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Research article

Sustainable digital transformation path for manufacturing outwards foreign direct investment firms: Gradual or leapfrogging

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ABSTRACT

Digital transformation plays an important role in improving the efficiency of production of enterprises and can provide strong support for green and sustainable development. Compared with domestic enterprises, outward foreign direct investment (OFDI) enterprises have greater access to advanced digital technology. This paper aims to analyze the path selection of green and sustainable production for the digital transformation of manufacturing outward foreign direct investment (OFDI) companies, whether gradual or leapfrogging. However, there is a lack of systemic game mechanisms and numerical simulation methods for heterogeneous enterprises. Based on the analysis of reverse technology spillover intensity of outward foreign direct investment (OFDI) and differences in the absorptive capacity of enterprises, we have proposed the evolutionary game model for different path selection of digital transformation of manufacturing enterprises, due to heterogeneous enterprises under different spillover degrees with numerical analysis methods. The research results show that: (i) Under low reverse technology spillover intensity, all enterprises evolve to a gradual transformation path, and enterprises with weaker absorptive capacity converge faster; (ii) There is a certain threshold for reverse technology spillover. When reverse technology spillover intensity exceeds the threshold, enterprises with stronger absorptive capacity converge to a leapfrog transformation path, but enterprises with weak absorptive capacity converge to a gradual transformation path; (iii) With high reverse technology spillover intensity, all enterprises evolve toward a leapfrog transformation path, and faster convergence happens to enterprises with higher absorptive capacity. The evolutionary game path of digital transformation in manufacturing enterprises is illustrated in Fig. 1.

1. Introduction

Smart manufacturing represents the developmental trajectory for manufacturing enterprises and is a central focus of the "Made in China 2025″ initiative. Manufacturing outward foreign direct investment (OFDI) enterprises typically exhibit considerable strength, competitive advantages, and growth potential. They play a pivotal role in elevating China's overall technological prowess within the manufacturing sector. However, when compared to the world's leading standards, there remains a substantial gap. The importance of

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the strategy to bolster the nation's manufacturing capabilities was underscored in the 19th National Congress report [1].

The term "digital economy" generally refers to an economic paradigm that harnesses data, either directly or indirectly, to guide the efficient allocation of resources, thereby fostering productivity growth. This economic domain encompasses various key technologies such as big data, cloud computing, blockchain, and artificial intelligence, with its primary objective being the attainment of industrial intelligence [2]. In the era of the digital economy, various industries are striving for quality and efficiency improvements through digital transformation. Sustainable digital transformation of manufacturing enterprises is an important way to achieve the high-end climb of the global value chain and solve the weak core technology for high-quality development. A characteristic feature of manufacturing enterprises is their relatively high level of engagement in outward foreign direct investment (OFDI) activities. Existing studies have indicated that digitization offers advantages for enhancing the quality of outward foreign direct investment (OFDI) activities in the manufacturing sector [3]. Its underlying mechanisms include the enhancement of innovation capabilities and the reduction of transaction costs, ultimately leading to improved investment efficiency (see Wang and Zhang [4], Qi et al. [5]).

According to the theory of technological diffusion, whether the leading technological advantages acquired by OFDI enterprises can rapidly disseminate among industry players, both upstream and downstream, depends on one hand, on the subjective intentions of the technology disseminators and, on the other hand, on the objective capabilities of technology adopters. Digital transformation has the potential to enhance the absorptive capacity of firms within the same industry value chain, thereby facilitating more substantial reverse technology spillover effects. Hence, the question of how manufacturing OFDI enterprises can leverage their technological advantages to expedite digital transformation for themselves and stimulate digitalization throughout the industry warrants exploration. In essence, this study's research question can be summarized as follows: How can manufacturing OFDI enterprises leverage their technological advantages to accelerate digital transformation and ultimately enhance the industry's technological innovation capabilities?

In the international open market, compared with the domestic manufacturing enterprises, the outward foreign direct investment (OFDI) manufacturing enterprises are stronger, and integrated into the international market environment, which are more susceptible to international technology influence and reverse technology spillover effect, and a more favorable digital transformation path are available for themselves. Under the impetus of digital transformation, the clean production efficiency of manufacturing enterprises can be improved and then these outcomes will not only win market dominance for enterprises but also promote the sustainable development of manufacturing enterprises [6]. In the process of digital transformation, heterogeneous manufacturing enterprises with limited rationality have a long-term game relationship.

However, the competitive relationship and mechanism are completely different when both sides choose different paths. The path choice of the rival will also have an impact on the selection of the digital transformation path of OFDI manufacturing enterprises [7]. Therefore, the research on the mechanism of sustainable digital transformation path of OFDI manufacturing enterprises will help both sides choose the appropriate path to achieve faster digital transformation, which is in great necessity.

The digital transformation of manufacturing enterprises has become a new trend in the development of various industries around the world, especially in the era of Industry 4.0(see Miao [8]). The digital transformation affects most industries in various countries. A survey of 30 companies studied by a Romanian management consulting firm found that the digital transformation of enterprises is affected by both internal and external factors which is presented by Crian and Stanca [9]. For example, the digital transformation of Korean enterprises is influenced by factors such as technology acceptance, awareness, enterprise scale and knowledge, and technology absorption and learning capacity, among which the larger the enterprise scale is, the higher the technology absorption and learning capacity is, and the stronger the demand for digital transformation of enterprises will be studied by Kim [10]. In an open market environment, because of the externalities of reverse technology spillover from OFDI, the choice of digital transformation path of manufacturing enterprises not only depends on their strength but also is affected by the reverse technology spillover effect of OFDI (see Ying et al. [11], Driffield et al. [12], Herzer [13], Luo and Feng [14]).

Previous research on the sustainable digital transformation of manufacturing enterprises is mainly on the influence factors and transformation paths, and the analysis of the influence factors is mostly from the perspective of enterprise management using surveys or qualitative methods, with less quantitative analysis and game approach analysis (see Ren and Xu [15], Tang et al. [16]). Moreover, current research has predominantly focused on the impact of outward foreign direct investment (OFDI) reverse technology spillovers on green technology innovation within the manufacturing industry [17]. However, the influence of OFDI reverse technology spillovers on the digital transformation of manufacturing enterprises remains underexplored. In fact, green technology innovation and digital transformation hold equal significance, with digital transformation arguably taking precedence. This is because the current direction in China emphasizes using digitalization to promote sustainability, making digital transformation an effective means to drive green technology innovation within manufacturing firms. From this perspective, this paper contributes to a more cohesive research framework by highlighting the interplay between these previously separate research streams.

