_T$, $R_E + P_E + R_{GE} < C_E$	$\lambda_1^3 > 0$; $\lambda_2^1 > 0$; $\lambda_3^3 > 0$; $\lambda_5^3 > 0$; $\lambda_6^2 > 0$; $\lambda_7^i < 0 (i = 1, 2, 3)$; $\lambda_8^3 > 0$;	E_1, E_2, E_3, E_5, E_6, E_8	E_7

Conditions	The values of other eigenvalues	Non-ESS points	ESS points
(b) Evolutionary stability analysis of each equilibrium point when $P_T > C_G + L_G$			
$P_T < C_G + R_E + L_G + R_S$, $R_{ZT} + L_T < C_T$, $R_{GE} > C_E$	$\lambda_1^i < 0 (i = 1, 2, 3)$; $\lambda_2^3 > 0$; $\lambda_3^2 > 0$; $\lambda_j^1 > 0 (j = 5, 8)$; $\lambda_j^3 > 0 (j = 6, 7)$	E_2, E_3, E_5, E_6, E_7, E_8	E_1
$P_E + P_T < R_S + C_G$, $R_{GE} < C_E$	$\lambda_1^3 > 0$; $\lambda_2^i < 0 (i = 1, 2, 3)$; $\lambda_3^3 > 0$; $\lambda_j^1 > 0 (j = 5, 6, 7, 8)$	E_1, E_3, E_5, E_6, E_7, E_8	E_2
$P_T < C_G + R_E + L_G + R_S$, $C_T < R_{ZT} + L_T$, $R_{GE} > C_E$	$\lambda_1^2 > 0$; $\lambda_2^3 > 0$; $\lambda_3^i < 0 (i = 1, 2, 3)$; $\lambda_6^3 > 0$; $\lambda_j^1 > 0 (j = 5, 7, 8)$	E_1, E_2, E_5, E_6, E_7, E_8	E_3
$P_T > C_G + R_E + L_G + R_S$, $R_{ZT} + L_T + P_T + R_T < C_T$, $R_E + P_E + R_{GE} > C_E$	$\lambda_j^1 > 0 (j = 1, 2, 3)$;$\lambda_5^i < 0 (i = 1, 2, 3)$;$\lambda_6^3 > 0$; $\lambda_7^2 > 0$, $\lambda_7^3 > 0$;$\lambda_8^2 > 0$;	E_1, E_2, E_3, E_6, E_7, E_8	E_5
$P_E + P_T > R_S + C_G$, $P_T + R_T < C_T$, $R_E + P_E + R_{GE} < C_E$	$\lambda_1^3 > 0$; $\lambda_2^1 > 0$; $\lambda_6^i < 0 (i = 1, 2, 3)$; $\lambda_7^2 > 0$; $\lambda_j^3 > 0 (j = 3, 5, 8)$	E_1, E_2, E_3, E_5, E_7, E_8	E_6
$P_E + P_T > R_S + C_G$, $P_T + R_T > C_T$, $R_E + P_E + R_{GE} < C_E$	$\lambda_1^3 > 0$; $\lambda_2^1 > 0$; $\lambda_6^2 > 0$; $\lambda_7^i < 0 (i = 1, 2, 3)$; $\lambda_j^3 > 0 (j = 3, 5, 8)$	E_1, E_2, E_3, E_5, E_6, E_8	E_7
$P_T > C_G + R_E + L_G + R_S$, $C_T < P_T + R_T + R_{ZT} + L_T$, $R_E + P_E + R_{GE} > C_E$	$\lambda_j^1 > 0 (j = 1, 2, 3)$; $\lambda_5^2 > 0$; $\lambda_6^3 > 0$; $\lambda_7^3 > 0$; $\lambda_8^i < 0 (i = 1, 2, 3)$	E_1, E_2, E_3, E_5, E_6, E_7	E_8

Table 6 The transition from initial ESS to ideal stable points E_3 and E_8 in model 1.

Initial ESS points	Main influencing factors	New ESS points	explanations
(a) The transition from initial ESS points to ideal ESS points when $P_T \le C_G + L_G$			
$E_1(0, 0, 1)$	Do not exist	-	ESS points do not change
$E_2(0, 0, 0)$	Do not exist	-	ESS points do not change
$E_3(0, 1, 1)$	Do not exist	-	ESS points do not change
$E_6(1, 0, 0)$	Do not exist	-	ESS points do not change
$E_7(1, 1, 0)$	Do not exist	-	ESS points do not change

Initial ESS points	Main influencing factors	New ESS points	Additional conditions
(b) The transition from initial ESS to ideal stable points E3 and E8 when $P_T > C_G + L_G$			
$E_1(0, 0, 1)$	$\{P_T\uparrow\}$ or $\{R_T\uparrow, R_S\downarrow, R_E\downarrow\}$	$E_8(1, 1, 1)$	-
$E_2(0, 0, 0)$	$\{(P_E \uparrow$ or $R_E\uparrow), P_T\uparrow\}$ or $\{P_E\uparrow, R_S\downarrow, R_E\downarrow\}$	$E_8(1, 1, 1)$	-
$E_3(0, 1, 1)$	$\{P_T\uparrow\}$ or $\{R_S\downarrow, R_E\downarrow\}$	$E_8(1, 1, 1)$	-
$E_5(1, 0, 1)$	$\{P_T \uparrow\}$ or $\{R_T\uparrow\}$	$E_8(1, 1, 1)$	-
$E_6(1, 0, 0)$	$\{P_T\uparrow, (P_E\uparrow$ or $R_E\uparrow)\}$ or $\{R_S\downarrow, R_T\uparrow, P_E\uparrow, R_E\downarrow\}$	$E_8(1, 1, 1)$	-
$E_7(1, 1, 0)$	$\{P_T\uparrow, (P_E\uparrow$ or $R_E\uparrow)\}$ or $\{R_S\downarrow, P_E\uparrow, R_E\downarrow\}$	$E_8(1, 1, 1)$	-
$E_8(1, 1, 1)$	$\{P_T\downarrow\}$ or $\{R_E\uparrow\}$ or $\{R_S\uparrow\}$	$E_3(0, 1, 1,)$	$C_T < R_{ZT} + L_T$, $R_{GE} > C_E$

rewards for the SMMEs is less than the governmental punishments for the SMMEs avoiding DT, the ESS is (1, 1, 1). In other words, when $X = 1$, governments regulate; when $Y = 1$, TDEs guide SMMEs to implement DT; when $Z = 1$, SMMEs perform DT.

P_T, R_E, R_T, P_E and R_S are the endogenous variables of governments, the rest are exogenous variables. Thus, the second conclusion of our research is: when governments are motivated to supervise SMMEs and TDEs, governments can keep existing rewards unaltered and merely step up punishments for SMMEs and TDEs, causing the total loss that TDEs suffer from guiding DT in SMMEs to stay below the total loss that TDEs suffer from avoiding guiding DT, and causing the total loss that SMMEs suffer from executing DT to stay below the total loss that SMMEs suffer from avoiding DT; such an governmental strategy can effectively prevent SMMEs and TDEs from avoiding conducting and guiding DT, respectively. Like Proposition 1, TDEs would finally guide SMMEs to implement DT under this case because the main factor restricting SMMEs and TDEs is the heavy fines from governments. The specific processes are shown in Table 6b. The second conclusion is very practical, and always applicable to the cases involving government regulations. Powerful deterrent's function when government punishments are severely enough, which is able to promote the effective execution of related policies.

The systems formed by governments, TDEs and SMMEs can expect to stabilize at the states represented by E_3 or E_8 but might stabilize at other unexpected equilibrium points. When the systems formed by governments, TDEs and SMMEs expect to convert from an initial non-ideal ESS point to an ideal ESS point or from an ideal ESS point to another ideal ESS point, governments can alter polices (i.e., alter the parameters related to governments in model 1) to realize such conversions. When the initial ESS point is one of E_1, E_2, E_3, E_5, E_6, E_7 and E_8, the possible ideal ESS point in the end and the corresponding switching conditions are presented in Table 6b, the derivation processes of which can refer to Appendix B.

