



Digitalization as a double-edged sword: A deep learning analysis of risk management in Chinese banks

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ABSTRACT

Digitalization presents both opportunities and formidable challenges for risk management in commercial banks. This study addresses the critical question of how digitalization influences banks' risk-taking behaviors. Applying an InstructGPT-inspired deep learning model, we developed a multidimensional bank digitalization index to analyze its effects on risk-taking, using data from 149 Chinese commercial banks from 2011 to 2020. The empirical results show that (1) digitalization significantly curtails risk-taking on the balance sheet, while concurrently escalating off-balance sheet risk exposure; (2) digitalization diminishes on-balance sheet risk by lessening distortions in competition due to government guarantees, manifested as a competition effect of on-balance sheet guarantee; (3) digitalization increases the upper limit of expected returns on bank financial products, thereby elevating off-balance sheet risk-taking, evident as an off-balance sheet price competition effect; (4) bank digitalization has a more obvious boosting effect on off-balance sheet risk-taking of banks with a longer average maturity of wealth management products. This paper enriches the measurement of the digitalization of banks and provides a reference for banks to deepen digital applications and strengthen risk management, which has important practical significance.

1. Introduction

In the contemporary era, advancements in digital technologies, epitomized by the proliferation of big data analytics and artificial intelligence (AI), have precipitated profound alterations within the financial industry. The advent of innovative financial services, including but not limited to digital payment systems, virtual banking platforms, and AI-driven investment advisory services, all facilitated by these technological advancements, has necessitated a paradigm shift among banking institutions. These entities are now compelled to undergo digital metamorphosis, aiming to augment their competitive stance and elevate their customer service efficacy. Existing literature indicates that in the process of utilizing digital technology for business growth and process innovation, commercial banks face more risks than other financial sectors (Chen et al., 2021). This may be due to the irreversible trend towards digitalization (Zhai, Cheng, & Xie, 2023). When the expansion of a business outpaces the underlying support and risk management capacities of a bank, it can result in a cascade of significant problems, thereby elevating the risk of defaults (Gu & Yang, 2018). Furthermore, research by some academics has indicated that the

digitalization of banking institutions may fuel the expansion of the shadow banking sector and amplify the banking system's tail risk (Gennaioli, La Porta, Lopez-de-Silanes, & Shleifer, 2013), enhance risk contagion (Buchak, Matvos, Piskorski, & Seru, 2018; Claessens, Ratnovski, & Singh, 2012), and even lead to a systemic financial crisis (Cabral, 2013; Plantin, 2015).

As the main body of the financial system, commercial banks' risk-taking plays a vital role in financial stability. In the context of the current systemic mismatch problem in the banking industry and the possibility that the global liquidity crisis may continue to spread, studying the impact of commercial banks' digitalization on their risk-taking is of great practical significance. Such research will not only deepen the financial application of digital technology but also strengthen bank risk governance. However, research on the digital transformation of banks is still in the exploratory stage, and the measurement of bank digitalization is rarely mentioned (Li, Li, & Zhu, 2023). As a result, there are few studies directly examining the relationship between digitalization and banks' risk-taking in the literature. Most related studies are based on analyses from perspectives such as financial technology, digital finance, and internet finance, and their conclusions vary. For instance, some

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scholars find that Internet finance has created many problems and challenges in systemic financial risks (Kero, 2013) and financial regulation (Hoque, Andriosopoulos, Andriosopoulos, & Douady, 2015), and has shifted risks to banks (Stoica, Mehdiian, & Sargu, 2015). Meanwhile, others believe that the impact of financial technology and Internet finance on banks' risk-taking presents a nonlinear relationship (Liu, 2016; Wang, Liu, & Luo, 2021; Wang, Ma, & Ye, 2021; Wang, Xiuping, & Zhang, 2021).

Utilizing data from 149 commercial banks in China spanning 2011 to 2020, we first construct a digital index for each bank, comprising five dimensions: product, technology, management, ecology, and risk control. This index is developed using a deep learning model trained with methods similar to those used in InstructGPT. We then examine the impact and mechanisms of bank digitalization on the risk-taking of commercial banks through panel regressions. The empirical results demonstrate that bank digitalization significantly inhibits on-balance sheet risk-taking and markedly promotes off-balance sheet risk-taking. Our analysis of the mechanisms reveals that bank digitalization reduces on-balance sheet risk-taking by diminishing the distortion caused by government guarantee competition, which is evident as an on-balance sheet guarantee competition effect. Conversely, it increases banks' off-balance sheet risk-taking by elevating the upper limit of expected returns on financial products, manifested as an off-balance sheet price competition effect. Additionally, we find that bank digitalization more significantly boosts off-balance sheet risk-taking in banks with a longer average maturity for their wealth management products.