Sustainable digital transformation of manufacturing enterprises has two paths: progressive transformation and leapfrog transformation. The progressive transformation requires low investment cost which is suitable for relatively weak enterprises. However, the leapfrog transformation requires more investment cost and is more suitable for relatively strong enterprises carried out by Li and Wang [18]. Exactly, the advanced technology spillover absorbed by OFDI firms will spill over to the upstream and downstream of the industry, and the reverse technology spillover effect obtained by different firms with different technology absorption capacities will be different (see Lasi et al. [19]). The intensity of OFDI reverse technology spillover affects the innovation path choice of Chinese manufacturing enterprises which is presented by 양일석 [20]. For example, the enterprise tends to choose the incremental path of imitation when the spillover intensity is higher.

As a result, the behavior of sustainable digital transformation of manufacturing OFDI enterprises is a dynamic process, influenced by the path choice of competing enterprises in the same industry, the essence of which is a game result. Prior research has indicated that the Cournot model features competitors with relatively equal market power, as exemplified by Kong et al.'s study [21], which investigated the impact of government subsidies on green innovation in Cournot games. In contrast, the Stackelberg game involves competitors with differing levels of market power, as elucidated by Li et al.'s research [22] on supplier operational strategy choices in Stackelberg games. Furthermore, scholars have integrated Cournot and Stackelberg games to construct dual-evolutionary game models that account for power differentials between competitors. For instance, Yang et al. [23] delved into the game-theoretic aspects of firms' choices in green technology innovation paths under FDI technology spillover. Cournot model and Stackelberg model provide a good solution to the choice problem brought by the difference in the market status of decision subjects. When the game subjects are in the same market status, the Cournot model is used for game simultaneous decision-making. However, when the game subjects are in different market statuses, the Stackelberg model is used for game decision making, and those in the high market status make decision first followed by those in the low market. Thus, the Cournot model and the Stackelberg model game can well solve the benefits of OFDI manufacturing enterprises in different situations, and perfectly portray the different path choices of enterprises brought by the differences in market status. However, there is a research gap in this aspect.

Based on the existing sustainable digital transformation research and the evolutionary game analysis, this study aims to explore the digital transformation path of OFDI manufacturing enterprises at the individual level by applying the Cournot model and Stackelberg model to reflect differences in individual status, in order to fill the research gap discussed in the previous section. First of all, based on previous studies, this study has reviewed the key factors affecting the digital transformation path of OFDI manufacturing enterprises to refine and define the influencing factors of digital transformation, including the benefits of digital transformation, the intensity of reverse technology spillover, the enterprises' technology absorption capacity, and the cost of transformation risks. Secondly, using the game profit matrix of digital transformation as a standard variable, the evolutionary game model of digital transformation of manufacturing enterprises has been established. Based on the dynamic equation of the absorptive capacity of competing enterprises in the same industry, by the Cournot and Stackelberg models, we determine the different paths for leading and following enterprises in competitive relationships in the same industry. Finally, the potential influence of different factors on the selection of digital transformation paths of OFDI manufacturing enterprises is simulated and analyzed. Besides, this paper also provides a referenceable research framework for a class of problems characterized by a firm's decision and how the specific outcomes of its implementation impact another decision within a complex market competition context. In the context of this paper's focus, the majority of literature primarily examines the direct consequences of manufacturing firms' outward foreign direct investment (OFDI) activities, such as their total factor productivity and development quality. However, there is less literature that explores the impact of such decisions on other critical decisions within manufacturing firms, such as green innovation or digital transformation. By doing so, this paper contributes not only to the body of literature on the consequences of manufacturing firms' OFDI activities but also offers a reference point for future explorations within this paradigm of research questions, ultimately enabling more efficient outcomes of OFDI activities.

The remainder of this paper is organized as follows. The literature related to theories, paths, and influencing factors of digital transformation of enterprises will be reviewed in section 2. The game model of the digital transformation between OFDI manufacturing enterprises in leading and following positions has been constructed in section 3, with the analysis of the stability of the model based on the payoff matrix, replicated dynamic phase diagrams, and the sensitivity of the model parameters. Section 4 has conducted a numerical simulation study of the game model to validate our predictions. The conclusions and policy recommendations are provided in section 5.

2. Literature review

2.1. Digital transformation of manufacturing enterprises

Before delving into the review of literature on the digital transformation of manufacturing enterprises, this paper first examines relevant literature concerning other determinants of high-quality development in the manufacturing sector. Factors such as regional disparities, government subsidies, and firm-specific characteristics have been observed to influence the operational efficiency of the intelligent equipment manufacturing industry (see Zheng and Luo [24]). From a broader perspective, factors at the national level can also exert an impact on a firm's outward foreign direct investment (OFDI) activities. For instance, firms like PSE are more inclined to leverage their technological, human, and political capital to engage in high-quality OFDI endeavors (see Hilger et al. [25]).

In the era of the digital economy, the focus of the research has been put on the digital transformation of manufacturing enterprises. The Chinese government states that we should accelerate digital development to build a digital country, especially the digital transformation of industries (see Zhang et al. [26], People's Daily [27]). The digital factor has increasingly become a new driving force for the realization of a green shift in manufacturing and the digital transformation of manufacturing enterprises has become a necessary condition to promote the economy (see Hao et al. [28]). Studies by Chen and Dagestani [29,30] found that the circular economy and clean energy development significantly impacted sustainable corporate development and smart cities in China. Digital transformation is an innovative process for companies which means that digital technology is applied to reshape their vision, strategy, organizational structure, processes, capabilities, and culture to adapt to the highly changing digital environment proposed by Gileva et al. [31]. Chopra et al. [32]. intended to fill the void of the topic of organizational, environmental, and socioeconomic sustainability's integration with digital technologies and they suggested more funding to produce environmentally friendly, greener technologies that can promote inclusive economic models and spur sustainable growth. Chen and Kim [33] found that digital transformation had a greater impact on the innovation of non-SOEs(state-owned enterprises), non-high-tech enterprises, and non-heavily polluting enterprises alleviating the gap between different types of firms. Some scholars found that a strong positive correlation between the implementation of digital technologies in general and their use in a sustainability management context indicated synergies and spillover effects [34,35]. Further research may identify scalable best practices, optimal enabling conditions, and environmental and social outcomes (see Schoggl et al. [36]). The digital transformation of the manufacturing industry is the use of a new generation of information technology to transform and upgrade manufacturing enterprises, which helps to gain sustainable competitive advantage prompted by Xue et al. [37]. A study on Chinese manufacturing companies found that digital transformation is still in its infancy in China, and factors including IT capabilities, company size, and R&D spending have a positive impact on digital transformation (see Chu et al. [38], Zheng and Jiang [39]). Besides, technological innovation, production methods, future trends, and changes in users' needs also affect the digital transformation of enterprises (see Abrell et al. [40], Ruiz et al. [41], Kutin et al. [42], Kusiak [43]).

