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Impacts of digital transformation on enterprise innovation resilience: A study from China

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Purpose: This study aims to investigate the impacts of digital transformation on enterprise innovation resilience, with a focus on understanding how digital transformation influences innovation resilience across different stages during the life cycle of an enterprise.

Design/methodology/approach: Data were collected from Chinese A-share listed companies from 2012 to 2022. Industries with unique financial reporting characteristics, special treatment (ST) samples, and samples with missing data are excluded to obtain a final dataset of 18 304 observations. A regression model is employed to examine the dual effect of digital transformation on enterprise innovation resilience.

Findings/results: The findings reveal a significant inverted U-shaped relationship between digital transformation and enterprise innovation resilience. For companies at different lifecycle stages, digital transformation significantly enhances innovation resilience during the growth phase. However, for mature and declining companies, digital transformation still exhibits an inverted U-shaped relationship with innovation resilience, albeit with a relatively lower empowerment effect during the decline phase.

Practical implications: Enterprises are advised to leverage the positive effects of digital transformation on innovation resilience while avoiding the pitfalls of excessive digitisation. Flexibility in adapting digital transformation strategies according to the enterprise lifecycle stage is recommended. Furthermore, enterprises should prioritise the coordinated development of various factors contributing to innovation resilience.

Originality/value: This study extends the examination of innovation resilience from macro-industry to micro-enterprise levels and provides insights into the dynamics of digital transformation effects on innovation resilience across different lifecycle stages. Additionally, it highlights the importance of considering multiple pathways through which digital transformation influences innovation resilience.

Keywords: digital transformation; innovation; enterprise innovation; innovation resilience; enterprise lifecycle; China.

Introduction

Innovation stands as a critical element in shaping the competitive advantage of enterprises and catalyses driving economic development forward (Adu-Yeboah et al., 2023; Memon & Ooi, 2023). Against the backdrop of a global economic downturn, some enterprises manage to navigate risks and continue to propel innovation (Thukral, 2021), while others struggle to gather innovation elements and bear the associated costs, leading to their withdrawal from the innovation arena. In China, enterprise innovation remains at a low level. As the micro-level agents of innovation and market leaders, investigation of enterprise innovation resilience (Zhang et al., 2021) is crucial for seizing opportunities presented by the new wave of technological revolution, enhancing core competitiveness and achieving sustainable development.

Currently, research on the theory and practical application of innovation resilience is still in its early stages (Zupancic, 2023). Some scholars (Bristow & Healy, 2018; Lv et al., 2018; Sabatino, 2016) argue that innovation resilience is the capacity of innovation systems to demonstrate stability, recovery and evolution when facing external crises. Robust innovation resilience can sustain continuous innovation amidst turbulent environments, maintaining a high level of innovation efficiency (Lv et al., 2018) and establish reinforcing mechanisms within innovation processes that translate into new capabilities (Wziątek-Kubiak & Pęczkowski, 2021). As a powerful strategy for resisting adversities and uncertainties (Fey & Kock, 2022), how to enhance innovation resilience has become a critical issue for enterprises in the current stage.

The advancement of digital technologies offers a novel perspective for addressing this issue. Enterprise digital transformation (Favoretto et al., 2022; Ghobakhloo & Iranmanesh, 2021) enables overcoming path dependence on traditional models, facilitates structural management changes, reduces information asymmetry through the flow of digital information, mitigates financing difficulties and connects to the innovation resource supply pool.

The digital transformation brought about by technological advancements faces dual scrutiny from both industry and academia. Excessive advancement in digital technology may lead to challenges for enterprises, including mismatches between digital capabilities and transformation needs, levels of management, lagging or imbalanced hardware facilities, as well as resulting in issues such as information overload (Himma, 2020; Roetzel, 2019) and digital divide (Chetty et al., 2018). Whether digital transformation exhibits a 'digital empowerment' effect, a 'digital disempowerment' effect or a combination of both in the process of fostering innovation resilience within enterprises requires a thorough examination of internal mechanisms and operational dynamics. Additionally, different lifecycle stages of the enterprise entail significant differences in resource infrastructure, human capital, management capabilities and business objectives (Mosca et al., 2021). In this heterogeneous, dynamic and boundary-defined context of enterprises, does digital transformation yield different integrated effects on innovation resilience?

This study utilises data from Chinese A-share listed companies between 2012 and 2022 to answer this question. Specifically, this study designs an innovation resilience index at the enterprise level and investigates the mechanisms through which digital transformation influences innovation resilience. Boundary effects associated with different lifecycle characteristics are analysed in-depth to uncover the underlying mechanisms of the dual effects of digital transformation on enterprise innovation resilience.

Literature review

Enterprise innovation resilience

Resilience is a concept widely studied and applied, originating from physics and engineering (Frigotto et al., 2022) and gradually extending into fields such as economics and organisational management (Hillmann & Guenther, 2021). In recent years, crises like the US–China trade friction and the technology blockade against China have had a significant negative impact on enterprises' (e.g. information and communication technology firms) technological innovation mainly by increasing their operating costs (Chen et al., 2023), thereby intensifying the risk of innovation interruption. Scholars have turned their attention to the resilience capability of innovation systems, namely innovation resilience. Studies (Boschma, 2017; Iacobucci & Perugini, 2021; Ryan et al., 2021) have embedded resilience concepts in various domains such as regional innovation ecosystems, high-tech manufacturing industry innovation, digital innovation, regional cooperative innovation and innovation project management, exploring how different innovation systems cope with adversity to achieve stable and sustained innovation processes.