This paper contributes to the existing literature in several ways. Firstly, it proposes a method for measuring bank digitalization using a deep learning model trained with methods similar to those used in InstructGPT, which is more adept at understanding sentence context semantics. This approach provides a more comprehensive and accurate digital index for commercial banks. Secondly, the study broadens the scope of research on the impact of digitalization on banks' risk-taking behaviors from a micro perspective. It goes beyond theoretical insights to provide practical recommendations for commercial banks. These suggestions aim to help banks better align their digital transformation initiatives with their risk management capabilities, thereby offering a roadmap for integrating technological advancements with traditional risk management practices. Thirdly, it examines the effects of bank digitalization on both on-balance sheet guarantee and off-balance sheet price competition, thereby enriching the theoretical understanding of how digitalization influences the risk-taking behaviors of commercial banks. Additionally, it outlines actionable strategies for banks to leverage digital technologies to enhance their competitive positioning and manage risks more effectively, presenting a dual perspective that bridges theoretical insights with practical applications. Fourthly, the analysis of the impact mechanisms and the heterogeneity of digitalization on off-balance sheet risk, particularly in the context of bank wealth management product data, opens new avenues for understanding how digitalization shapes risk management strategies. This investigation not only contributes a novel perspective to academic research but also offers banking professionals innovative approaches to off-balance sheet risk control in the digital age.

2. Theories and hypotheses

2.1. Bank digitalization and on-balance sheet risk-taking

Digital transformation in banking significantly lowers the costs associated with managing risk throughout the entire credit process, serving as a primary direct financing route for commercial banks. This transformation streamlines operations across pre-loan, during-loan, and post-loan phases. Initially, traditional credit methods are inefficient and labor-intensive. Through digital transformation, banks can now deploy advanced, automated credit assessment systems using big data and AI, reducing operational expenses. When a loan is active, digital tools help

banks create sophisticated systems for early detection of potential loan issues, leveraging real-time big data to oversee the customer's journey effectively, minimizing operational risks and lowering monitoring expenses. After the loan issuance, traditional recovery methods like physical visits and legal actions are expensive. The adoption of digital practices enables banks to use algorithms for creating smart platforms for debt recovery, accurately predicting which late-paying customers are likely to settle their debts and enabling efficient, ongoing loan surveillance via mobile technologies. By leveraging digital technologies to enhance risk assessment and management, banks are not only reducing operational costs but are also able to take on a more calibrated approach to risk-taking. This includes the ability to dynamically adjust credit policies based on real-time risk assessments, enhancing the bank's agility in responding to market changes. Furthermore, digital platforms facilitate a more granular analysis of both credit and market risks, enabling banks to tailor their risk-taking strategies with greater precision.

The regulatory framework of China also helps reduce on-balance sheet risks. Banks must adhere to compliance principles when advancing their digitalization strategies, especially in managing on-balance sheet risks. The regulatory institutions in China impose strict regulations on data protection, consumer rights protection, and cybersecurity, among others. These regulations ensure that banks comply with the necessary regulatory requirements during the lending process, optimizing their on-balance sheet risk management. Additionally, the positive reception of financial technology innovations by Chinese society provides strong market incentives for banks to adopt new technologies, further optimizing their on-balance sheet risk management. Based on the aforementioned analysis, we hereby put forward the following hypothesis:

H1. : Bank digitalization reduces on-balance sheet risk-taking.

2.2. Bank digitalization and off-balance sheet risk-taking

Dong, Tan, Dong, & Wu, 2023 have found that digital credit lowers the transaction threshold, and digital finance, relying on cutting-edge technologies, encompassing big data, blockchain, and cloud computing, creates a more inclusive and open financing environment (Beck, Pamuk, Ramrattan, & Uras, 2018). However, while digitalization brings about inclusivity (Banna & Alam, 2021; Gomber, Koch, & Siering, 2017; Huang & Qiu, 2021), the rapid expansion of digital finance exerts competitive pressure on traditional banks (Pramanik, Kirtania, & Pani, 2019; Wang, 2015). Consequently, the proportion of retail deposits decreases, resulting in banks becoming increasingly reliant on wholesale funds, such as those from the interbank lending market. This dependence forces banks to pursue higher-risk assets to offset increased costs (Qiu, Huang, & Ji, 2018). To expand market share (Zhang, Lin, & Zhu, 2021), banks use digital technology to broaden their user channels and to tap into the 'long tail market' of small and medium-sized enterprises, which may increase their risk-taking (Dong et al., 2023; Xie & Wang, 2022).