Some scholars have selected two tobacco processing and manufacturing enterprises, representing the gradual transformation requiring step-by-step digitalization and the direct upgrade to digital technology, respectively [44]. They find that for enterprises adopting a leapfrog digital transformation, their marketing resources are positioned externally and continuously capture core user data resources from the outside. They engage in "networked layouts" as much as possible, promote the integration and flow of platform resources, conduct "efficiency-enhancing" resource allocation, and create value for users. In contrast, for enterprises adopting a gradual digital transformation, data sources in the manufacturing process come from within the company. They collect data from the physical world through multiple dimensions and methods, creating data assets. These companies follow a "gradual layout," gradually completing digital transformation (see Yang et al. [44]).

The digital transformation for enterprises has been conducted on two paths: gradual transformation and leapfrog transformation. To be specific, gradual transformation generally refers to the gradual realization of intelligent manufacturing through cascading upgrades, which is suitable for relatively weak manufacturing enterprises. As to leapfrogging transformation, it means discontinuous transformation, multiple upgrades, and cross-cutting to realize smart manufacturing faster, applied to relatively strong manufacturing enterprises. It is obvious that choices vary in transformation paths in industries and enterprises with different strengths. Compared with gradual transformation, leapfrog transformation requires more transformation costs to achieve a higher level of digitalization, all companies are far from choosing leapfrog transformation. For weaker manufacturing companies, it may be better to choose gradual transformation (see Meng et al. [45]). Moreover, the effect of choices of competitors is also possible to influence the choice of digital transformation paths for companies in the industry. Reis and Melão [46] pointed out that the organizational, technological, and social dimensions are still pivotal in digital transformation, while sustainability and small cities still need to be explored in the existing literature.

2.2. Digital transformation of manufacturing outward enterprises as an evolutionary game-model

Digital transformation, as a kind of innovation activity of manufacturing enterprises, will also be affected by OFDI reverse technology spillover. Emerging market multinationals (EM MNEs) are designed to capture knowledge spillovers by using OFDI from developed markets to improve their technological capabilities at home, as OFDI reverse technology spillovers proposed by Abrell et al. [40]. Previous literature on OFDI enterprises suggests that the spillover of advanced technology absorbed by OFDI companies will flow to the upstream and downstream of their industry. The study of OFDI reverse technology spillover on the choice of innovation path has found that enterprises choose different innovation paths owing to different spillover intensities, and the higher spillover intensity is likely to make imitation innovation (see Yang and Wang [47], Yang and Liu [48]). The innovation paths for enterprises are related to the different technology gaps and absorption capacities of enterprises by Chen et al. [49]. In an open market environment, the choice of a manufacturing enterprise's digital transformation path not only depends on its strength but also is affected by the reverse technology spillover effect of OFDI. However, little literature is devoted to the digital transformation of manufacturing OFDI enterprises.

The evolutionary game method is useful in explaining the problem of strategy choice for different subjects. Yang et al. [50] have proposed the evolutionary game model for technology diffusion on sustainable development by analyzing the influence mechanism of technology diffusion on sustainable development, such as the initial investment willingness, technology spillover effects, absorptive capacity, etc. Some scholars use game models to study R&D team knowledge sharing and breakthrough innovation in OFDI enterprises [48]. The higher the reverse technology spillover effect of OFDI is, the more manufacturing companies are inclined to choose breakthrough innovation strategies. Because the absorption capacity of both companies is conducive to reducing R&D cost input. When the benefits of technology spillovers exceed costs and penalties, manufacturing enterprises tend to achieve value chain transitions through innovation breakthroughs and low-end locks (see Xiao et al. [51], Zhao et al. [52], Yang et al. [53]). Obviously, the digital transformation of manufacturing OFDI enterprises should be considered for the intensity of reverse technology spillover and absorptive capacity, whereas there are few studies in this area. Therefore, the evolutionary game method is applied in this study to research the digital transformation strategy choice of manufacturing OFDI enterprises and local enterprises, according to the strength of reverse technology spillover of OFDI and the absorptive capacity of enterprises, with analytical framework of Cournot model and Stackelberg model, leading to analyze the difference of path choice under different situations of low, medium and high spillover, eventually to better understand the digital transformation of manufacturing OFDI enterprises.

2.3. Contribution of the paper

The existing research on the digital transformation of manufacturing enterprises has focused on the qualitative analysis of intra-firm management, ignoring the role of reverse technology spillover from OFDI and the complex competitive relationships among enterprises in reality. It is not difficult to see that the choice of digital transformation path for manufacturing enterprises is also related to the rise or fall of their competitive position in the market. As a subject of bounded rationality, its transformation path will be adjusted according to the transformation path selection of the opponent to obtain a higher market position. There is a long-term game relationship in the choice of digital transformation path for heterogeneous manufacturing enterprises in the same industry, and the limited rationality of companies also leads to a long process in the game behavior between the two parties. We construct a Cournot model and a Stackelberg model for the digital transformation of heterogeneous manufacturing enterprises to measure the differences in the benefits and positions of enterprises in different contexts. Based on this, model solving and simulation analysis of the method is significant in theory and practice.

Therefore, we list the main contributions as follows.

- We have defined two different paths of sustainable digital transformation for OFDI manufacturing enterprises.
- We have formulated optimal sustainable digital transformation mechanisms for manufacturing enterprises based on different absorptive capacities and reverse technology spillover intensities.
- We have evaluated the proposed model through numerical analysis and simulations based on the different effects of reverse technology spillover under the difference in absorptive capacity.
- Our research has provided some decision-making guidance for OFDI manufacturing enterprises and enterprises with heterogeneous absorptive capacity in the industrial chain.

3. A dual-evolution game model based on Cournot and Stackelberg competition

3.1. Variable definition and model assumptions

In the game of digital transformation evolution of manufacturing enterprises, leading manufacturing enterprises, with their strong strength and innate advantages, take the lead in OFDI activities to obtain foreign advanced technology spillover. For example, due to the externality of the reverse technology spillover effect, the unavoidable technology exchange may occur in relevant business activities, so other manufacturing enterprises in the upstream and downstream of their industries can also absorb a certain degree of technology spillover. There is a threshold for the technical reserve of digital transformation for manufacturing enterprises, which means the digital transformation path is in line with the reality of the enterprises. Only in this way can the enterprise achieve the goal of digital transformation more quickly. Therefore, considering the influence of factors such as the intensity of reverse technology spillover, the high or low absorption capacity of enterprises, and the competitive relationship of peer enterprises, manufacturing enterprises will choose two different digital transformation paths, namely leapfrog transformation and gradual transformation.

In summary, the mechanistic analyses of the evolutionary game path of the digital transformation of manufacturing enterprises in this paper are shown in Figs. 1 and 2.

Based on this, this paper puts forward the following hypothesis.