From an intrinsic perspective, resilience can be viewed through the lenses of capacity, process and outcome. Innovation resilience is defined as the capability to cope with uncertainties (Lv et al., 2018) and adversities (Fey & Kock, 2022) associated with innovation. Pinto (2018) defines innovation resilience as the ability of innovation systems to maintain or create innovation trajectories when facing external crisis impacts or systemic failures. From a process standpoint, Wziątek-Kubiak and Pęczkowski (2021) treat innovation resilience as a dynamic evolutionary process resulting from the characteristics, especially the cumulative nature of knowledge. From an outcome perspective, Fey and Kock (2022) argue that the purpose of innovation resilience behaviour is to enable project teams to identify deviations and steer back to the right path.

From our perspective, these definitions emphasise that innovation resilience is not only an inherent trait but also a demonstrated capability. Inherent traits refer to the essential characteristics of anticipating, responding to, adapting and even surpassing evolution under external shocks while demonstrated capabilities enable the reaggregation of innovation elements, investment in innovation resources, iterative optimisation of innovation structures, improvement of innovation environments, thereby shaping innovation aggregation, stimulating innovation vitality and enhancing innovation efficiency.

Digital transformation and innovation

Digital transformation (Majchrzak et al., 2016) has become a critical opportunity for enterprises in the era of data and information, enabling them to pursue digital value dividends and enhance their innovation capabilities iteratively. By integrating digital technologies and restructuring management frameworks, enterprise digital transformation systematically upgrades aspects such as organisational structure, production, management and value creation, profoundly impacting innovation activities within firms (Nambisan et al., 2017). For instance, the growing digitalisation in manufacturing processes facilitates the establishment of new flexible routines with the introduction of advanced machinery in production (Aversa et al., 2021) while establishing digital platforms aids in identifying customer value demands (Nadkarni & Prügl, 2021). Leveraging data accelerates the flow and search efficiency of resource elements, thereby reshaping traditional innovation pathways, empowering innovation capabilities and enhancing innovation performance. Some studies (Ciarli et al., 2021; Usai et al., 2021) explored the intrinsic mechanisms by which data elements and digital technologies empower innovation, highlighting widespread participation, precise matching and value co-creation as dominant pathways.

Furthermore, digital transformation stimulates innovation drive and improves innovation performance through mechanisms such as cost reduction, revenue increase and efficiency enhancement.

Scholars argue that digital transformation not only brings about the effect of information cost but also alters the pattern of enterprise resource allocation, leading to an inverted U-shaped relationship between digital technologies and innovation (Li & Wang, 2023). Digital transformation can be categorised into four dimensions: digital construction level, digital access level, digital application level and digital circulation level. Different dimensions of digitalisation influence both incremental and radical innovation capabilities, thereby affecting the performance of new product development in a non-linear manner. The adoption of digital technologies may also cause the 'too much of a good thing' effect, which can be moderated by mechanisms such as knowledge accumulation and knowledge integration capability (Gong et al., 2023). Therefore, leveraging other critical capabilities to prolong the positive impact of digital technology is crucial. Moreover, the personal characteristics of managers play a key role in ensuring the empowerment effect and enhancing competitiveness during enterprise digital transformation (Martínez-Peláez et al., 2023). Hence, digital transformation may simultaneously have positive and negative effects, necessitating a thorough exploration of its boundary mechanisms (Li et al., 2023).

With the deepening and expansion of the study on innovation, scholars have begun to focus on the continuity and linkage of innovation systems. Some studies have separately examined how fintech innovation improves productivity, promotes transformation and fosters sustainability of enterprises (Luo et al., 2022) and the new logic of evolution in innovation ecosystems in the digital economy era (Benitez et al., 2020). In the context of frequent external crises, neither innovation sustainability (Adams et al., 2016) nor innovation ecosystems (Oh et al., 2016) can fully explain the ability of enterprise innovation systems to resist, adapt to and recover from shocks. Sustainability is often operationalised and measured using environmental, economic and social indicators (Elkington, 1994), lacking the ability to respond to specific external shocks and changes (Lv et al., 2018). Innovation ecosystems complement innovation resilience by emphasising comprehensive collaboration among various stakeholders (Ramezani & Camarinha-Matos, 2020).

In summary, current efforts mainly focus on how digital transformation promotes enterprise innovation, but limited research reports how digital transformation affects the stability, adaptability and evolution processes of innovation systems under shocks. Although some literature explores how digital technology enhances the resilience of specific industry systems, it often overlooks the heterogeneity of micro-level enterprise entities and fails to describe the diverse effects of digitisation on other industries and enterprises. This oversight may lead to a biased understanding of its effects. Furthermore, the lack of empirical evidence at the enterprise level leaves room for studying the impact of digital transformation on the resilience of enterprise innovation.

Theoretical analysis and research hypotheses

Digital transformation and enterprise innovation resilience

The resilience theory posits that resilient systems exhibit four major system characteristics, namely diversity, efficiency, adaptability and cohesion (Bhamra et al., 2011; Fiksel, 2003). Enterprises pursuing digital transformation to capture digital value can avoid traditional path dependencies, improve their operation performance and reshape new business models, thereby comprehensively improving their fundamental characteristics, demonstrating the positive effects of 'digital empowerment' (Jiang et al., 2023). However, some enterprises blindly chase high digital dividends, influenced by peer imitation and subsidy exploitation. As enterprise capabilities struggle to keep pace with the leapfrog development of digital technologies, negative effects of digital disempowerment (Chib et al., 2022) emerge. Consequently, within the realm of enterprise innovation resilience analysis, both 'empowerment' and 'disempowerment' in digital transformation persist.