Model 2: the tripartite evolutionary game model considering SMMEs' risk aversion. Implementing DT is risky, during which SMMEs could exhibit diverse risk-adverse behaviors. This section tries to establish a tripartite evolutionary game model considering the risk aversion of manufacturing enterprises. Existing literature proposes many methods to measure risk, and the mean variance model is a frequently used method because it is intuitive and easy to operate (Simaan 1997). Our paper uses this method to model the risk preferences of SMMEs. The expected utility of mean variance models is expressed as $E(U_i) = E(\prod_i) - \frac{\lambda}{2}\mathrm{Var}(\prod_i)$, where λ denotes the risk-adverse coefficient of SMMEs and $\lambda = 0$ represents that enterprise are risk-neutral. Based on mean variance models and the above payoff matrices, the replicator dynamic equations considering the risk aversion of SMMES are given as follows:

$$F(X) = \frac{dX}{dt} = X(1-X)\left[P_E + P_T - R_S - C_G - Z(R_E + P_E + L_G)\right] \quad (5)$$

$$F(Y) = \frac{dY}{dt} = Y(1-Y)\left[X(R_T + P_T) + Z(R_{ZT} + L_T) - C_T + \frac{\lambda}{2}Z^2\delta^2\right] \quad (6)$$

$$F(Z) = \frac{dZ}{dt} = Z(1-Z)\left[X(P_E + R_E) + R_{GE} - C_E - \frac{\lambda}{2}\delta^2(Y-1)^2\right] \quad (7)$$

The specific construction processes of Eqs. (5)–(7) are shown in Appendix C. Similarly, let $a = P_E + P_T - R_S - C_G$, $b = P_E + R_E + L_G$, $c = P_T + R_T$, $d = R_{ZT} + L_T$, $e = R_E + P_E$, $f = R_{GE} - R_{NGE}$ and $g = R_{NGE} - C_E$, and Eqs. (5)–(7) can be simplified as:

$$\begin{cases} \frac{dX}{dt} = X(1-X)(a - bZ) \\ \frac{dY}{dt} = Y(1-Y)(cX + dZ - C_T + \frac{\lambda}{2}\delta^2 Z^2) \\ \frac{dZ}{dt} = Z(1-Z)(eX + f + g - \frac{\lambda}{2}\delta^2(Y-1)^2) \end{cases} \quad (8)$$

By solving $\frac{dX}{dt} = 0$, $\frac{dY}{dt} = 0$ and $\frac{dZ}{dt} = 0$, 12 equilibrium points of Eq. (8) can be obtained. Of these ten equilibrium points, pure equilibrium points include $E_1(0, 0, 1)$, $E_2(0, 0, 0)$, $E_3(0, 1, 1)$, $E_4(0, 1, 0)$, $E_5(1, 0, 1)$, $E_6(1, 0, 0)$, $E_7(1, 1, 0)$ and $E_8(1, 1, 1)$, and mixed equilibrium points contain $E_9E_9\left(1, 1-\sqrt{\frac{2(e+f+g)}{\lambda\delta^2}}, \frac{\sqrt{d^2-2\lambda\delta^2(c-C_T)}-d}{\lambda\delta^2}\right)$, $E_{10}\left(0, 1-\sqrt{\frac{2(f+g)}{\lambda\delta^2}}, \frac{\sqrt{d^2+2\lambda\delta^2 C_T}-d}{\lambda\delta^2}\right)$, $E_{11}\left(\frac{\frac{1}{2}\lambda\delta^2-f-g}{e}, 0, \frac{a}{b}\right)$,

Table 7 The eigenvalues at each equilibrium point of Eq. (8).

Equilibrium points	Eigenvalues
$E_1(0, 0, 1)$	$\lambda_1^1 = a - b$, $\lambda_1^2 = d - C_T + \frac{\lambda}{2}\delta^2$, $\lambda_1^3 = -(f + g - \frac{\lambda}{2}\delta^2)$
$E_2(0, 0, 0)$	$\lambda_2^1 = a$, $\lambda_2^2 = -C_T$, $\lambda_2^3 = f + g - \frac{\lambda}{2}\delta^2$
$E_3(0, 1, 1)$	$\lambda_3^1 = a - b$, $\lambda_3^2 = C_T - d - \frac{\lambda}{2}\delta^2$, $\lambda_3^3 = -(f + g)$
$E_4(0, 1, 1)$	$\lambda_4^1 = a$, $\lambda_4^2 = C_T$, $\lambda_4^3 = f + g$
$E_5(1, 0, 1)$	$\lambda_5^1 = -(a - b)$, $\lambda_5^2 = c + d - C_T + \frac{\lambda}{2}\delta^2$, $\lambda_5^3 = -(e + f + g - \frac{\lambda}{2}\delta^2)$
$E_6(1, 0, 0)$	$\lambda_6^1 = -a$, $\lambda_6^2 = c - C_T$, $\lambda_6^3 = e + f + g - \frac{\lambda}{2}\delta^2$
$E_7(1, 1, 0)$	$\lambda_7^1 = -a$, $\lambda_7^2 = C_T - c$, $\lambda_7^3 = e + f + g$
$E_8(1, 1, 1)$	$\lambda_8^1 = -(a - b)$, $\lambda_8^2 = C_T - c - d - \frac{\lambda}{2}\delta^2$, $\lambda_8^3 = -(e + f + g)$
E_9, E_{10}, E_{11}, E_{12}	At least one eigenvalue is greater than zero.

$\left(-\frac{f+g}{e}, 1, \frac{a}{b}\right)$,

$E_{12}\left(\frac{2b^2C_T-\lambda\delta^2a^2-2bad}{2b^2c}, 1-\sqrt{\frac{2b^2eC_T-\lambda e\delta^2a^2-2bade+2b^2c(f+g)}{b^2c\lambda\delta^2}}, \frac{a}{b}\right)$.

The Jacobian matrix of Eq. (8) is:

$$J = \begin{bmatrix} \frac{\partial F(X)}{\partial X} & \frac{\partial F(X)}{\partial Y} & \frac{\partial F(X)}{\partial Z} \\ \frac{\partial F(Y)}{\partial X} & \frac{\partial F(Y)}{\partial Y} & \frac{\partial F(Y)}{\partial Z} \\ \frac{\partial F(Z)}{\partial X} & \frac{\partial F(Z)}{\partial Y} & \frac{\partial F(Z)}{\partial Z} \end{bmatrix} = \begin{bmatrix} (1-2X)(a-bZ) & 0 & -X(1-X)b \\ cY(1-Y) & (1-2Y)(cX+dZ-C_T+\frac{\lambda}{2}\delta^2Z^2) & Y(1-Y)(d+\lambda\delta^2Z) \\ eZ(1-Z) & \mathrm{Z}(1-\mathrm{Z})(-\lambda\delta^2(\mathrm{Y}-1)) & (1-2Z)(eX+f+g-\frac{\lambda}{2}\delta^2(Y-1)^2) \end{bmatrix}$$

The eigenvalues of Jacobian matrix J with different equilibrium points are shown in Table 7.

Among the ten eigenvalues of Eq. (8), equilibrium points E_4, E_9, E_{10}, E_{11} and E_{12} all have at least one eigenvalue that is greater than zero and are saddle points. E_1, E_2, E_3, E_5, E_6, E_7 and E_8 can possess three eigenvalues that are all less than zero under certain conditions and are thus the potential ESS points;. When the seven equilibrium points are stable respectively, the EES point may not be unique, as Table 8a, b shows.

In model 2, E_3 and E_8 represent that SMMEs conduct DT under the guidance of TDEs and are thus ideal stable points. Certain conditions need to be satisfied if E_3 and E_8 desire to become ideal ESS points. Table 9a, b shows the conditions that E_3 and E_8 are ESS points.

Proposition 3. Considering the risk aversion of SMMEs, $E_3(0, 1, 1)$ is an ESS point when $P_T<C_G+R_E+R_S+L_G$, $C_T<R_{ZT}+L_T+\frac{\lambda}{2}\delta^2$, $R_{GE}>C_E$. Further, if $R_{GE}>C_E+\frac{\lambda\delta^2}{2}$, or if $P_E+P_T>C_G+R_S$ and $P_T+R_T>C_T$, $E_3(0, 1,1)$ is the unique ESS point, that is, governments do not regulate, and SMMEs propel DT under the guidance of TDEs.