3.1.1. Related parameters of production revenue and production cost

The market position is generally reflected by the order of output decision-making, so the parameters of the output, price, and cost are set at first. As mentioned earlier, there are two manufacturing enterprises, enterprise 1 and enterprise 2 in the same industry that produce the same products with different strengths. Supposed that the output of enterprise 1 is q_1, and the output of enterprise 2 is q_2, then the total output is $q_1 + q_2$, so the price is

$$p = a - b(q_1 + q_2)\ (a > 0, b > 0),$$

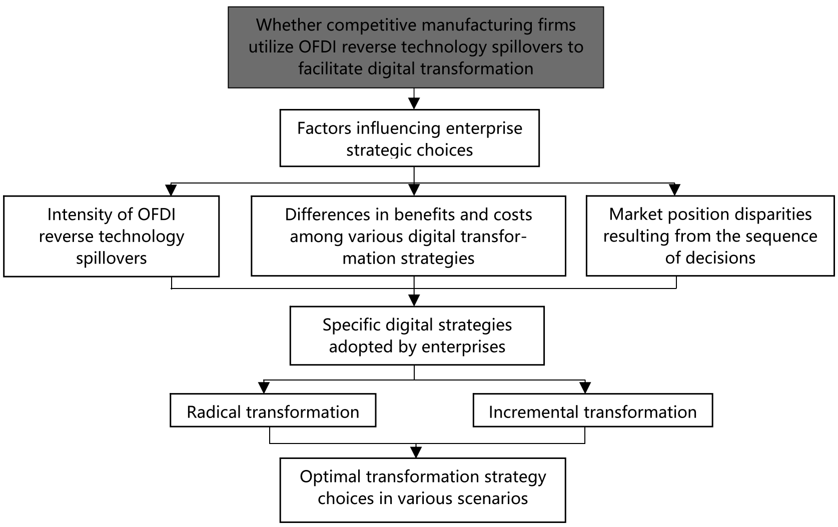

Fig. 1. The evolutionary game path of digital transformation in manufacturing enterprises.

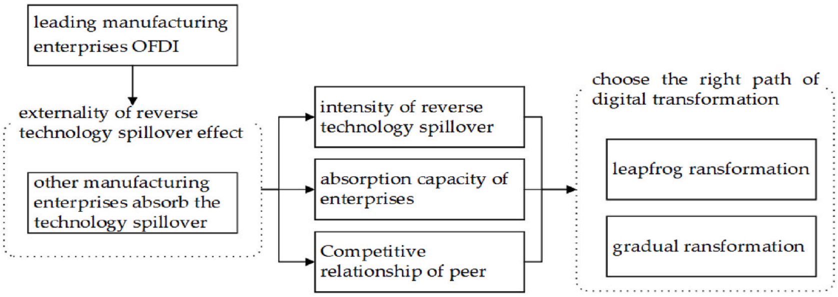

Fig. 2. Diagram of sustainable digital transformation game path for manufacturing firms.

Here, a is the market scale coefficient, b for the sensitivity coefficient of price to output. It's assumed that the unit cost is c, then the enterprise profit is

$$\pi_i = pq_i - cq_i \ (i = 1, 2).$$

3.1.2. Related parameters of digital transformation

There are two paths for companies to choose such as leapfrogging transformation and gradual transformation, the difference of which is mainly reflected in the cost of transformation and the level of digitalization that can be achieved. Assuming that the input level of leapfrog transformation is m, and the input level of gradual transformation is n ($m > n$). As the innovation rates, the two are both g. Under the A-J classic assumption, the cost of leapfrog transformation turns to be $gm^2/2$, and the cost of gradual transformation changes to be $gn^2/2$. Compared with gradual transformation, leapfrog transformation can bring a higher level of digitization, which will have an impact on the production income and production cost of the enterprise. As we all know, the higher level of data collection and analysis and the level of phantomization of the operation method will increase the production revenue ξ, and the higher the level of digitization of the production process will bring about the reduction of production costs λ. Moreover, the leapfrog transformation has a greater improvement in the technological strength of the enterprise. Therefore, compared with the gradual transformation, the leapfrog transformation will increase the absorptive capacity of the enterprise by a similar amount γ.

3.1.3. Related parameters of OFDI reverse technology overflow

In an open market environment, OFDI's reverse technology spillover effect will also have an impact on the choice of digital transformation path of manufacturing enterprises. Assuming that OFDI's reverse technology spillover coefficient is α, the absorptive capacity coefficient of the stronger enterprise 1 is β_1 and the absorptive capacity coefficient of the weaker enterprise 2 is β_2 ($\beta_1 > \beta_2$). Therefore, when it comes to a gradual transformation, the extent of profit improvement for enterprises by using OFDI reverse technology spillover are: $\alpha\beta_1$ and $\alpha\beta_2$. When it comes to a leap-forward transformation, the extent of profit improvement for enterprises by using OFDI reverse technology spillover change to be $\alpha\beta_1(1+\gamma)$ and $\alpha\beta_2(1+\gamma)$.zz

3.1.4. Related parameters of the Game's main body's strategy choice

Supposed that the probability of enterprise 1 choosing the leapfrog transformation and the gradual transformation path are x and $1-x$, and the probability of enterprise 2 choosing the leapfrog transformation and the gradual transformation path are y and $1-y$.The definition of the effect of low or high reverse technology spillover is generally represented as the coefficient of the reverse technology spillover. Generally, low, medium, and high-intensity reverse technology spillover is defined as the change in the profit margin of digital transformation of manufacturing enterprises due to absorption of reverse technology spillover. We assume that the reverse technology spillover coefficient is α, and the strategy of low reverse technology spillover on both sides is analyzed to be $\alpha = 0.2$, then the impact of high reverse technology spillover on the strategic choices of both parties is assumed as $\alpha = 0.8$, and the impact of mid-reverse technology spillover on the strategic choices of both parties is shown as $\alpha = 0.5$.

3.2. Profit matrix construction

Based on the basic assumptions of the model, the situation of different path choices between enterprise 1 and enterprise 2 is analyzed.

3.2.1. Case 1

When enterprise 1 and enterprise 2 choose the same leapfrog transformation path, the two parties are in Cournot competition, and the original market position will not change. At this time, the income of enterprise 1 and enterprise 2 are derived as equation (1):

$$\begin{cases} \pi_{11}{}^{(1)} = [1+\alpha\beta_1(1+\gamma)][pq_1(1+\xi) - cq_1(1-\lambda)] - gm^2/2 \\ \pi_{11}{}^{(2)} = [1+\alpha\beta_2(1+\gamma)][pq_2(1+\xi) - cq_2(1-\lambda)] - gm^2/2 \end{cases} \quad (1)$$

3.2.1.1. Let

$$R_1 = \frac{\{a(1+\xi)(2+b-\lambda+\xi) - c[(-1+\lambda)(-2+\lambda-\xi) + b(1+2\lambda+3\xi)]\}}{3b(1+\xi)}$$

then, we can get:

$$\begin{cases} \pi_{11}{}^{(1)} = [1+\alpha\beta_1(1+\gamma)]R_1 - gm^2/2 \\ \pi_{11}{}^{(2)} = [1+\alpha\beta_2(1+\gamma)]R_2 - gm^2/2 \end{cases} \tag{2}$$