1. *The empowerment effect of digital transformation drives a shift in organisational paradigms*. By enhancing information operability, digital technologies transcend organisational and geographical boundaries (Enkel et al., 2020), reducing information lags and asymmetries. External investors can more easily assess the investment value of enterprises, thereby alleviating financing constraints and increasing the influx of external funds (Sadeghi & Biancone, 2018). Against the backdrop of government-led digital strategies, enterprises in the early stages of digital transformation can also receive government grants and policy support. This circulation of funds provides the financial reserves needed for innovation systems, enhancing the ability of enterprises to respond to external shocks and increasing innovation resilience. In terms of collaborative culture, employees utilise digital tools such as instant messaging and cloud storage platforms for multi-party interactive collaboration, facilitating real-time information sharing and team interaction, fostering a collaborative culture, removing barriers to knowledge sharing and establishing a diverse innovation environment (Appio et al., 2021). The dissemination and coupling of diverse background knowledge among research and development personnel stimulate innovative thinking, improve the flexibility and adaptability of innovation systems to external changes and strengthen innovation resilience. Foundational digital platforms (De Reuver et al., 2018) support enterprises in tracking, recording and reporting social and environmental performance, meeting stakeholders' demands for information disclosure and accountability, facilitating diverse value creation and building symbiotic stakeholder relationships. Symbiotic relationships strengthen the

adaptability and resilience of enterprise innovation systems through mechanisms of risk sharing and joint resistance (Das, 2024). Stakeholders' resources and expertise help enterprises find solutions and innovative coping strategies. Additionally, the supervisory effects of symbiotic relationships promote knowledge accumulation and the enhancement of innovation capabilities through feedback and learning cycles, further bolstering enterprise innovation resilience.

2. *The disempowerment effect of digital transformation*. The widespread and deepening digital transformation imposes higher demands on enterprise organisational structures, management systems and resource allocations (Leso et al., 2023). Without synchronous enhancement of enterprise capabilities alongside the rapid development of digital technologies, there is a risk of falling into a digital trap (Marx et al., 2023). In such circumstances, a stark conflict arises between the rapid increase in data and information and the limited capacity for digital processing, leading to information overload (Heilig et al., 2017). Enterprises struggle to sift through, analyse and apply critical information within vast datasets, exacerbating information asymmetry. In environments with significant information disparities, the alignment between the resource pool sustaining the innovation system and external funding channels gradually deviates, weakening the innovation system's resource foundation. Additionally, the failure to concurrently cultivate employees' abilities to identify, decompose and transform digital information may lead to information overload and communication noise (Leso et al., 2023), impacting team collaboration efficiency. Over-reliance on virtual collaboration platforms and other digital tools reduces opportunities for face-to-face communication within enterprises (Wu, 2022), potentially weakening their collaborative culture. This can lead to heterogeneous research and development entities becoming isolated innovation knowledge islands, limiting the collision of innovative ideas and inspirations, thereby reducing research and development efficiency (Jacobides et al., 2018). This detachment from diverse entities affects the resilience of the innovation system in responding to external shocks. Introducing cutting-edge technologies, data and business models may generate new social and environmental hazards (Saarikko et al., 2020), for example, data privacy and security issues and changes in labour demand. The lack of transparency and accountability mechanisms within enterprises or the damage to employee welfare and job stability, undermines trust and symbiotic relationships with stakeholders, resulting in a lack of external support from symbiotic stakeholders and reducing the innovation system's ability to adjust its structure and aggregate resources in the face of external shocks. Additionally, Usai et al. (2021) also argued that the excessive use of digital technologies may even deplete the long-run innovation capability of firms, for instance, by impoverishing the relational capital.

In summary, the empowerment and disempowerment effects of digital transformation on enterprise innovation resilience can be manifested through three aspects: the information resource effect, the collaborative culture effect and the stakeholder symbiosis effect. Based on this, the following hypothesis is proposed:

H1: With the continuous deepening of digital transformation, the enabling effect tends to weaken while the disabling effect tends to strengthen, resulting in an inverted U-shaped relationship about enterprise innovation resilience.

Effect analysis based on the dynamic perspective of enterprise lifecycle

The development of enterprises parallels the lifecycle of living organisms, undergoing a progression from inception to growth, maturity, decline and ultimately extinction (Dickinson, 2011). Past research (Mosca et al., 2021) has highlighted significant differences in financial characteristics, development patterns and organisational inertia across various stages of enterprise development. Differential resource provision and organisational adaptability can impact an enterprise's resilience to innovation during the process of digital transformation (Mugge et al., 2020). Therefore, it is imperative to analyse the heterogeneous effects of digital transformation from the perspective of the enterprise lifecycle, encompassing dynamic changes from growth to decline.

Enterprise lifecycle stage – Growth: Enterprises at the growth stage possess certain profit and growth conditions (Dickinson, 2011), with continuous expansion of product market opportunities and shares. They are open to new developments, demonstrate innovation awareness and market acumen and are willing to collaborate with partners while maintaining entrepreneurial spirit. At this stage, they have not yet established fixed organisational structures or management processes, exhibiting low organisational inertia. These characteristics facilitate their ability to adapt to changes and create new opportunities, driving sustained development and growth (Ren et al., 2023).