Proposition 3 indicates that when the revenue of SMMEs earned by conducting DT under the guidance of TDEs exceeds the corresponding cost, when governmental punishments for TDEs are not enough to pay for governmental rewards and subsidies for enterprises, governmental regulation cost etc., and when the difference that the directive cost of TDEs subtracts the loss that TDEs suffer due to avoiding guiding DT is less than the total returns that TDEs obtain from SMMEs due to guiding DT and the risk aversion of manufacturing enterprises, the ESS is (0, 1, 1). The third conclusion of our research is: considering the risk aversion of SMMEs, when governments choose not to regulate, if SMMEs and TDEs have two kinds of stable strategies in natural environments, governments can enhance the punishments for SMMEs and the rewards for TDEs, in order to motivate SMMEs and TDEs to implement DT and guide DT, respectively; if SMMEs and TDEs can hardly realize stable execution and guidance in natural environments, respectively, governments cannot drive SMMEs to implement DT under the guidance of TDEs by altering incentive and punitive measures.

Besides, the fourth conclusion of our paper is deduced as follows: when governments choose not to regulate, if SMMEs and TDEs in natural environments cannot stabilize at executing and guiding states at the same time, respectively, governments must enhance the punishments for TDEs and turn to supervision simultaneously, with the purpose to motivate SMMEs implement DT under the guidance of TDEs.

Proposition 4. Considering the risk aversion of SMMEs, $E_8(1, 1,1)$ is an ESS point when $P_T>C_G+R_E+R_S+L_G$, $C_T<P_T+R_T+R_{ZT}+L_T+\frac{\lambda}{2}\delta^2$ and $R_E+P_E+R_{GE}>C_E$; further, if $R_E+P_E+R_{GE}>C_E+\frac{\lambda}{2}\delta^2$ or $P_T+R_T>C_T$ holds, $E_8(1, 1,1)$ is the unique ESS point, that is, governments regulate, and SMMEs propel DT under the guidance of TDEs.

The fifth conclusion of our research is: considering the risk aversion of SMMEs, when governments regulate, there may exist two stable states for SMMEs and TDEs: executing DT and guiding DT, avoiding executing DT and guiding DT. If SMMEs and TDEs can hardly stabilize at executing and guiding states respectively, or if they have two stable states, governments should set heavy punishments for the enterprises.

Similarly, governments make the systems formed by governments, TDEs and SMMEs to convert from an initial non-ideal ESS point to an ideal ESS point or from an ideal ESS point to another ideal ESS point by changing their strategies. Table 10 and Fig. 1 together show the switching paths from initial ESS points to ideal ESS points (i.e., E_3 and E_8) and the corresponding conditions.

When it comes to the conditions that governments select to regulate, Proposition 2 does not consider the risk aversion of manufacturing enterprises and only requires that the total price caused by the DT evasion behaviors of SMMEs and TDEs is greater than the total price induced by the implementing and guiding behaviors related to DT in SMMEs and TDEs, respectively, whereas Proposition 4 considers the loss caused by the risk aversion of SMMEs. This comparison reveals that the risk aversion of manufacturing enterprises deeply inhibits their DT behaviors, and thus governments should raise the punishments for manufacturing enterprises. TDEs may be faced with the plight that SMMEs refuse to implement DT to evade DT risks. To handle such a case, governments only need to enlarge the penalties for enterprises.

This paper mainly investigates how to realize stability from a governmental standpoint, and the exploration in terms of enterprises is not discussed. By summarizing Propositions 1–4, we can obtain the following inferences.

Table 8 Evolutionary stability analysis of each equilibrium point in model 2.

Conditions	The values of eigenvalues	Non-ESS points	ESS points	The number of ESS points
(a) Evolutionary stability analysis of each equilibrium point when $P_T \le C_G + L_G$				
$P_T < C_G + R_E + R_S + L_G$, $R_{ZT} + L_T + \lambda\delta^2/2 < C_T$, $R_{GE} > C_E + \lambda\delta^2/2$	$\lambda_1^i < 0 (i = 1, 2, 3)$; $\lambda_3^2 > 0$; $\lambda_j^3 < 0 (j = 2, 6, 7)$	E_2, E_3, E_6, E_7	E_1	1
$P_E + P_T < R_S + C_G$, $R_{GE} < C_E + \lambda\delta^2/2$	$\lambda_1^3 > 0$; $\lambda_2^i < 0 (i = 1, 2, 3)$; $\lambda_j^1 < 0 (j = 6, 7)$; $\lambda_3^i (i = 2, 3)$ are uncertain	E_1, E_6, E_7	E_2	≥ 1
$P_T < C_G + R_E + R_S + L_G$, $C_T < R_{ZT} + L_T + \lambda\delta^2/2$, $R_{GE} > C_E$	$\lambda_1^2 > 0$; $\lambda_3^i < 0 (i = 1, 2, 3)$; $\lambda_7^3 > 0$; $\lambda_2^i (i = 1, 3)$ and $\lambda_6^i (i = 1, 2, 3)$ are uncertain	E_1, E_7	E_3	≥ 1
$P_E + P_T > R_S + C_G$, $P_T + R_T < C_T$, $R_E + P_E + R_{GE} < C_E + \lambda\delta^2/2$	$\lambda_1^3 > 0$; $\lambda_2^1 > 0 \lambda_6^i < 0 (i = 1, 2, 3)$; $\lambda_7^2 > 0$	E_1, E_2, E_7	E_6	≥ 1
$P_E + P_T > R_S + C_G$, $P_T + R_T > C_T$, $R_E + P_E + R_{GE} < C_E$	$\lambda_j^3 < 0 (j = 1, 3)$; $\lambda_2^1 > 0$; $\lambda_6^2 > 0$; $\lambda_7^i < 0 (i = 1, 2, 3)$	E_1, E_2, E_3, E_6	E_7	1
(b) Evolutionary stability analysis of each equilibrium point when $P_T > C_G + L_G$				
$P_T < C_G + R_E + R_S + L_G$, $R_{ZT} + L_T + \lambda\delta^2/2 < C_T$, $R_{GE} > C_E + \lambda\delta^2/2$	$\lambda_1^i < 0 (i = 1, 2, 3)$; $\lambda_j^3 > 0 (j = 2, 6, 7)$; $\lambda_3^2 > 0$; $\lambda_j^1 > 0 (j = 5, 8)$	E_2, E_3, E_5, E_6, E_7, E_8	E_1	1
$P_E + P_T < R_S + C_G$, $R_{GE} < C_E + \lambda\delta^2/2$	$\lambda_1^3 > 0$; $\lambda_2^i < 0 (i = 1, 2, 3)$; $\lambda_3^i (i = 2, 3)$ are uncertain; $\lambda_j^1 > 0 (j = 5, 6, 7, 8)$	E_1, E_5, E_6, E_7, E_8	E_2	≥ 1
$P_T < C_G + R_E + R_S + L_G$, $C_T < R_{ZT} + L_T + \lambda\delta^2/2$, $R_{GE} > C_E$	$\lambda_1^2 > 0$; $\lambda_3^i < 0 (i = 1, 2, 3)$; $\lambda_7^3 > 0$; $\lambda_j^1 > 0 (j = 5, 8)$; $\lambda_2^i (i = 1, 3)$ and$\lambda_6^i (i = 1, 2, 3)$ are uncertain	E_1, E_5, E_7, E_8	E_3	≥ 1
$P_T > C_G + R_E + R_S + L_G$, $P_T + R_T + R_{ZT} + L_T + \lambda\delta^2/2 < C_T$, $R_E + P_E + R_{GE} > C_E + \lambda\delta^2/2$	$\lambda_j^1 > 0 (j = 1, 2, 3)$; $\lambda_5^i < 0 (i = 1, 2, 3)$; $\lambda_j^3 > 0 (j = 6, 7)$; $\lambda_8^2 > 0$	E_1, E_2, E_3, E_6, E_7, E_8	E_5	1
$P_E + P_T > R_S + C_G$, $P_T + R_T < C_T$, $R_E + P_E + R_{GE} < C_E + \lambda\delta^2/2$	$\lambda_j^3 > 0 (j = 1, 5)$; $\lambda_6^i < 0 (i = 1, 2, 3)$; $\lambda_7^2 > 0$; $\lambda_3^i (i = 1, 2, 3)$ and $\lambda_8^i (i = 1, 2, 3)$ are uncertain;	E_1, E_2, E_5, E_7	E_6	≥ 1
$P_E + P_T > R_S + C_G$, $P_T + R_T > C_T$, $R_E + P_E + R_{GE} < C_E$	$\lambda_2^1 > 0$;$\lambda_6^2 > 0$; $\lambda_7^i < 0 (i = 1, 2, 3)$; $\lambda_j^3 > 0 (j = 1, 3, 5, 8)$	E_1, E_2, E_3, E_5, E_6, E_8	E_7	1
$P_T > C_G + R_E + R_S + L_G$, $C_T < P_T + R_T + R_{ZT} + C_T + \lambda\delta^2/2$, $R_E + P_E + R_{GE} > C_E$	$\lambda_j^1 > 0 (j = 1, 2, 3)$; $\lambda_5^2 > 0$; $\lambda_6^i (i = 2, 3)$ are uncertain; $\lambda_7^3 > 0$; $\lambda_8^i < 0 (i = 1, 2, 3)$	E_1, E_2, E_3, E_5, E_7	E_8	≥ 1

Table 9 The conditions that E_3 and E_8 are ESS points.