3.2.2. Case 2

When enterprise 1 has a preference for a leapfrog transformation path as a leader in the market, and enterprise 2 chooses a gradual transformation path as a follower in the market, when they compete in Stackelberg, the income of enterprise 1 and enterprise 2 are shown as follow:

$$\begin{cases} \pi_{12}{}^{(1)} = [1+\alpha\beta_1(1+\gamma)][pq_1(1+\xi) - cq_1(1-\lambda)] - gm^2/2 \\ \pi_{12}{}^{(2)} = (1+\alpha\beta_2)(pq_2 - cq_2) - gn^2/2 \end{cases} \tag{3}$$

Let:

$$R_2 = \frac{[a(1+\xi) + c(-1+3\lambda+2\xi)]^2}{16b(1+\xi)},$$

$$R_3 = \frac{[a(1+\xi) - c(1+\lambda+2\xi)]^2}{8b(1+\xi)^2},$$

then, we can get

$$\begin{cases} \pi_{12}{}^{(1)} = [1+\alpha\beta_1(1+\gamma)]R_2 - gm^2/2 \\ \pi_{12}{}^{(2)} = (1+\alpha\beta_2)R_3 - gn^2/2 \end{cases} \tag{4}$$

3.2.3. Case 3

When enterprise 2 takes the leapfrog transformation path in the leading place in the market, and enterprise 1 chooses the gradual transformation path following enterprise 1 in the market, when they are in the Stackelberg competition, the income of enterprise 1 and enterprise 2 are respectively shown in equation (5):

$$\begin{cases} \pi_{21}{}^{(1)} = (1+\alpha\beta_1)R_3 - gn^2/2 \\ \pi_{21}{}^{(2)} = [1+\alpha\beta_2(1+\gamma)]R_2 - gm^2/2 \end{cases} \tag{5}$$

3.2.4. Case 4

When both enterprise 1 and enterprise 2 are on the path to a gradual transformation in the Cournot competition, and the original market position will not change. At this time, the income of enterprise 1 and enterprise 2 are respectively represented in equation (6):

$$\begin{cases} \pi_{22}{}^{(1)} = (1+\alpha\beta_1)(pq_1 - cq_1) - gn^2/2 \\ \pi_{22}{}^{(2)} = (1+\alpha\beta_2)(pq_2 - cq_2) - gn^2/2 \end{cases} \tag{6}$$

Let $R_4 = (2+b)(a-c)/3b$, thus we can get

$$\begin{cases} \pi_{22}{}^{(1)} = (1+\alpha\beta_1)R_4 - gn^2/2 \\ \pi_{22}{}^{(2)} = (1+\alpha\beta_2)R_4 - gn^2/2 \end{cases} \tag{7}$$

Therefore, the game payoff matrix is shown in Table 1.

3.3. Construction of expected return function

Assuming that the expected return of enterprise 1 in the leapfrog transformation path is U_{11}, and the expected return of the gradual

Table 1
Game income matrix.

Strategy combination	Enterprise1	Enterprise2
(leapfrog transformation, leapfrog transformation)	$[1+\alpha\beta_1(1+\gamma)]R_1 - gm^2/2$	$[1+\alpha\beta_2(1+\gamma)]R_1 - gm^2/2$
(leapfrog transformation, gradual transformation)	$[1+\alpha\beta_1(1+\gamma)]R_2 - gm^2/2$	$(1+\alpha\beta_2)R_3 - gn^2/2$
(gradual transformation, leapfrog transformation)	$(1+\alpha\beta_1)R_3 - gn^2/2$	$[1+\alpha\beta_2(1+\gamma)]R_2 - gm^2/2$
(gradual transformation, gradual transformation)	$(1+\alpha\beta_1)R_4 - gn^2/2$	$(1+\alpha\beta_2)R_4 - gn^2/2$

transformation path is U_{12}. Thus the average expected return is $\overline{U}_1$, then

$$U_{11} = y\{[1+\alpha\beta_1(1+\gamma)]R_1 - gm^2/2\} + (1-y)\{[1+\alpha\beta_1(1+\gamma)]R_2 - gm^2/2\}$$

$$U_{12} = y[(1+\alpha\beta_1)R_3 - gn^2/2] + (1-y)[(1+\alpha\beta_1)R_4 - gn^2/2]$$

$$\overline{U}_1 = xU_{11} + (1-x)U_{12}$$

So, the replicated dynamic equation for enterprise 1 in the leapfrog transformation path over time is listed in equation (8)

$$F(x) = dx/dt = x(U_{11} - \overline{U}_1) = x(1-x)(U_{11} - U_{12}) = x(1-x)(yA_1 + A_3) \tag{8}$$

where

$$A_1 = [1+\alpha\beta_1(1+\gamma)](R_1 - R_2) - (1+\alpha\beta_1)(R_3 - R_4)$$

$$A_3 = [1+\alpha\beta_1(1+\gamma)]R_2 - gm^2/2 - (1+\alpha\beta_1)R_4 + gn^2/2$$

Assuming that the expected return of enterprise 2 in the leapfrog transformation path is U_{21}, and the expected return of the gradual transformation path is U_{22}. So the average expected return is $\overline{U}_2$, then

$$U_{21} = x\{[1+\alpha\beta_2(1+\gamma)]R_1 - gm^2/2\} + (1-x)\{[1+\alpha\beta_2(1+\gamma)]R_2 - gm^2/2\}$$

$$U_{22} = x[(1+\alpha\beta_2)R_3 - gn^2/2] + (1-x)[(1+\alpha\beta_2)R_4 - gn^2/2]$$

$$\overline{U}_2 = yU_{21} + (1-y)U_{22}$$

So, the replicated dynamic equation for enterprise 2 in the leapfrog transformation path over time is shown in equation (9)

$$F(y) = dy/dt = y(U_{21} - \overline{U}_2) = y(1-y)(U_{21} - U_{22}) = y(1-y)(xA_2 + A_4) \tag{9}$$

where

$$A_2 = [1+\alpha\beta_2(1+\gamma)](R_1 - R_2) - (1+\alpha\beta_2)(R_3 - R_4)$$

$$A_4 = [1+\alpha\beta_2(1+\gamma)]R_2 - gm^2/2 - (1+\alpha\beta_2)R_4 + gn^2/2$$

After combining function $F(x)$ and function $F(y)$, it turns out to be a dimensional discrete dynamic system, which describes the dynamic game process of enterprise 1 and enterprise 2 in the choice of transformation path.