Regarding digital transformation, enterprises at the growth stage are capable of bearing the consumption of basic resources and promptly adjusting organisational structures and management models. They progressively advance digital transformation through agile methods (Zhu et al., 2021), gradually introducing and applying digital technologies. Continual optimisation and improvement are pursued, with timely training provided to employees for adapting to new technologies and platforms, synchronising their managerial capabilities with digital advancements. This collaborative approach enhances the enterprise's capacity to handle the influx of data from digital transformation and filter key information, while nurturing employees' skills in managing information overload and communication noise (Smith et al., 2017).

An environment of moderate information asymmetry reduces financing constraints (Liu, Li, et al. 2023; Zhang et al., 2024), providing a resource foundation for digital transformation. The prevalence of a culture of collaboration within enterprises fosters conditions for heterogeneous research and development entities, promoting collisions of innovative thinking. The alignment of digital technology and organisational capabilities (Konopik et al., 2022) effectively mitigates social and environmental risks brought about by new technologies. By facilitating smooth transitions of employment positions and considering social responsibility and sustainable development, enterprises respond to the diverse value demands of stakeholders, thereby maintaining symbiotic relationships and strengthening the adaptability of innovation systems to external changes.

Based on the resilience of innovation within enterprises, growing-stage companies sustain the enabling effect of digital transformation. Thus, the following hypothesis is proposed:

H2a: Digital transformation primarily exerts an enabling effect on the innovation resilience of growth-stage enterprises, manifesting as a significant positive relationship.

Enterprise lifecycle stage – Maturity: Upon entering the mature stage, companies typically possess stable market shares, strong profitability and ample cash flow (Dickinson, 2011). The initial phase of digital transformation presents mature-stage enterprises with increased opportunities for external financing, enriching their resource base. This not only aids in overcoming transitional challenges but also significantly enhances their innovation resilience through the empowerment effect of digital transformation. Adequate funding supports the introduction of digital tools and equipment, facilitating the creation of digital ecosystems and providing a foundational platform for diverse innovation entities, thereby stimulating the flow of innovative elements (Peng & Tao, 2022). However, during this period, organisational structures tend to become more refined, management practices mature, managerial positions stabilise and organisational inertia solidifies (Wang & Liu, 2024), leading to a scarcity of promotion opportunities and a relative reduction in the demand for management skill upgrades. The alteration of existing organisational structures and management processes because of digital transformation becomes increasingly challenging (Bilgeri et al., 2017; Mirković et al., 2019). As the transformation progresses, the discrepancy between entrenched management capabilities and the expansion of digital technologies constrains the effectiveness of the transformation and may even accelerate the company's descent into a digital trap. Based on this analysis, the following hypothesis is proposed:

H2b: The enabling effect of digital transformation on innovation resilience in mature-stage enterprises tends to weaken, while the negative effect tends to strengthen, exhibiting an inverted U-shaped relationship. Moreover, the range of the enabling effect is relatively low, with the inflection point of the curve shifting to the left.

Enterprise lifecycle stage – Decline: Enterprises face challenges such as declining market share in the decline stage, decreased profitability, increased competitive pressure, outdated products or services, limited cash flow, organisational rigidity and slow decision-making (Dickinson, 2011). Although digital transformation brings about high fluidity and integration of data and information (Zhu et al., 2021), enhancing proximity with external investors and establishing a transparent consensus space with stakeholders, thus alleviating financing constraints to some extent and promoting the resilience of the innovation system in crisis (Liu et al., 2023), the lack of funds and organisational rigidity in declining companies (Mirković et al., 2019) lead to the proliferation of conservative thinking, making it difficult to synchronously update management skills to match the requirements of digital transformation. This reduces the range of digital transformation pressure that innovation resilience can withstand. Compared to mature companies, the digital empowerment effect in declining companies reaches its peak faster (Liu et al., 2023). Based on the above analysis, the following hypothesis is proposed:

H2c: The 'empowerment' effect of digital transformation on innovation resilience in declining companies significantly weakens, while the 'disempowerment' effect significantly strengthens. Although the overall trend still exhibits an inverted U-shaped relationship, the range of the 'empowerment' effect is lower, and the inflection point of the curve shifts noticeably to the left.

Methodology

Data

This study focuses on Chinese A-share listed companies from 2012 to 2022. Patent data were collected from a third-party patent database, while digital transformation data were extracted from the disclosed intangible assets in the financial reports of listed companies. Financial characteristics and corporate governance control variables at the enterprise level primarily were sourced from a third-party database, while provincial-level control variables were designed from provincial statistical yearbooks and the China Statistical Yearbook. Sample selection involved excluding industries with unique financial reporting characteristics, such as finance and insurance, as well as special treatment (ST) samples like ST and particular treatment (PT), and samples with insolvency issues, resulting in 18787 company-year samples. Considering the relatively low proportion of missing data and their random distribution, samples with missing values for key variables were excluded, leaving a final dataset of 18304 company-year observations. To mitigate the impact of extreme outliers on model estimation, all continuous variables underwent Winsorization at 1% and 99%.