Initial conditions	Additional conditions	The values of eigenvalues	Note
(a) The conditions that E_3 and E_8 are ESS points when $P_T \le C_G + L_G$			
$P_T < C_G + R_E + R_S + L_G$, $C_T < R_{ZT} + L_T + \lambda\delta^2/2$, $R_{GE} > C_E$	–	$\lambda_1^2>0$; $\lambda_3^i<0(i=1,2,3)$; $\lambda_7^3>0$; $\lambda_2^i(i=1,3)$ and $\lambda_6^i(i=1,2,3)$ are uncertain	E_3 is an ESS point
	$P_E + P_T > R_S + C_G$ $P_T + R_T > C_T$ $R_{GE} > C_E + \lambda\delta^2/2$	$\lambda_1^2>0$; $\lambda_3^i<0(i=1,2,3)$; $\lambda_j^3>0(j=2,6,7)$	E_3 is the unique ESS point
$P_T < C_G + R_E + R_S + L_G$, $C_T < P_T + R_T + R_{ZT} + C_T + \lambda\delta^2/2$, $R_E + P_E + R_{GE} > C_E$	–	$\lambda_8^1>0$	E_8 is not an ESS point
(b) The conditions that E_3 and E_8 are ESS points when $P_T > C_G + L_G$			
$P_T < C_G + R_E + R_S + L_G$, $C_T < R_{ZT} + L_T + \lambda\delta^2/2$, $R_{GE} > C_E$	–	$\lambda_1^2>0$; $\lambda_3^i<0(i=1,2,3)$; $\lambda_7^3>0$; $\lambda_j^1>0(j=5,8)$; $\lambda_2^i(i=1,3)$ and $\lambda_6^i(i=1,2,3)$ are uncertain	E_3 is an ESS point
	$P_E + P_T > R_S + C_G$ $P_T + R_T > C_T$ $R_{GE} > C_E + \lambda\delta^2/2$	$\lambda_1^2>0$; $\lambda_3^i<0(i=1,2,3)$; $\lambda_j^3>0(j=2,6,7)$; $\lambda_j^1>0(j=5,8)$	E_3 is the unique ESS point
$P_T > C_G + R_E + R_S + L_G$, $C_T < P_T + R_T + R_{ZT} + C_T + \lambda\delta^2/2$, $R_E + P_E + R_{GE} > C_E$	–	$\lambda_1^i>0(i=1,2,3)$; $\lambda_5^2>0$; $\lambda_6^i(i=2,3)$ are uncertain;$\lambda_7^3>0$; $\lambda_8^i<0(i=1,2,3)$	E_8 is an ESS point
	$P_T + R_T > C_T$	$\lambda_1^i>0(i=1,2,3)$; $\lambda_j^2>0(j=5,6)$; $\lambda_7^3>0$; $\lambda_8^i<0(i=1,2,3)$	E_8 is the unique ESS point
	$R_E + P_E + R_{GE} > C_E + \lambda\delta^2/2$	$\lambda_1^i>0(i=1,2,3)$; $\lambda_5^2>0$; $\lambda_j^3>0(j=6,7)$; $\lambda_8^i<0(i=1,2,3)$	

By analyzing E_3 and E_8, respectively, we can obtain Propositions 3 and 4.

Inference 1. Governments always have measures to prevent SMMEs and TDEs from avoiding implementing and guiding DT, respectively.

Whether SMMEs are risk-neutral or risk-adverse, and whether governments regulate or not, governments can use effective polices to make manufacturing enterprises and TDEs implement DT and guide DT, respectively; specifically, governments can set heavy penalties in supervised scenes, and can set high rewards in unsupervised scenes.

Inference 2. Heavy punishments can effectively prevent SMMEs and TDEs from avoiding implementing DT and guiding DT, respectively.

By comparing Propositions 1 and 4, this paper finds a consistent revelation, that is, high penalties can prevent SMMEs and TDEs from avoiding implementing DT and guiding DT separately. The dissimilarities between the two propositions are stated as follows: when heavy punishments are used as deterrents, the minimum feasible penalty in Proposition 4 exceeds that in Proposition 2; when the risk-adverse coefficient increases, the minimum feasible penalty in Proposition 4 become greater, and the difference between the minimum feasible penalties in the two propositions increases.

Numerical simulations

This section uses MATLAB to conduct numerical simulation to validate the proposed tripartite evolutionary game models (i.e., model 1 and model 2), and then to visually show the evolutionary paths when governments, manufacturing enterprises and TDEs are playing games.

The evolutionary paths of stakeholders. To verify the before-mentioned propositions, this section tries to analyze the evolutionary paths of model 1 and model 2 toward ESS points (0, 1, 1) and (1, 1, 1), as well as without ESS points. The parameter values are shown in Table 11. Besides, we set the initial values of variables X, Y and Z as follows: $X \in \{0.2, 0.7\}$, $Y \in \{0.2, 0.7\}$, $Z \in \{0.2, 0.7\}$.

Based on the parameter values in Table 11, we can obtain the evolutionary paths of the stakeholders toward ESS point (0, 1, 1), as shown in Fig. 2. The results presented by Fig. 2 indicate that when the prerequisites in the proposed propositions are met, the ESS point is (0, 1, 1) no matter what the initial values of X, Y and Z (i.e., the initial strategies of the stakeholders) are. To be specific, since there are eight combinations for the initial values of X, Y and Z, eight curves appear in Fig. 2a, b; as time goes on, the values of X, Y and Z in Fig. 2a, b tend to converge and finally stabilize at (0, 1, 1). Consequently, Propositions 1 and 3 are validated.

To verify the third conclusion of our research, the initial values of X, Y and Z are set as 0.2, 0.7 and 0.7, respectively, let P_E range from 0 to 5, and leave the remaining parameters unchanged. Then, we can obtain Fig. 3. Figure 3 shows that governments can increase the punishments for SMMEs to make SMMEs perform DT under the guidance of TDEs. Thus, the third conclusion of our research is proved.

Based on the parameter values in Table 11, we can obtain the evolutionary paths of the stakeholders toward ESS point (1, 1, 1), as shown in Fig. 4a, b. The results displayed by Fig. 4 demonstrate that when the corresponding conditions are satisfied, the ESS point is (1, 1, 1) no matter what the initial strategies of the stakeholders are. Therefore, Proposition 2 and Proposition 4 are proved.

Similarly, based on the parameter values in Table 11, we can obtain the evolutionary paths of the stakeholders when model 1 and model 2 do not have an ESS, as shown in Fig. 5. To model 1, if $C_G - P_E - L_G < P_T < C_G + R_E$ and $R_{GE} < C_E < R_{GE} + R_E + P_E$ hold, model 1 does not have ESS points no matter what the initial values of X, Y and Z are, as Fig. 5a shows; to model 2, if $C_G - P_E - L_G < P_T < C_G + R_E$ and $R_{GE} < C_E < R_{GE} + R_E + P_E - \frac{\lambda}{2}\delta^2$ are met, model 2 does not have ESS points no matter what the initial values of X, Y and Z are, as Fig. 5b shows.

The conditions without ESS points manifest that when governmental regulation cost (i.e., C_G) exceeds governmental

Table 10 The transition from initial ESS points to ideal ESS points in model 2.