3.4. *Equilibrium point stability analysis*

From $F(x)$ and $F(y)$, it can be concluded that there are five equilibrium points in the system, such as $(0,0),(0,1),(1,0),(1,1),(x*,y*)$, where

$$x* = -A_4/A_2, y* = -A_3/A_1$$

The Jacobian matrix of the system is as follows

$$J = \begin{pmatrix} (1-2x)(yA_1 + A_3) & x(1-x)A_1 \\ y(1-y)A_2 & (1-2y)(xA_2 + A_4) \end{pmatrix} \tag{10}$$

The corresponding determinant value is derived in equation (11)

$$DetJ = (1-2x)(yA_1 + A_3)(1-2y)(xA_2 + A_4) - x(1-x)A_1 y(1-y)A_2 \tag{11}$$

The value of the trace of the Jacobian matrix is as follows

$$TrJ = (1-2x)(yA_1 + A_3) + (1-2y)(xA_2 + A_4) \tag{12}$$

Table 2
Determinant value and trace value of each equilibrium point.

Equilibrium point	*DetJ*	*TrJ*
$(0,0)$	A_3A_4	$A_3 + A_4$
$(0,1)$	$-(A_1+A_3)A_4$	$(A_1+A_3) - A_4$
$(1,0)$	$-(A_2+A_4)A_3$	$(A_2+A_4) - A_3$
$(1,1)$	$(A_1+A_3)(A_2+A_4)$	$-(A_1+A_3) - (A_2+A_4)$
$(x*,y*)$	$-[A_1A_2A_3A_4(A_1+A_3)(A_2+A_4)]/(A_1{}^2A_2{}^2)$	0

The determinant and trace value corresponding to each equilibrium point are calculated as the basis to judge the stability (see Table 2).

For simplification and convenience of subsequent analysis, $A_1 + A_3$ is recorded as (I), $A_2 + A_4$ as (II), A_3 as (III) and A_4 as (IV). Where (I) represents the difference in the benefits of enterprise 1 between the two paths when enterprise 2 is on the path to the leapfrog transformation; (II) indicates the difference in the benefits between enterprise 1 in the leapfrog transformation path and enterprise 2 in the gradual transformation path when enterprise 1 chooses the leapfrog transformation path; (III) represents the difference in the benefits of enterprise 1 between the two transformation path when enterprise 2 chooses the gradual transformation path; (IV) indicates the difference in the benefits of enterprise 2 between the two transformation path when enterprise 1 picks the gradual transformation path.

3.4.1. Case 1

When $(\mathrm{I}) > 0, (\mathrm{II}) > 0$ and $(\mathrm{III}) > 0, (\mathrm{IV}) > 0$, the positive and negative determinant and trace values are shown as follows, which are the basis to analyze the stability of equilibrium points. As shown in Table 3.

At this time, the dominant strategy of the system is (leapfrog transformation, leapfrog transformation). That is, no matter where the initial state is in the region, finally, both parties are on the path of the leapfrog transformation. The evolution phase diagram of the system is shown in Fig. 3.

3.4.2. Case 2

When $(\mathrm{I}) < 0, (\mathrm{II}) < 0$ and $(\mathrm{III}) < 0, (\mathrm{IV}) < 0$, the positive and negative determinant and trace values are shown as follows, as the basis to analyze the stability of equilibrium points. As shown in Table 4.

At this time, the dominant strategy of the system is (gradual transformation, gradual transformation). That is, no matter where the initial state is in the region, in the end both parties pick the leapfrog transformation path. The evolution phase diagram of the system is shown in Fig. 4.

3.4.3. Case 3

When $(\mathrm{I}) < 0, (\mathrm{II}) > 0$ and $(\mathrm{III}) > 0, (\mathrm{IV}) < 0$ or $(\mathrm{I}) > 0, (\mathrm{II}) < 0$ and $(\mathrm{III}) < 0, (\mathrm{IV}) > 0$, the positive and negative determinants and trace values are as follows to analyze the stability of equilibrium points. As shown in Table 5.

At this time, it's clear that there is no dominant strategy in the system. At a certain point in time, if enterprise 2 chooses the leapfrog transformation path, it is most advantageous for enterprise 1 to choose the gradual transformation path. If enterprise 1 picks the gradual transformation path, enterprise 2 will also select the gradual transformation path. If enterprise 2 wants the gradual transformation path, enterprise 1 will turn to the leapfrog transformation path. At this time, it is most beneficial for enterprise 2 to decide the leapfrog transformation path. Therefore, the selection of the transformation path of both parties will continue to cycle periodically as described above. The evolution phase diagram of the system is shown in Fig. 5.

3.4.4. Case 4

When $(\mathrm{I}) > 0, (\mathrm{II}) > 0$ and $(\mathrm{III}) < 0, (\mathrm{IV}) < 0$, the positive and negative determinant and trace values are illustrated as follows, which is used to analyze the stability of equilibrium points. As shown in Table 6.

At this time, the dominant strategies of the system are (progressive transformation, progressive transformation) and (leapfrog transformation, leapfrog transformation). If the initial state is in the lower-left region, both sides finally make the selection of the gradual transformation path. If the initial state is in the upper-right region, both sides eventually decide the leapfrog transformation path.

The evolution phase diagram of the system is shown in Fig. 6.

3.4.5. Case 5

When $(\mathrm{I}) < 0, (\mathrm{II}) < 0$ and $(\mathrm{III}) > 0, (\mathrm{IV}) > 0$, the positive and negative determinant and trace values are listed as follows to analyze the stability of equilibrium points. As shown in Table 7.

At this time, the dominant strategies of the system are (progressive transformation, progressive transformation) and (leapfrog transformation, leapfrog transformation). If the initial state is in the upper-left area, enterprise 1 chooses the gradual transformation path while enterprise 2 chooses the leapfrog transformation path; If the initial state is in the lower-right area, in the end, enterprise 1 picks the leapfrog transformation path while enterprise 2 selects the gradual transformation path. The evolution phase diagram of the system is shown in Fig. 7.

Table 3
Analysis results of Case 1.

Equilibrium point	DetJ symbol	TrJ symbol	Stability
$(0,0)$	+	+	Instable
$(0,1)$	–	N	Saddle point
$(1,0)$	–	N	Saddle point
$(1,1)$	+	–	ESS

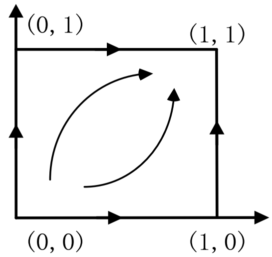

Fig. 3. The evolution phase diagram in case 1.

Table 4
Analysis results of case 2.

Equilibrium point	DetJ symbol	TrJ symbol	Stability
$(0,0)$	+	–	ESS
$(0,1)$	–	N	Saddle point
$(1,0)$	–	N	Saddle point
$(1,1)$	+	+	Instable

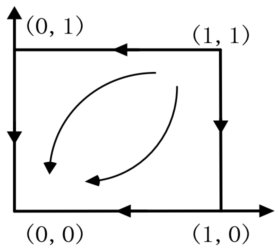

Fig. 4. The evolution phase diagram in case 2.