Variable definitions and indices

Enterprise innovation resilience

As innovation resilience refers to the ability to manage and overcome the uncertainties and challenges inherent in the innovation process (Fey & Kock, 2022; Lv et al., 2018), its measurement can be defined by selecting innovation indicators that are sensitive to external shocks. Innovation inputs like Research and Experimental Development (R&D) expenditure and proportion of R&D personnel and outputs, for example, sales revenue from new products, number of patent applications and number of patents granted, are usually employed as variables to evaluate enterprise innovation activities. However, innovation input indicators may be influenced by the absorptive capacity of different enterprises for innovation funds, making it difficult to directly reflect the level of innovation. Additionally, data on sales revenue from new products in listed companies can hardly be obtained. Therefore, this study adopts the number of patent applications as a key indicator. The number of patent applications by enterprises is closely related to their R&D environment and demonstrates sensitivity to external shocks (Milani & Neumann, 2022; Paula & Silva Rocha, 2021). Inspired by the measurement paradigms proposed by Martin and Gardiner (2019), this study employs changes in the number of patent applications to assess the level of innovation resilience of enterprises. Formally,

$$EIR_{i,t} = (\Delta P_i - \Delta E_i)/|\Delta E_i|,$$

$$\Delta P_i = P_{i,t} - P_{i,t-1},$$

$$\Delta E_i = [(P_{c,t} - P_{c,t-1})/P_{c,t-1}] \times P_{i,t-1}, \quad \text{[Eqn 1]}$$

where $EIR_{i,t}$ represents the relative innovation resilience of enterprise i in year t. ΔP_i denotes the change in patent applications for enterprise i. ΔE_i estimates the patent application status of the enterprise i from $t-1$ to t based on changes in the overall patent application volume in the city where the enterprise is located. $P_{i,t}$ and $P_{i,t-1}$, respectively, indicate the number of patent applications of enterprise i in years t and $t-1$. $P_{c,t}$ and $P_{c,t-1}$ are the number of patent applications in the city where the enterprise is located in years t and $t-1$.

A higher $EIR_{i,t}$ indicates better performance of the innovation resilience of enterprise i relative to the city's overall performance in year t and vice versa. This study recalibrates innovation resilience through two methods for robustness testing: computing EIR1 using the number of patent grants as a key proxy and calculating EIR2 on the industry scale rather than the city scale.

Digital transformation

Based on disclosure in the financial reports of listed companies, this study organised and identified specific items of intangible assets at year-end to determine those related to digital technologies. Subsequently, the proportion of these relevant items to total intangible assets was calculated as a proxy indicator of the level of digital transformation within the company. Specifically, intangible asset items containing key digital technology-related terms, such as 'management systems', 'smart manufacturing', 'networks', 'cloud computing' and 'informatics' or those involving related patents, were flagged as digitally relevant. To present the data more intuitively, the ratio of digitally relevant assets to total intangible assets was multiplied by 100 to derive the final digital transformation index.

Enterprise lifecycle

This study employs cash flow patterns to identify the lifecycle stages of enterprises (Dickinson, 2011). Concretely, the net cash flows from operating, investing and financing activities are observed to categorise the lifecycle stages of companies. Within the growth phase, further divisions are made into the inception stage and the expansion stage. In the inception stage, characteristics of net cash flows include negative operating and investing cash flows alongside positive financing cash flows, whereas in the expansion stage, characteristics involve positive operating cash flows, negative investing cash flows and positive financing cash flows. Companies meeting these criteria are classified as being in the growth phase, resulting in the identification of 8517 samples. Similarly, based on the characteristics of net cash flows, samples representing maturity and decline phase of companies are identified. Following these principles, a total of 6645 mature phase samples and 3142 decline phase samples are ultimately identified. Table 1 summarises the details of the lifecycle stages of enterprises using a cash flow-based approach.

Control variables

This study rigorously controls for variables related to corporate organisational structure, financial characteristics and governance practices. These include enterprise size (ES), age (EA), ownership structure (OS), return on equity (ROE), cash flow ratio (CFA), asset turnover ratio (ATR), dual leadership roles (DLR) and equity balance (EB). Additionally, human capital level (HCL) and innovation level (IL) as control variables are also considered, acknowledging their impact on innovation resilience across different regions. Furthermore, to mitigate interference from industry and year effects, time and industry effects are controlled. Table 2 presents the definitions and notations of the control variables.

TABLE 1: Cash flow characteristics at different stages during the enterprise lifecycle.

Type	Net operating cash flow	Net investing cash flow	Net financing cash flow
Growth phase			
Inception	-	-	+
Expansion	+	-	+
Maturity phase			
Maturity	+	-	-
Decline phase			
Decline 1	-	-	-
Decline 2	+	+	+
Decline 3	+	+	-
Elimination 1	-	+	+
Elimination 2	-	+	-

TABLE 2: Definitions and notations of control variables.

Notation	Control variable	Definition
EIR	Enterprise innovation resilience	See equation (1)
DT	Digital transformation	(Intangible assets related to digital technology/Total intangible assets) × 100%
ES	Enterprise size	*ln*(1 + End-of-year total assets)
EA	Enterprise age	*ln*(Current year – Year of establishment + 1)
OS	Ownership structure	1 for state-owned holding companies, otherwise 0
ROE	Return on equity	Net profit/Average shareholder equity × 100%
CFA	Cash flow ratio	Net operating cash flow/Total assets × 100%
ATR	Asset turnover ratio	Operating income/Average total assets × 100%
DLR	Dual leadership roles	1 if the Chairman and CEO are the same person, otherwise 0
EB	Equity balance	Proportion of shares held by the second largest shareholder/Proportion of shares held by the largest shareholder
HCL	Human capital level	Number of undergraduate students in the province/Total population
IL	Innovation level	*ln*(Number of invention patent applications in a province)
IE	Industry effect	Industry dummy variable
YE	Year effect	Time dummy variable

Note: *ln*(●) denotes the natural logarithm.