Initial ESS points	Main influencing factors	New ESS points	Explanations
(a) The transition from initial ESS points to ideal ESS points when $P_T \le C_G + L_G$			
$E_1(0, 0, 1)$	Inexistent	-	The ESS point cannot change
$E_2(0, 0, 0)$	Inexistent	-	The ESS point cannot change
$E_3(0, 1, 1)$	Inexistent	-	The ESS point cannot change
$E_6(1, 0, 0)$	Inexistent	-	The ESS point cannot change
$E_7(1, 1, 0)$	Inexistent	-	The ESS point cannot change

Initial ESS points	Main influencing factors	New ESS points	Additional conditions
(b) The transition from initial ESS points to ideal ESS points when $P_T > C_G + L_G$			
$E_1(0, 0, 1)$	$\{P_T\uparrow\}$ or $\{R_S\downarrow, R_E\downarrow, R_T\uparrow\}$	$E_8(1, 1, 1)$	-
$E_2(0, 0, 0)$	$\{P_T\uparrow, (P_E\uparrow$ or $R_E\uparrow)\}$ or $\{R_S\downarrow, R_E\downarrow, R_T\uparrow, P_E\uparrow\}$	$E_8(1, 1, 1)$	-
$E_3(0, 1, 1)$	$\{P_T\uparrow\}$ or $\{R_E\downarrow, R_S\downarrow\}$	$E_8(1, 1, 1)$	-
$E_5(1, 0, 1)$	$P_T\uparrow$ or $R_T\uparrow$	$E_8(1, 1, 1)$	-
$E_6(1, 0, 0)$	$\{P_T\uparrow, (P_E\uparrow$ or $R_E\uparrow)\}$ or $\{R_S\downarrow, R_E\downarrow, R_T\uparrow, P_E\uparrow\}$	$E_8(1, 1, 1)$	-
$E_7(1, 1, 0)$	$\{P_T\uparrow, (R_E\uparrow$ or $P_E\uparrow)\}$ or $\{R_S\downarrow, R_E\downarrow, P_E\uparrow\}$	$E_8(1, 1, 1)$	-
$E_8(1, 1, 1)$	$\{P_T\downarrow\}$ or $\{R_E\uparrow\}$ or $\{R_S\uparrow\}$	$E_3(0, 1, 1)$	$C_T < R_{ZT} + L_T + \lambda\delta^2/2$, $R_{GE} > C_E$

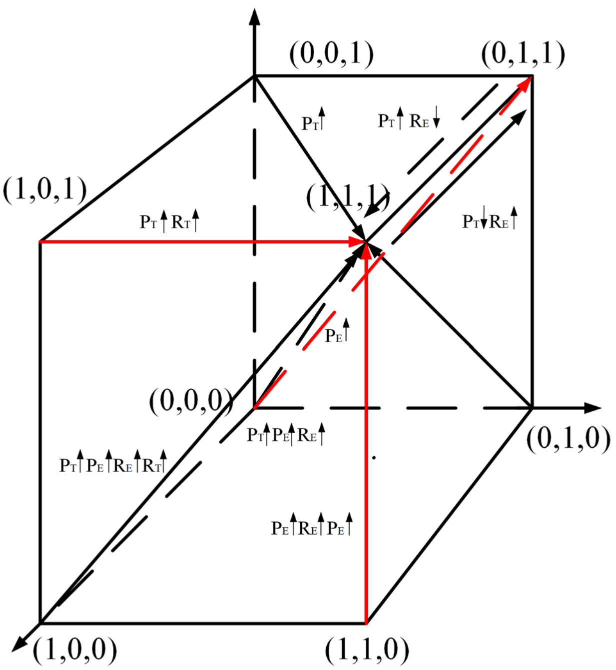

Fig. 1 State transfer analysis. The state transition from other equilibrium points to ideal equilibrium points in model.

regulation revenue (i.e., P_T - R_E), and when the DT cost in SMMEs (i.e., C_E) is above the maximum revenue that SMMEs obtain from the DT (i.e., R_{GE}), SMMEs might select DT even if TDEs do not provide guidance. On the contrary, when the sum of governmental penalties for enterprises and the loss of social welfare is higher than governmental regulation cost (i.e., $C_G < P_E + L_G + P_T$), and when the cost the SMMEs reject DT exceeds the cost that SMMEs implement DT (i.e., $C_E - (R_{GE} + R_E) < P_E$), the probability that SMMEs conduct DT can approach 1 or even equal 1 as time goes on. According to the conditions that model 1 and model 2 do not possess ESS points and the simulation results indicated by Fig. 5, we can get Note 1.

Note 1. When governments are not motivated to regulate, when SMMEs have an incentive to avoid DT, and when TDEs are of void guiding willingness, SMMEs would also select to execute DT in some cases.

The phenomenon shown in Note 1 is comprehensible, and mainly originates from the deterrence of punishments. Although governments have no motives for long-term regulation when the regulation cost of governments exceeds their regulation revenue, it does not mean that they would avoid regulation forever. Once SMMEs choose to avoid DT and take the selection as a stable strategy, governments can get high fines in a given interval of regulatory period and do not always stay at unsupervised states if the sum of fines and regulation revenue exceeds regulation cost. If fines are heavy enough, SMMEs would not choose to avoid DT prematurely but at the right time. Note 1 also explain the case that SMMEs escape from executing DT again, indicating that governments need to take adequate measures to prevent SMMEs from avoiding executing DT, not just deterrent means.

Sensitivity analysis. This section discusses how tripartite evolutionary game models switch from other stable points to ideal stable points $E_3(0,1,1)$ and $E_8(1,1,1)$ when parameters change. During the switching processes, the most obvious sign is the decision-making changes of SMMEs and TDEs, that is, stable states could convert from $Y = 0$ and $Z = 0$ to $Y = 1$ and $Z = 1$. Based on Figs. 1 and 5, this section first discusses the processes that models 1 and 2 switch from E_8 to E_3. The initial conditions of model 1 are set as $X = 0.7$, $Y = 0.7$ and $Z = 0.7$, the settings for other parameters are shown in the third line of Table 11; besides, the initial conditions of model 2 are set as $X = 0.2$, $Y = 0.7$ and $Z = 0.7$, the settings for other parameters are shown in the sixth line of Table 11. Then, we can obtain the evolutionary processes of models 1 and 2 converting from E_8 to E_3, as shown in Fig. 6.

In model 1 and model 2, $P_T\downarrow$or $C_G\uparrow$or $R_E\uparrow$can lead to the transition from $E_8(1, 1, 1)$ to $E_3(0, 1, 1)$, that is, $X = 1$ is altered as $X = 0$ under stable states. It indicates that $E_8(1, 1, 1)$ tends to turn into $E_3(0, 1, 1)$ when governmental punishments for TDEs decrease governmental regulation cost increases, or governmental rewards for SMMEs raise. Take model 1 as example, Fig. 6 shows how the change of P_T affects the final stable states starting from $E_8(1, 1, 1)$. As we can see from Fig. 6, $P_T = C_G + R_E$ is the crucial condition for $E_8(1, 1, 1)$ to transform into $E_3(0, 1, 1)$. To be specific, when $P_T > C_G + R_E$, $X = 1$ is the stable strategy; when $P_T < C_G + R_E$, $X = 0$ is the stable strategy; when $P_T = C_G + R_E$, $X = 1$ and $X = 0$ are all the stable strategies, and the probability

Table 11 Parameter values of two models toward (0, 1, 1), (1, 1, 1) and without ESS points.

Models	ESS points	Parameters													
		P_E	P_T	R_S	C_G	R_E	L_G	R_T	R_{ZT}	L_T	C_T	R_{GE}	C_E	λ	δ
Model 1	(0, 1, 1)	4	3	2	2	4	5	2	5	1	3	10	8	-	-
	(1, 1, 1)	4	6	2	1	2	5	2	5	1	3	10	8	-	-
	Inexistent	3	5	2	4	4	1	2	5	1	3	8	10	-	-
Model 2	(0, 1, 1)	3	3	2	2	4	5	2	5	1	3	10	8	0.4	5
	(1, 1, 1)	3	4	2	1	2	5	2	5	1	3	10	8	0.4	5
	Inexistent	3	5	2	4	4	1	2	5	1	3	9	10	0.4	5

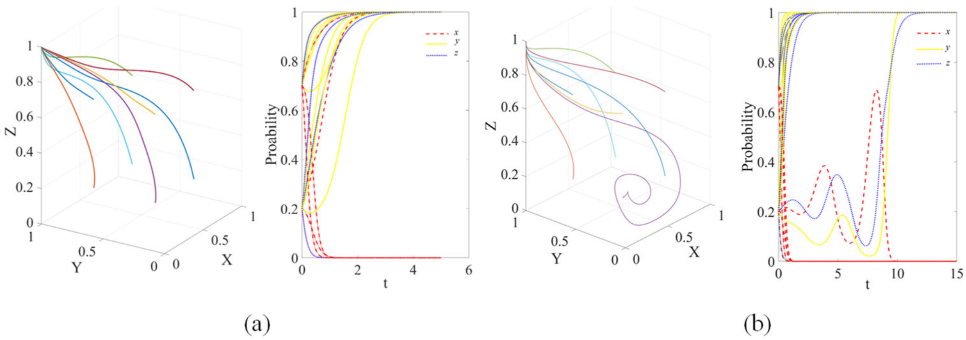

Fig. 2 The evolutionary paths analysis of ESS (0, 1, 1). The evolutionary paths toward ESS (0, 1, 1) of two models: **a** model 1 and **b** model 2.