Besides, bank digitalization influences off-balance sheet risk-taking by affecting banks' risk preferences. Digitalization enhances banks' ability to gather and process information, allowing for more precise assessment of customer credit risk. However, this enhanced information processing capability could also lead banks to over-rely on algorithms and big data analytics, neglecting traditional risk management practices and intuitive judgement. Moreover, by increasing market accessibility and participation, digitalization intensifies market competition, forcing banks to pursue higher-risk investment strategies to maintain competitiveness and market share.

Given the relatively underdeveloped nature of China's securitization market, the shadow banking system is primarily distinguished by the off-balance sheet activities conducted by traditional commercial banks. Essentially, China's shadow banking system can be viewed as an integral

component of the off-balance sheet asset business of these banks, and its operations are intricately linked to the level of risk-taking within these institutions, as highlighted by Wang & Chen (2019). The credit intermediary chain in the shadow banking system generates systemic risk through term mismatch, liquidity conversion, credit risk transfer or guarantee, and leverage (Plantin, 2015). This situation can lead to bank runs and large-scale fund transfers, resulting in the rapid contagion of financial risks. The existing regulatory risk control model, akin to a 'black box', is still insufficient to fully explain the banks' off-balance sheet products. This inadequacy prevents regulatory authorities from effectively identifying the stability of such loans (Huang & Qiu, 2021), thus motivating banks to increase their off-balance sheet risk-taking. Therefore, we put forward the following hypothesis:

H2. : The digitalization of banks increases off-balance sheet risk-taking.

2.3. Bank digitalization's competition effect on on-balance sheet guarantees

The distortion of government implicit guarantee competition increases commercial banks' on-balance sheet risk-taking. Government implicit guarantee refers to a scenario where a specific economic entity obtains an implicit asset at a specific time based on the matching of government support attributes and the economic entity's attributes under a certain belief (Meng & Wang, 2023). The government tends to provide implicit guarantees to large commercial banks which are often seemed as "too big to fail," while small and medium-sized banks do not yet possess the public trust that large commercial banks gain through government credit (Lu & Xiao, 2008). Thus, small and medium-sized banks are often become a vulnerable group in guarantee competition. On the one hand, despite the existence of the deposit insurance system, the implicit guarantee will also weaken the constraint of the franchise value on the risk behavior of big banks (Li & Han, 2008), and give rise to the issue of moral hazard, as identified by Demirgüç-Kunt & Detragiache (2002). As the distortion of guarantee competition increases, banks that enjoy "high protection" will have more motivation to operate with low capital and bear high risks (Wilcox & Yasuda, 2019). On the other hand, Hakenes & Schnabel (2010) find that government guarantees are expected to increase the competitive advantage of banks under implicit government credit protection, and at the same time, they will heighten the incentive for smaller and medium-sized banks, operating under "low protection," to engage in risky behaviors through competitive distortions (Wu & Wang, 2021).

Bank digitalization can alleviate distortions in guarantee competition. Digital finance can effectively mitigate information asymmetry and reduce transaction costs in bank credit business, helping to overcome the negative effects of poor internal governance and challenging financing conditions that small and medium-sized banks may face (Wu, Xiang, & Liu, 2020). It also improves their advantages in customer acquisition and risk control (Wang, Huang, Gou, & Qiu, 2022; Wang & Liu, 2021). The digital transformation of banks can alleviate the difficulties in tracking and supervision caused by the lack of collateral and insufficient credit investigation of long-tail customers (Yu & Wu, 2021). It enhances the risk identification ability of small and medium-sized banks, making their credit decisions more scientific (Shu & Strassmann, 2005). As a result, they are more prone to securing government guarantees, thereby mitigating the distortions in guarantee competition. Thus, we put forward the following hypothesis:

H3. : The digitalization of banks will reduce on-balance sheet risk-taking by alleviating the distortion of interbank guarantee competition, which is manifested as the competition effect of on-balance sheet guarantees.