Model settings

This study establishes a baseline regression model to examine the dual effect of digital transformation on innovation resilience in enterprises. The model is defined as

$$EIR_{i,t} = \alpha_0 + \alpha_1 DT_{i,t} + \alpha_2 DT^2_{i,t} + \alpha_3 \sum CV_{i,t} + \sum YE_{i,t} + \sum IE_{i,t} + r_{i,t}, \quad \text{[Eqn 2]}$$

where α_0 represents the constant term; α_1, α_2 and α_3 are coefficients. $CV_{i,t}$ denotes the combination of control variables, and $r_{i,t}$ represents a random disturbance term.

Empirical analysis

Descriptive statistics and overview of lifecycle characteristics

The descriptive statistics of the overall sample are presented in Table 3. The data of descriptive statistics indicates that the mean of enterprise innovation resilience is 0.644, with a maximum value of 16.550 and a standard deviation of 1.824. The innovation resilience level of Chinese enterprises is generally low, with insufficient momentum to advance towards higher levels of innovation resilience. The results from lifecycle characteristic variables indicate a higher proportion of enterprises in the growth and mature stage within the sample.

From the financial perspective of enterprises, mature-stage enterprises demonstrate the best performance in terms of cash flow and net asset returns, followed by growth-stage enterprises, and worst in decline-stage enterprises. In terms of enterprises as a whole, mature-stage enterprises exhibit the highest resilience in the innovation systems, followed by growth-stage enterprises. Mature-stage enterprises have the highest resilience indicating a robust resource base to support the sustained operation of innovation systems in mature-stage enterprises. The flexible organisational structures and innovative awareness of growth-stage enterprises have a strong potential for enhancing innovation resilience.

Benchmark regression analysis

The benchmark regression results of digital transformation on enterprise innovation resilience are presented in Table 4.

TABLE 3: Descriptive statistics of the sample.

Variable coefficient	Mean	s.d.	Minimum value	Maximum value
EIR	0.644	1.860	-1.000	16.560
DT	0.304	0.600	0.000	4.840
DT^2	0.442	2.110	0.000	23.400
ES	22.270	1.280	19.530	26.440
EA	2.870	0.341	1.100	3.620
OS	0.322	0.467	0.000	1.000
ROE	0.066	0.127	-1.080	0.406
CFA	0.048	0.066	-0.224	0.257
ATR	0.653	0.408	0.053	2.910
DLR	0.287	0.453	0.000	1.000
EB	0.362	0.285	0.006	1.000
HCL	0.020	0.004	0.012	0.035
IL	10.830	1.180	7.170	12.300

Note: DT^2 is the square of *DT*. In Tables 3-5, DT^2 refers to the coefficient value of DT^2 computed using [Eqn 2].

EIR, enterprise innovation resilience; DT, digital transformation; ES, enterprise size; EA, enterprise age; OS, ownership structure; ROE, return on equity; CFA, cash flow ratio; ATR, asset turnover ratio; DLR, dual leadership roles; EB, equity balance; HCL, human capital level; IL, innovation level; s.d., standard deviation.

Model 1 considers only time and industry effects, while Model 2 incorporates additional control variables. The results indicate no significant difference between Model 1 and Model 2.

The results of Model 2 were validated using the inverted U-shaped curve theory, and we found, (1) The value of *DT* was significantly positive and the value of DT^2 was significantly negative. (2) When *DT* is at its minimum, the slope of the curve ($\alpha_1 + 2\alpha_2 DT_{min}$) is 0.157, which is greater than 0. When *DT* is at its maximum, the slope of the curve ($\alpha_1 + 2\alpha_2 DT_{max}$) is –0.211, which is less than 0. (3) The inflection point of the curve ($-\alpha_1/2\alpha_2$) is at 2.058, within the range of *DT* values. These three findings are visually represented in Figure 1. Consequently, the impact of digital transformation on enterprise innovation resilience exhibits a clear inverted U-shaped relationship, indicating a combination of enabling and debilitating effects. Model 3 controls for the time trend term *T* for each province, and Model 4 incorporates the cubic term DT^3 for digital transformation. The results for Models 3 and 4 indicate that the inclusion of *T* did not result in a significant change in the estimates, nor did the inclusion of the cubic term improve the model fit. The impact of the *T* and

TABLE 4: The results of benchmark regression.