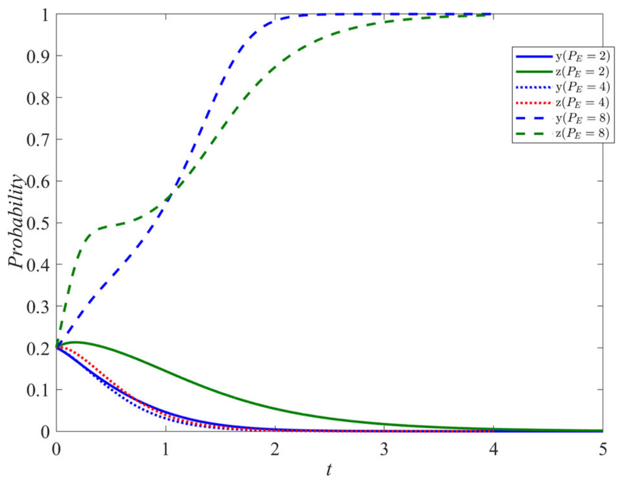

Fig. 3 Analysis of evolutionary influencing factors. The impact of changing P_E on model 2 evolving toward ESS (0, 1, 1).

that governments select regulation (i.e., X) is inclined to a stable value which would not be 0 or 1.

Subsequently, this paper discusses how model 1 switch from other equilibrium points to the ideal stable point E_8(1,1,1). The initial values of three variables are set as $X = 0.7$, $Y = 0.7$ and $Z = 0.7$, and the remaining parameter values under different transitions are shown in Table 12. Then, we can obtain the evolutionary processes from E_1, E_2, E_5, E_6 and E_7 to E_8, as shown in Fig. 7.

In model 1, P_T↑ could lead to the transition from E_1(0, 0, 1) to E_8(1, 1, 1), that is, $X = 0$ and $Y = 0$ are altered as $X = 1$ and $Y = 1$ under stable states, respectively. It manifests that governments would tighten sanctions to TDEs when they choose to regulate. Such governmental behaviors could overawe TDEs to provide DT guidance to manufacturing enterprises, and then E_1 tends to convert into E_8, as shown in the first sub-graph of Fig. 7.

P_E↑or synchronously increasing P_T and R_E (i.e., P_T↑ and R_E↑) could lead to the transition from E_2(0, 0, 0) to E_8(1, 1, 1), that is, $X = 0$, $Y = 0$ and $Z = 0$ are altered as $X = 1$, $Y = 1$ and $Z = 1$ under stable states, respectively. It indicates that governments can prompt SMMEs to execute DT by raising the punishments for SMMEs or by simultaneously increasing the punishments for TDEs and the rewards for SMMEs implementing DT. In this situation, TDEs would choose to guide SMMEs to conduct DT, as the second sub-graph of Fig. 7 shows.

P_T ↑ or R_T↑ would cause the transition from E_5(1, 0, 1) to E_8(1, 1, 1), that is, $Y = 0$ is altered as $Y = 1$ under stable states. It shows that governments could urge TDEs to guide SMMEs to conduct DT by enhancing the penalties or rewards for TDEs on condition that governments exercise supervision, as shown in the third sub-graph of Fig. 7.

P_T ↑and increasing P_E or R_E (i.e., P_E↑ or R_E↑) would result in the transition from E_6(1, 0, 0) to E_8(1, 1, 1), that is, $Y = 0$ and $Z = 0$ is altered as $Y = 1$ and $Z = 1$ under stable states, respectively. It indicates that governments could motivate SMMEs to conduct DT by adding the fines for TDEs or increasing the penalties or rewards for SMMEs on condition that governments exercise supervision. In this situation, TDEs would choose to provide DT guidance to SMMEs, as the fourth sub-graph of Fig. 7 shows.

P_T ↑ and increasing P_E or R_E (i.e., P_E↑ or R_E↑) would result in the transition from E_7(1, 1, 0) to E_8(1, 1, 1), that is, $Z = 0$ is altered as $Z = 1$ under stable states. It shows that governments could spur SMMEs to perform DT by adding the fines for TDEs or increasing the penalties or rewards for SMMEs on condition that governments exercise supervision, as depicted in the fifth sub-graph of Fig. 7.

The parameter settings of model 2 from other equilibrium points to E_8 are like those of model 1. According to the parameter settings, we can obtain the evolutionary processes from E_1, E_2, E_5, E_6 and E_7 to E_8, as Fig. 8 depicts. Dissecting the evolutionary processes of model 2 is parallel to that of model 1 and is not unfolded in our research.

Contributions and managerial implications

Contributions. Our research mainly has three contributions. First, our research is unlike previous literature focusing on technical innovation and enterprise transformation from the view of theoretical innovation and presents a brand-new angle to explore how governmental regulation and the guidance of TDEs affect the DT of manufacturing enterprise. With the fast-growing information technology and rapidly changing market demands, manufacturing enterprises need to determine whether to venture into DT or remain unchanged. Executing DT may encounter failures, which could bring insolvent risks to manufacturing enterprises. Continuing to maintain original production modes may lose market shares but enables manufacturing enterprises to evolve on an even keel. Faced with this dilemma, this paper employs evolutionary game theory to investigate the selection of manufacturing enterprises, which differs from existing studies and provides more specific theoretical supports to solve the dilemma. Second, unlike general studies about evolutionary game, this paper takes behavioral factors into account (e.g., the risk-averse behavior of manufacturing enterprises in model 2) and analyzes the optimal decisions. Our research fully considers

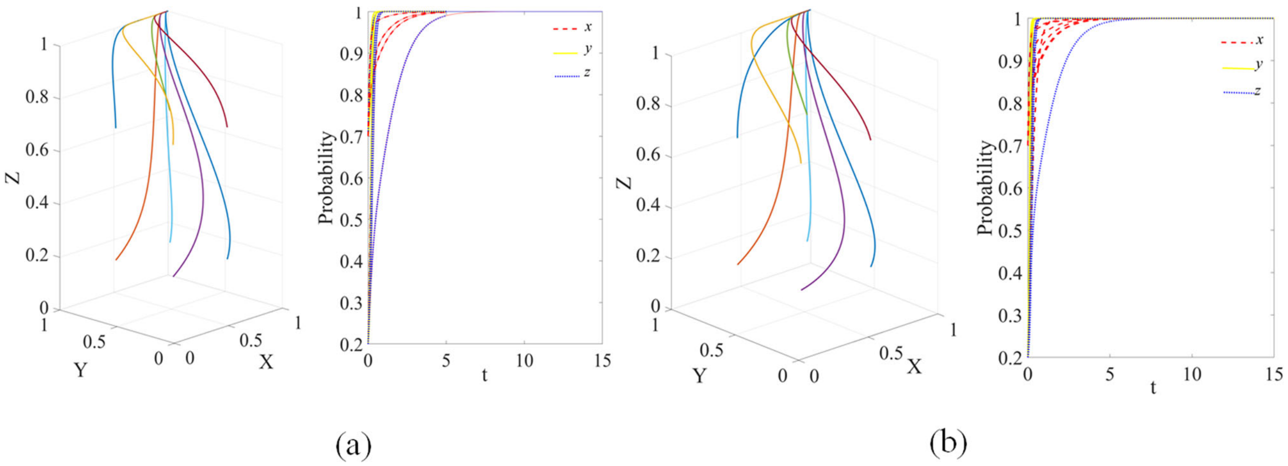

Fig. 4 The evolutionary paths analysis of ESS (1, 1, 1). The evolutionary paths toward ESS (1, 1, 1) of two models: **a** model 1 and **b** model 2.