Table 5
Analysis results of case 3.

Equilibrium point	DetJ symbol	TrJ symbol	Stability
$(0,0)$	–	N	Saddle point
$(0,1)$	–	N	Saddle point
$(1,0)$	–	N	Saddle point
$(1,1)$	–	N	Saddle point
$(x*,y*)$	+	0	Center point

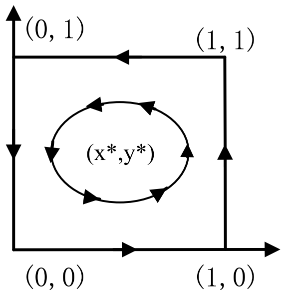

Fig. 5. The evolution phase diagram in case 3.

Table 6
Analysis results of case 4.

Equilibrium point	DetJ symbol	TrJ symbol	Stability
$(0,0)$	+	–	ESS
$(0,1)$	+	+	Instable
$(1,0)$	+	+	Instable
$(1,1)$	+	–	ESS
$(x*,y*)$	–	0	Saddle point

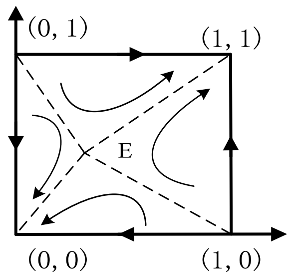

Fig. 6. The evolution phase diagram in case 4.

Table 7
Analysis results of case 5.

Equilibrium point	DetJ symbol	TrJ symbol	Stability
$(0,0)$	+	+	Instable
$(0,1)$	+	–	ESS
$(1,0)$	+	–	ESS
$(1,1)$	+	+	Instable
$(x*,y*)$	–	0	Saddle point

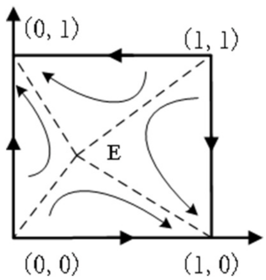

Fig. 7. The evolution phase diagram in case 5.

4. Path selection for the digital transformation of manufacturing OFDI enterprises under different levels of reverse technology spillovers

The relevant theoretical analysis has been detailedly carried out above, and the specific evolution paths of both parties will be analyzed through evolutionary game simulation. The parameter settings are as follows:

$$a = 5, b = 0.5, c = 1.5, n = 3, m = 5, g = 0.5, \xi = 0.5, \lambda = 0.5, \gamma = 1, \beta_1 = 0.5, \beta_2 = 0.25.$$

4.1. *Sustainable digital transformation path in case of low OFDI reverse technology spillover intensity*

Setting the reverse technology spillover coefficient to $\alpha = 0.2$, the evolution path at the low spillover intensity can be seen in Fig. 8. From Fig. 7, the evolution characteristics at low spillover intensity are shown as follows.

- No matter how high the initial willingness of manufacturing enterprises to choose a leapfrog transformation path, path selection of both sides will eventually converge into the direction of gradual transformation.

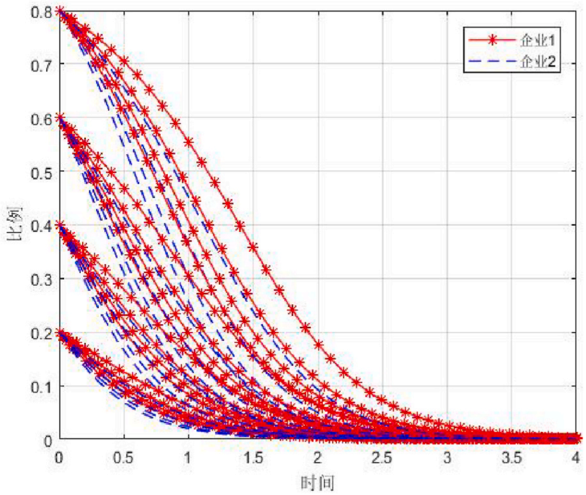

Fig. 8. Case of low OFDI reverse technology spillover intensity.

- Compared with enterprise 1, enterprise 2 with weaker absorptive capacity converges faster.
- The lower the initial willingness of manufacturing enterprises to choose a leapfrog transformation path is, the faster their path selection converges into the direction of gradual transformation.

In reality, the low intensity of OFDI reverse technology spillover intensity shows the strong technical protection of the host country and the unsatisfactory effect of enterprises from the home country absorbing foreign advanced technology spillovers by OFDI activities. In addition, the leapfrog transformation path needs more cost input, which means that enterprises need to bear a greater transformation risk in the case of low spillover intensity, deviating from the target of enterprises pursuing the maximization of profits. However, with relatively less cost input, although gradual transformation has limited improvement in the digitalization of manufacturing enterprises, it is more in line with the enterprises' appeal in the short term. Therefore, at low spillover intensity, the path selection of all enterprises will converge in the direction of gradual transformation.

4.2. Sustainable digital transformation path in case of medium OFDI reverse technology spillover intensity

Setting the reverse technology spillover coefficient to $\alpha = 0.5$, the evolution path at the medium intensity can be seen in Fig. 9. From Fig. 8, the evolution characteristics at medium spillover intensity are shown as follows.

- No matter how high the initial willingness of manufacturing enterprises to choose a leapfrog transformation path, the path selection of enterprise 1 with stronger absorptive capacity will converge into the direction of leapfrog transformation, and the path selection of enterprise 2 with weaker absorptive capacity will converge into the direction of gradual transformation.

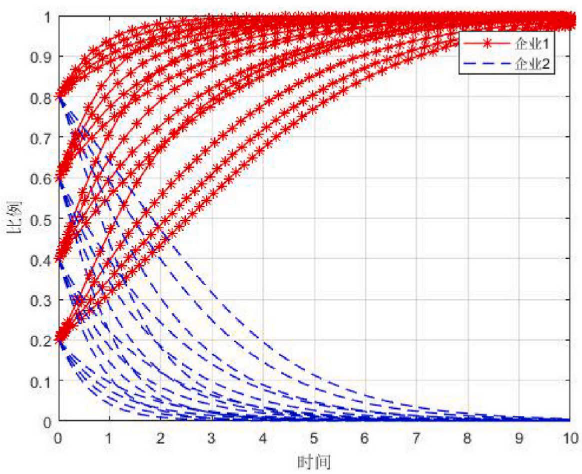

Fig. 9. Case of medium OFDI reverse technology spillover intensity.

- The lower the initial willingness of enterprise 1 to pick a leapfrog transformation path is, the more slowly its path selection converges into the direction of leapfrog transformation. The lower the initial willingness of enterprise 2 to choose a leapfrog transformation path is, the faster its path selection converges into the direction of gradual transformation.
- Compared with the case of low spillover intensity, in the case of medium intensity, path selection of both sides will take longer to evolve into a stable state.