Variable coefficient	Model 1	*t*	Model 2	*t*	Model 3	*t*	Model 4	*t*
DT	0.157***	3.11	0.157***	3.012	0.153***	3.003	0.239***	2.068
DT^2	-0.038***	-3.11	-0.038***	-3.015	-0.037***	-3.005	-0.109	-1.064
DT^3	-	-	-	-	-	-	0.012	1.011
ES	-	-	0.073***	5.006	0.074***	5.068	0.073***	5.066
EA	-	-	0.098**	2.018	0.070	1.056	0.099**	2.020
OS	-	-	0.014	0.387	0.012	0.316	0.014	0.383
ROE	-	-	-0.453***	-4.073	-0.440***	-4.057	-0.453***	-4.073
CFA	-	-	-0.060	-0.278	-0.139	-0.643	-0.068	-0.321
ATR	-	-	0.043	1.016	0.051	1.033	0.043	1.014
DLR	-	-	-0.043	-1.049	-0.041	-1.040	-0.043	-1.049
EB	-	-	-0.155***	-3.021	-0.161***	-3.028	-0.155***	-3.021
HCL	-	-	1.060	0.408	12.046	0.196	1.062	0.414
IL	-	-	0.036***	2.088	0.647	0.196	0.036***	2.087
IE	Yes	-	Yes	-	Yes	-	Yes	-
YE	No	-	No	-	Yes	-	No	-
Constant term	0.907***	5.81	-1.026***	-3.045	-7.026***	-2.068	-1.024***	-3.048
Adj-R^2	0.019	-	0.023	-	0.024	-	0.023	-

Note: *** and ** represent significance at the 1% and 5% levels, respectively. Regression adopts individual-level clustering criteria, *t*, indicates the number of years - as defined in [Eqn 1]. DT^2 is the square of *DT*. In Tables 3-5, DT^2 refers to the coefficient value of DT^2 computed using [Eqn 2]. DT^3 is the cube of *DT*. In Tables 3-5, DT^3 refers to the coefficient value of DT^3 computed using [Eqn 2].
Adj, adjusted; DT, digital transformation; ES, enterprise size; EA, enterprise age; OS, ownership structure; ROE, return on equity; CFA, cash flow ratio; ATR, asset turnover ratio; DLR, dual leadership roles; EB, equity balance; HCL, human capital level; IE, industry effect; IL, innovation level; YE, year effect.

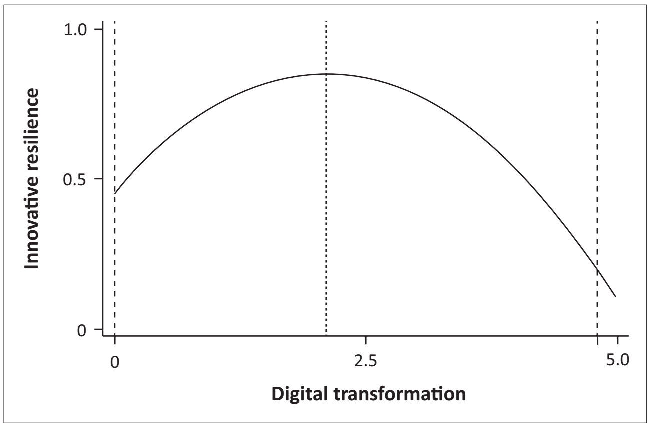

FIGURE 1: The relationship between digital transformation and innovation resilience.

DT^3 further strengthens the support for the inverted U-shaped relationship and validates H1.

Regression analysis across different lifecycle stages

The regression results across different lifecycle stages are presented in Table 5. Model 1 represents the regression for the entire sample. Comparing Model 2 and Model 3, the linear fit of digital transformation is evident to innovation resilience outperforms the regression model of quadratic terms. In both models, the coefficient for *DT* is significantly positive at the 5% level, indicating that during the growth stage, digital transformation continuously empowers innovation systems to withstand external crises and adapt to environmental changes. Models 4 and 5 show that the *DT* coefficient is significantly positive at the 1% and 10% levels, respectively, while the DT^2 coefficient is significantly negative at the 1% and 5% levels.

The inflection points of the curves are 1.869 and 1.596, respectively, both within the range of *DT* values, suggesting a dual superimposed effect of digital transformation during the mature stage and decline stage. The dual superimposed effect leads to an inverted U-shaped relationship between digital transformation and innovation resilience. In the decline stage, the rapid peak in the empowering effect of digital transformation on innovation resilience is attributed to rigid organisational structures and weaker financial strengths. The smaller inflection points in Figure 2 evidence this finding. In summary, H2a, H2b and H2c are all confirmed.

Robustness test

From a perspective of reverse causality, better performance in innovation resilience of enterprises has higher levels of acceptance and adoption of new technologies. The higher correlation indicates a greater capability of the enterprise to mobilise and allocate resources to support the process of digital transformation. This endogenous problem may lead to a misinterpretation of an inverted U-shaped relationship. The instrumental and lagged variable methods were employed in this study to mitigate the interference of the endogenous problem. The mean of digital transformation across the year-industry-region of enterprise is selected as the instrumental variable for *DT*, and the square term serves as the instrumental variable for DT^2. The regression results do not change significantly, proving the robustness of H1.

To further validate the reliability of the research conclusions, we conducted the following tests, (1) Recalculated the explanatory variables of innovation resilience, including selecting the number of patents granted by enterprises as the core key indicator to obtain EIR_1. Replaced the city standard with the industry standard in the benchmark regression to obtain EIR_2. (2) The independent variable 'digital transformation' was recalculated based on textual analysis by extracting 76 indicators from five dimensions: artificial

TABLE 5: Regression results of digital transformation on innovation resilience by enterprise lifecycle.