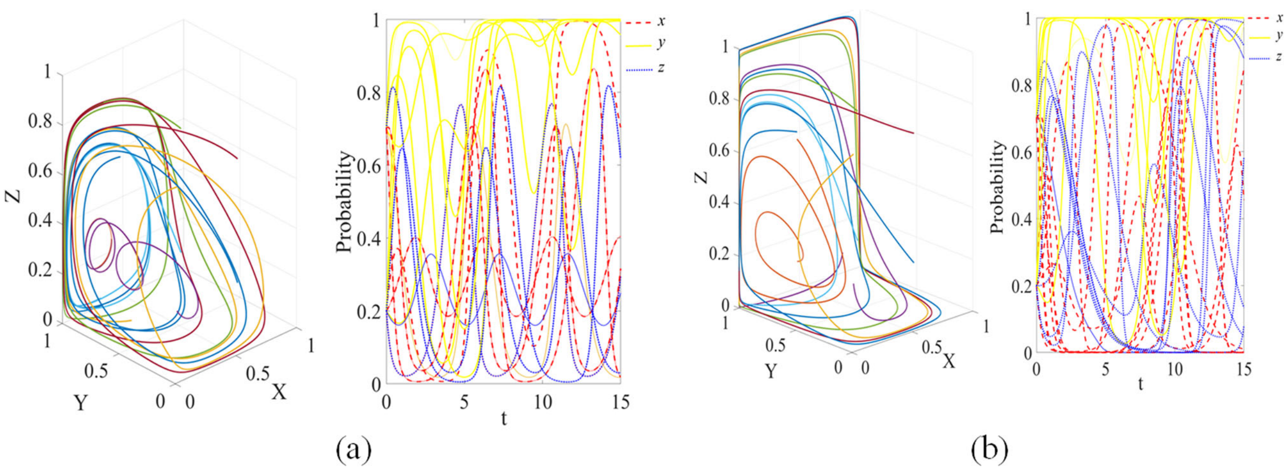

Fig. 5 Analysis of two model evolutionary paths. The evolutionary paths of two models without an ESS: **a** model 1 and **b** model 2.

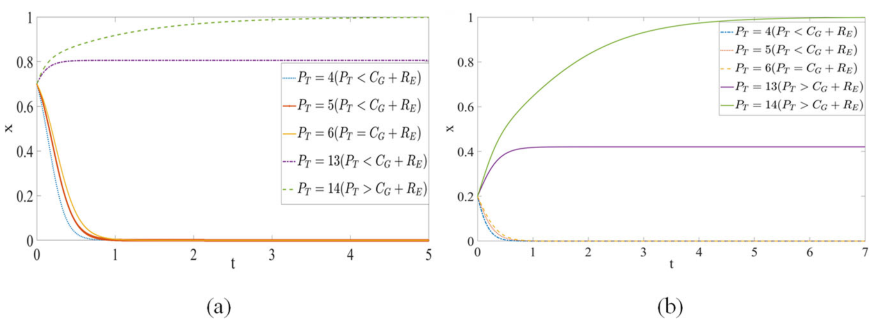

Fig. 6 The switching processes of E_3. The switching processes of two models from E_8 to E_3: **a** model 1 and **b** model 2.

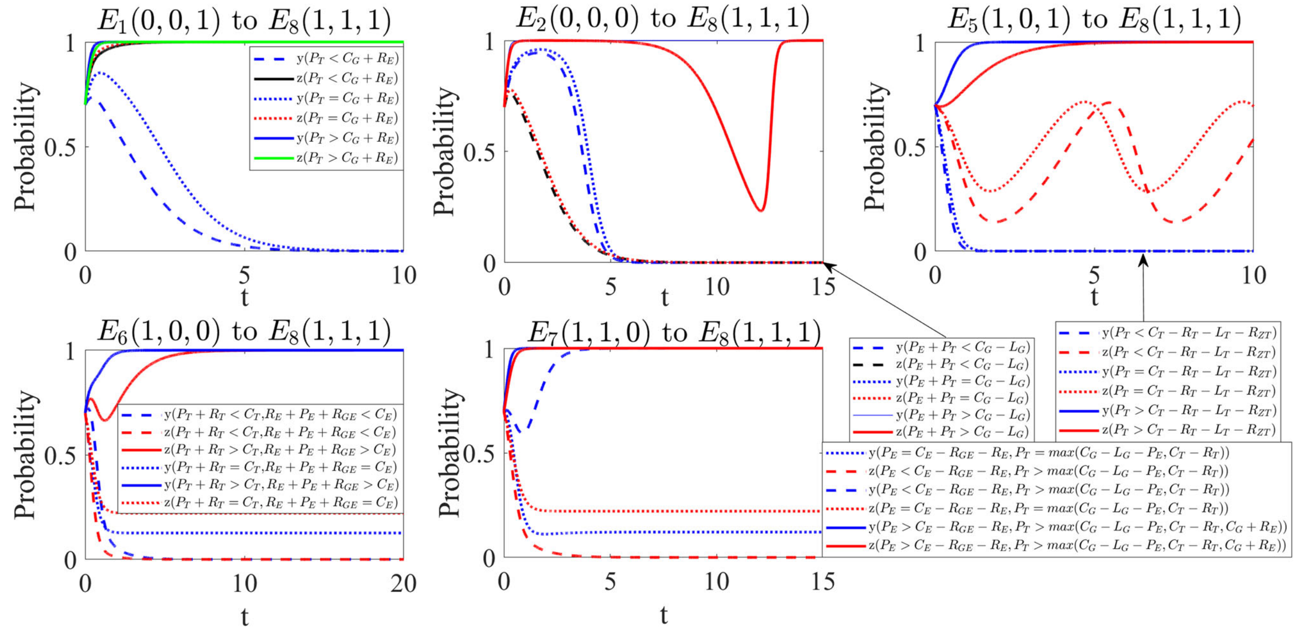

Fig. 7 The switching processes of E_8 in model 1. The transiting processes of model 1 from other equilibrium points to E_8.

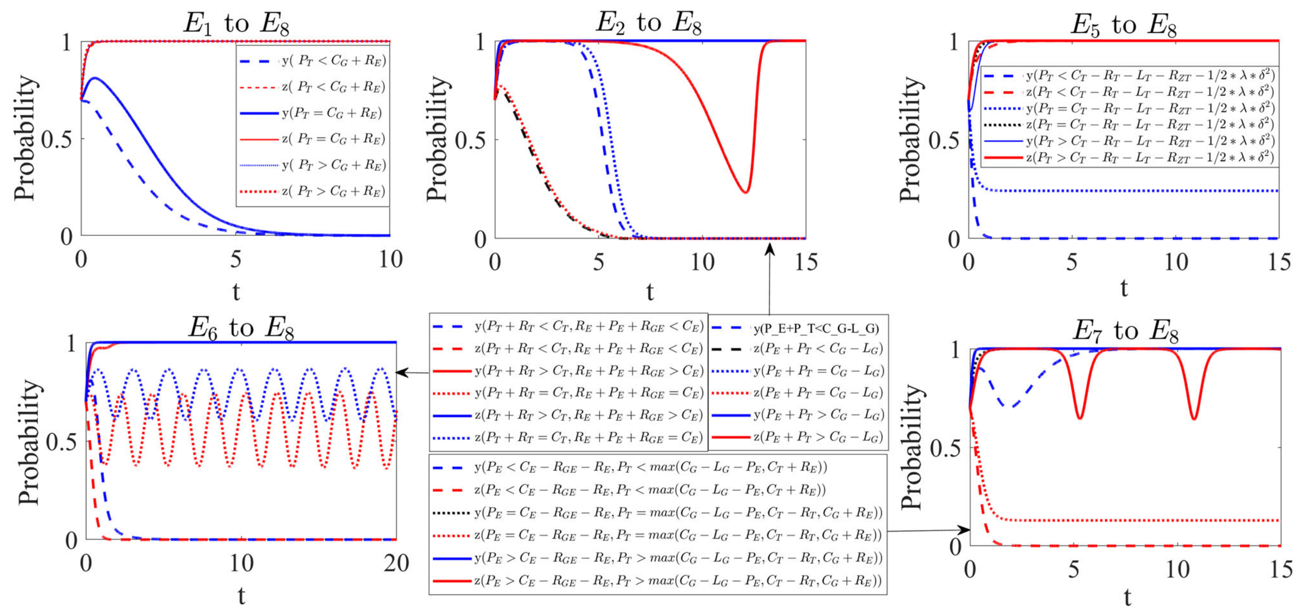

Fig. 8 The switching processes of E_8 in model 2. The transiting processes of model 2 from other equilibrium points to E_8.

the periodical features of DT in manufacturing enterprises and applies evolutionary game to innovate. Finally, our research is able to provide valid references for governments to formulate regulation policies. Governments just need to alter game variables (e.g., adjust penalties with regulation and adjust rewards without regulation), to control evolutionary games, such as preventing manufacturing enterprises and TDEs from avoiding executing and guiding DT, respectively. This study also finds that the deterrence of governmental penalties can promote manufacturing enterprises to implement DT for a certain time, but not for long. Simulation results show that the behaviors of avoiding DT in manufacturing enterprises can occur again, indicating that it is not enough to restrain manufacturing enterprises from avoiding DT by governmental punishments, and something else must be done.