Actually, for enterprise 1 of the leapfrog transformation path with stronger absorptive capacity, although the spillover intensity does not fully meet the technical requirements of leapfrog transformation, after absorbing this part of the technology spillover, the profit of the enterprise will be improved. Therefore, in that case, enterprise 1 will eventually go on a leapfrog transformation path with a considerable evolution time. In contrast, limited by its technical strength, absorbing medium OFDI reverse technology spillover intensity still makes it impossible to earn more profit for enterprise 2 of a leapfrog transformation path than the cost, so it is more inclined to choose a gradual transformation path.

4.3. Sustainable digital transformation path in case of high OFDI reverse technology spillover intensity

Setting the reverse technology spillover coefficient to $\alpha = 0.8$, the evolution path at the medium intensity can be seen in Fig. 9. From Fig. 10, the evolution characteristics at medium spillover intensity are shown as follows.

- No matter how high the initial willingness of manufacturing companies to choose a leapfrog transformation path, eventually, the path selection of both sides will evolve in the direction of leapfrog transformation.
- Compared with enterprise 2, enterprise 1 with stronger absorptive capacity converges faster.
- The lower the initial willingness of manufacturing enterprises to choose a leapfrog transformation path is, the more slowly their path selection converges into the direction of leapfrog transformation.

In fact, in the case of high spillover intensity, both enterprise 1 and enterprise 2 can meet the threshold requirements of leapfrog transformation relying on their technical strength to absorb foreign advanced technology spillovers. However, due to the difference in absorptive capacity between both sides, the value added by enterprise 1 will be greater, so its path selection will quickly converge in the direction of leapfrog transformation. While the value added by enterprise 2 in the short term is relatively small, so its path selection will experience a long process of evolution to eventually stabilize in the leapfrog transformation.

5. Discussion and analysis based on research findings and future prospects

This study examines the impact of reverse technology spillover intensity on the digital transformation path selection of manufacturing OFDI enterprises. The research subjects can be summarized as heterogeneous manufacturing firms, with their strategic choices encompassing two distinct digital transformation strategies characterized by differential input-output ratios. The study investigates how reverse technology spillover intensity affects the strategic choices of heterogeneous agents. The underlying logic of this study carries implications for relevant literature in various domains, such as the influence of environmental regulation intensity on the green technology innovation strategies (substantive innovation and formal innovation) of environmentally heterogeneous firms (green firms and polluting firms). Moreover, the study relates to the effects of digital regulation intensity on strategic choices made by heterogeneous agents. Even the influence of intellectual property protection intensity on the green innovation path selection of patent-intensive heterogeneous enterprises exhibits a certain degree of relevance to the underlying logic of this study (see Zhou et al. [54], Xiao and Li [55], and Zhang et al. [56]). Sharma et al. [57] tracked the development of the field of digital sustainability over time through CitNetExplorer analysis and found a much more developed coverage of digital sustainability in the scholarship of management/business and therefore revealed a clear need for greater exploration of the sociological and economic aspects of digital sustainability.

The limitations of this study lie in its failure to further explore the impact of other secondary effects related to reverse technology spillovers on the digital transformation strategy choices of manufacturing OFDI enterprises, such as profit feedback effects and R&D cost-sharing effects. This could be a potential avenue for future research. Additionally, the study could consider the influence of digital regulation policies on its research findings. Government regulation, as a critical external control mechanism, has been extensively studied in the context of environmental regulation. However, digital regulation, as another form of regulation, may also exert an influence on the strategic choices of manufacturing OFDI enterprises in their digital transformation journey (See Jiang et al. [58]). The impact of enterprise digital transformation on corporate environmental performance, greenwashing behavior, and firm value is also a topic worthy of further exploration (See Chen and Dagestani [59], Chen and Hao [60]). Finally, the study might contemplate the impact of two-way FDI on the digital transformation strategy choices of manufacturing enterprises, thereby delving into the optimal digital transformation paths for these enterprises in more specialized contexts.

6. Recapitulation of key research points and policy recommendations

6.1. Contribution to theory

This paper enhances and complements existing theories in several ways. First, in the realm of research concerning the economic

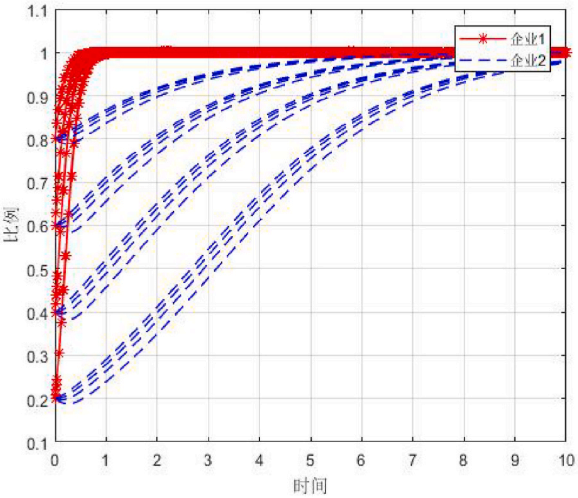

Fig. 10. Case of high OFDI reverse technology spillover intensity.

consequences of manufacturing firms engaging in outward foreign direct investment (OFDI) activities, this study investigates the impact of OFDI activities on the digital transformation strategy choices of manufacturing firms, thereby expanding the research on microeconomic consequences. Second, in terms of the application of evolutionary game theory methods, this paper calculates game payoff formulas for manufacturing firms under different market competition scenarios, based on both Cournot and Stackelberg models. It subsequently utilizes these formulas to construct evolutionary game models, thereby broadening the scope of methodological application.

6.2. Contribution to practice

The research findings of this paper hold implications for both government and enterprises. For government entities, it can inform the formulation of relevant regulatory policies, thereby providing robust institutional support for manufacturing firms leveraging OFDI activities to promote digital transformation. For enterprises, it suggests considering their specific circumstances and market competitive positions to select the most suitable digital transformation strategy.

6.3. Research limitations

This study has two main limitations. First, it does not delve into the impact of profit feedback and R&D cost-sharing effects of OFDI activities on the digital transformation strategy choices of manufacturing enterprises. Second, it does not account for the moderating role of external government regulations.

6.4. Recommendations for future research

Future research endeavors could explore further intersections between game theory and digital transformation, investigating intriguing areas such as the choice of green technology innovation paths for digitally heterogeneous enterprises under government digital regulations.

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Ethics statement

Informed consent was not required for this study because no participants or patients were involved in this study.

Data availability statement

No data was used for the research described in the paper.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Xiaohua Yang: Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Cheng Liu:** Visualization, Validation, Software, Investigation, Data curation. **Qiancheng Wei:** Writing – review & editing, Supervision, Software, Resources, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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