Variable coefficient	Entire sample		Growth stage				Mature stage		Decline stage	
	Model 1	*t*	Model 2	*t*	Model 3	*t*	Model 4	*t*	Model 5	*t*
DT	0.157***	3.12	0.080**	2.10	0.015	0.173	0.229***	2.94	0.182*	1.79
DT^2	-0.038***	-3.15	-	-	0.022	1.004	-0.061***	-3.35	-0.057**	-2.38
CV	Yes	-	Yes	-	Yes	-	Yes	-	Yes	-
IE	Yes	-	Yes	-	Yes	-	Yes	-	Yes	-
N	18 304.000	-	8517.000	-	8517.000	-	6645.000	-	3142.000	-
Constant term	-1.023***	-3.45	-0.764	-1.40	-0.769	-1.040	-1.087***	-3.01	-1.023*	-1.68
Adj-R^2	0.023	-	0.020	-	0.020	-	0.032	-	0.023	-

Note: *, Stands for significance at the 10% level, ** and *** represent significance at the 5% and 1% levels, respectively, *t*, indicates the number of years - as defined in [Eqn 1]. DT^2 is the square of *DT*. In Tables 3-5, DT^2 refers to the coefficient value of DT^2 computed using [Eqn 2].

Adj, adjusted; CV, control variable; DT, digital transformation; IE, industry effect.

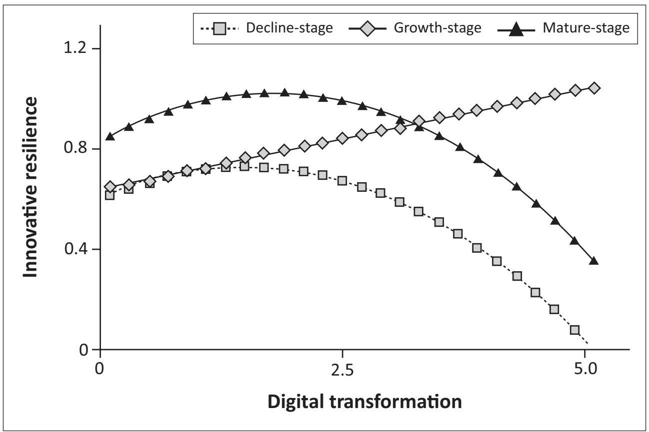

FIGURE 2: The results of variance analyses for different lifecycle stages.

intelligence, blockchain, cloud computing, digital technology applications and big data. (3) Considering the potential interference of external shocks on the innovation resilience of enterprises during normal periods, specific year samples (the stock market crash in 2015 and the COVID-19 pandemic in 2020–2021) were excluded from the analysis. (4) Given that the high-tech industry relies heavily on innovation and prioritises investment in innovation activities to shape innovation resilience. Samples from the high-tech industry were omitted to mitigate potential biases in the research findings. (5) The enterprise lifecycle was re-segmented employing the comprehensive indicator method. The examination results based on the above adjustments are not substantially different from the results of benchmark regression, again validating the robustness of this study's conclusions.

Conclusions

The major findings of this study include two folds. Firstly, there is a significant inverted U-shaped relationship between digital transformation and enterprise innovation resilience, highlighting the crucial importance of moderate digitalisation in maintaining and fortifying innovation resilience. Secondly, the enterprise lifecycle moderates this relationship. While digital transformation positively enhances innovation resilience during the growth phase, it still exhibits an inverted U-shaped pattern during the mature and decline phases, albeit with a relatively lower empowerment effect in the decline phase.

The contributions of this study are summarised in two main aspects. Firstly, this study extends the examination of innovation resilience from macro-industry to micro-enterprise levels. By investigating the dual effects of digital transformation embedded within enterprises, this study uncovers how digital transformation influences innovation resilience through pathways such as information resource effects, collaborative culture effects and stakeholder symbiosis effects. Secondly, this study longitudinally compares the effects of digital transformation on innovation resilience at different stages of the business lifecycle, explaining the contingencies of the empowerment and disempowerment effects of digital transformation. This provides theoretical support for devising digital transformation strategies to cultivate innovation resilience for enterprises at different lifecycle stages.

This study provides the managerial implications for strategic transformation and innovation decision-making in enterprises. Firstly, enterprises should leverage the positive empowering effect of digital transformation on innovation resilience while guarding against negative effects, avoiding excessive and indiscriminate pursuit of digitisation that may lead to falling into a digital trap. Secondly, enterprises should adopt a flexible approach to the relationship between digital transformation and innovation resilience, making rational use of changes in this relationship. For example, enterprises in the growth phase can harness the positive driving force of digital transformation, while those in the mature phase should focus on establishing comprehensive digital technology plans and regulatory mechanisms. Lastly, enterprises should emphasise the coordinated development of multiple factors contributing to innovation resilience. Digital transformation is just one aspect affecting innovation resilience, and enterprises should accumulate resources from various aspects, enhance capabilities and actively plan and gradually promote the development of innovation initiatives systematically.

This study also has some limitations. Firstly, this study relies on the performance of cities and industries as benchmarks to measure the relative level of enterprise innovation resilience, which tends to be an outcome-oriented perspective and may not fully capture the dynamic evolution of enterprise innovation systems. Future research could construct innovation resilience indicators from perspectives such as processes and capabilities. For example, crisis resistance, recovery and evolutionary capabilities of enterprise innovation systems can be measured using comprehensive scales. Secondly, in the face of external shocks, enterprises require comprehensive coordination to maintain the stability of their innovation systems and even evolve to higher levels. Future research could delve into how heterogeneous innovation resources, leaders' cognition and capabilities regarding innovation and the intersection with digital transformation affect enterprise innovation resilience.

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Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

Y.P. and L.J. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

Ethical considerations

This article followed all ethical standards for research without direct contact with human or animal subjects.

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Data availability

The data that support the findings in this study are available from the corresponding author upon reasonable request.

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