Managerial implications. To precisely provide governments with policy suggestions to manage DT, this paper first clarifies the composition of governmental revenues in a game. Governmental revenues mainly include governmental punishments for SMMEs avoiding DT (i.e., P_E), governmental punishments for TDEs rejecting guiding DT (i.e., P_T), the tax revenues that governments obtained if TDE guide SMMEs to execute DT (i.e., R_G), and the tax revenues that governments obtained if SMMEs conduct DT independently (i.e., R_{NG}). When governments select regulation, they would pay for regulation cost C_G; if manufacturing enterprises are found avoiding DT, governments would impose a penalty P_E on them, to regain the loss of social welfare (i.e., L_G) and the special subsidies provided to support DT in SMMEs (i.e., R_S). In the supervised environment, if SMMEs are found executing DT, governments would give rewards

Table 12 Parameter values of model 1 converging to $E_8(1, 1, 1)$ from other equilibrium points.

Transitions	Conditions	Parameters											
		P_E	P_T	R_S	C_G	R_E	L_G	R_T	R_{ZT}	L_T	C_T	R_{GE}	C_E
$E_1 \rightarrow E_8$	$P_T < C_G + R_E$	3	3	2	2	4	5	2	3	1	5	10	8
	$P_T = C_G + R_E$	3	6	2	2	4	5	2	3	1	5	10	8
	$P_T > C_G + R_E$	3	14	2	2	4	5	2	3	1	5	10	8
$E_2 \rightarrow E_8$	$P_E + P_T < C_G - L_G$	1	1	2	4	4	1	2	5	1	3	8	9
	$P_E + P_T = C_G - L_G$	1.5	1.5	2	4	4	1	2	5	1	3	8	9
	$P_E + P_T > C_G - L_G$	8	9	2	4	4	1	2	5	1	3	8	9
$E_5 \rightarrow E_8$	$P_T < C_T - R_T - L_T - R_{ZT}$	3	4	2	1	2	5	1	3	1	10	4	8
	$P_T = C_T - R_T - L_T - R_{ZT}$	3	5	2	1	2	5	1	3	1	10	4	8
	$P_T > C_T - R_T - L_T - R_{ZT}$	3	10	2	1	2	5	1	3	1	10	4	8
$E_6 \rightarrow E_8$	$P_T + R_T < C_T$, $R_E + P_E + R_{GE} < C_E$	3	4	2	2	2	5	2	5	1	7	4	10
	$P_T + R_T = C_T$, $R_E + P_E + R_{GE} < C_E$	4	5	2	2	2	5	2	5	1	7	4	10
	$P_T + R_T > C_T$, $R_E + P_E + R_{GE} > C_E$	5	6	2	2	2	5	2	5	1	7	4	10
$E_7 \rightarrow E_8$	$P_E < C_E - R_{GE} - R_E$, $P_T > \max\{C_G - L_G - P_E, C_T - R_T\}$	3	4	2	1	2	5	6	3	1	10	4	10
	$P_E = C_E - R_{GE} - R_E$, $P_T = \max\{C_G - L_G - P_E, C_T - R_T\}$	4	5	2	1	2	5	6	3	1	10	4	10
	$P_E > C_E - R_{GE} - R_E$, $P_T > \max\{C_G - L_G - P_E, C_T - R_T\}$	10	10	2	1	2	5	6	3	1	10	4	10

R_E to them; meanwhile, if TDEs are found offering DT guidance to SMMEs, governments would give rewards R_T to them in the form of tax cuts. The behavior that SMMEs execute DT could bring additional tax revenue (i.e., R_G or R_{NG}) to governments. When governments select laissez-faire, they would lose social welfare (i.e., L_G) and the special subsidies provided to support DT (i.e., R_S) if SMMEs avoid DT; at the same time, TDEs are likely to provide no DT guidance to SMMEs, which makes SMMEs escape from DT more possible. The unsupervised behavior of governments makes the rewards given to SMMEs executing DT and TDEs guiding DT empty, which doubtlessly discourages SMMEs and TDEs in DT.

Therefore, this research tells us that governmental revenue is affected by the decisions of SMMEs and TDEs. When the risk aversion of manufacturing enterprises is considered, governmental revenue can also be influenced by the risk-averse factor. By summarizing the analysis and conclusions of this study, the following suggestions are proposed: (1) in unsupervised cases, governments can adjust rewarding levels for SMMEs and TDEs; (2) in supervised cases, governments can utilize punishments. When governments regulate, they can maintain original rewarding levels. High penalties are viable options to prevent SMMEs from avoiding executing DT, but higher penalties do not always mean better. Specially, on one side, excessive punishments are unable to obviously shorten the time that SMMEs reach stable states; on the other side, excessive punishments could increase the trial-and-error cost of SMMEs, making SMMEs believe that governments are too hard. In brief, excessive punishments go against the development of enterprises. The processes of advancing DT in China still exist in many gray areas, and governments ought to accelerate the speed to perfect relevant rules and regulations.

Conclusions

This work studies the design of regulatory mechanisms that governments use to prevent SMMEs from executing DT and considers the guiding role of TDEs in the DT processes of SMMEs. Our work takes two key points: the methods to prevent SMMEs from avoiding executing DT, and the effects that risk aversion exerts on SMMEs executing DT. This paper utilizes evolutionary game theory to establish two tripartite evolutionary game models. One model (i.e., model 1) considers risk-neutral SMMEs, and the other (i.e., model 2) considers risk-averse SMMEs. By solving and analyzing the equilibrium points of the two models, three important conclusions are drawn.

First, to prevent SMMEs from avoiding executing DT, we find that there exist two ideal game equilibrium points when SMMEs are risk-neutral and risk-averse. Hence, there are feasible measures to prevent SMMEs from avoiding executing DT in supervised and unsupervised cases.

Second, the attitude of SMMEs toward risk makes a difference to regulatory policies. When SMMEs are risk-neutral, governments should enhance rewarding levels for SMMEs in unsupervised cases, and governments should set heavy penalties for SMMEs and TDEs and maintain rewards unchanged in supervised cases. When SMMEs are risk-averse, governments can increase the penalties for SMMEs and the rewards for TDEs if they do not regulate; however, there exists a scenario that governmental policies are invalid, and SMMEs choose not to implement DT; in such scenarios, governments should turn to regulate and add the penalties for TDEs at the same time. In risk-averse and unsupervised environments, governments are supposed to set high punishments for SMMEs or TDEs, and the punishments need to increase with risk-averse factors.

Finally, the deterrence originated from heavy punishments set by governments would restrain SMMEs and TDEs from avoiding executing DT and providing DT guidance, respectively. If governments do not possess the impetus for long-term supervision, if SMMEs have no incentive to conduct DT, and if TDEs have no intention of directing DT, SMMEs sometimes choose to perform DT. If rewards or penalties are big enough, SMMEs would not readily choose to avoid implementing DT even if governments do not supervise; on the contrary, SMMEs usually do not choose to avoid executing DT immediately and wait for the proper time to avoid. This selection explains why SMMEs avoid executing DT again and again. Besides, it also manifests that governments need to take enough measures because the deterrence deriving from fines cannot permanently curb SMMEs to avoid executing DT.

Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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