2.4. Bank digitalization's off-balance sheet price competition effect

With the advancement of digital transformation in banks, it has become increasingly common for banks to use digital technology to launch off-balance sheet business products, such as wealth management and interbank markets, to evade regulation (Luo, He, Liu, & Zhai, 2020; Sun & Ju, 2022). The competitive strategy of China's banking industry has gradually shifted from institutional expansion to homogeneous price competition (Gao & Xiang, 2020; Wagner, 2010). Many scholars have noted that banks are using digital innovation to introduce an increasing number of wealth management products, intensifying this price competition (Jia & Han, 2023; Yu, Zhang, & Peng, 2021). This is manifested by a rise in the proportion of wealth management products with market-oriented interest rates, suggesting a spontaneous marketization of interest rates and compressing bank profit margins (Huang, Guo, & Li, 2016; Sun & Ju, 2022). As technology companies deepen their cooperation with the banking industry, they also challenge the core business of commercial banks, further eroding their profit margins (Pramanik et al., 2019). Luo et al. (2020) found that in the wealth management product market, the lower-ranked 'loser' banks tend to increase the yield of wealth management products by a greater relative margin in the subsequent period, creating a price competition mechanism where 'losers' catch up with 'winners' and reducing bank marginal profits (Wagner, 2010). According to the bank's 'risk transfer hypothesis' (Dell'Ariccia, Laeven, & Suarez, 2017), banks may choose high-risk assets to offset losses and maintain profitability, thereby increasing the bank's moral hazard (Liu, 2016). Simultaneously, banks might lower their credit standards to maintain market share, increasing the moral hazard of wealth management product customers and consequently heightening the banks' off-balance sheet risk-taking (Guo & Shen, 2015; Marcus, 1984; Qiu et al., 2018). Based on this analysis, we put forward the following hypothesis:

H4. : The digitalization of banks intensifies the price competition of bank wealth management products, thereby increasing banks' off-balance sheet risk-taking, manifested as the off-balance sheet price competition effect.

3. Design of the empirical study

With constant changes in the external environment and advancements in technological means, the global banking industry is undergoing continuous upgrades and transitions into the digital banking era. Currently, in the academic world, various studies have proposed different definitions and generalizations regarding bank digitalization. We consolidate existing research pertaining to the digital transformation of banks and measure the level of digitalization in commercial banks across five dimensions to construct a digitalization index. This index captures how commercial banks use digital means for proactive risk control. In the empirical analysis, we include digitalization indexes both with and without risk constraints to compare their different impacts on banks' risk-taking.

3.1. Construction of the digitalization index of banks

We construct an objective and comprehensive measure of the digitalization level of Chinese commercial banks in this paper. This objective is achieved by comprehensively evaluating five key dimensions: product, technology, management, ecology, and risk control. Details of these five dimensions are as follows.

- (1) Digital Product: Guo & Shen (2015) describe digital finance as encompassing six dimensions: payment, credit, investment, monetary fund, insurance, and credit investigation. Du et al. (2021) define the digital transformation of banks as the ability of banks to reshape their business processes and enhance insight

into customer needs. This transformation is achieved by leveraging their resources and capabilities along with innovative digital technologies such as blockchain and artificial intelligence, thereby providing consumers with more digitized financial products and services. Thus this dimension encompasses both digital product and digital service.

- (2) **Digital Technology:** With the entry of Internet technology companies into the financial sector, traditional banks, which originally relied on offline manual methods of loan issuance, are also actively developing and applying artificial intelligence technology to improve their market competitiveness. This has led to a 'technological equipment race' among banks, typically characterized by technological development and digital transformation (Zhang, Lin, & Zhu, 2021). In recent years, commercial banks have integrated the application of big data, artificial intelligence, and blockchain, among others, to accurately identify customers' personalized needs and preferences. They have applied 5G, artificial intelligence, and other emerging technologies to build integrated online and offline customer service systems and innovate marketing and communication modes. Furthermore, they have utilized biometrics, intelligent machines (such as Virtual Teller Machines or VTM), and other technologies to enhance the service experience at their outlets. Key terms pertaining to digital technology encompass technical jargon from diverse fields, including big data, artificial intelligence, blockchain, cloud computing, biotechnology, and cloud architecture.
- (3) **Digital Management:** According to the theory of managerial attention, the establishment of management committees, departments, centers, or research institutes related to the digital economy and fintech can reflect, to a certain extent, the management's focus on digital transformation. With the empowerment of digital intelligence tools, enterprises can timely identify and address problems and risks that arise in a crisis, enabling them to adaptively reconfigure organizational management to avoid risks (Shan, Xu, Zhou, & Zhou, 2021). With the deepening application of financial technology, various banking institutions have expanded their financial technology initiatives, adjusting their organizational structures to continuously align with the primary direction of digital transformation needs. Therefore, this paper measures the digital management dimension based on whether a separate digitalization-related management committee, department, service center, or research institute has been established; whether executives have a professional background in digitalization; and whether an online approach is employed to develop employees' digital literacy.
- (4) **Digital Ecology:** China's banking sector is undergoing a transformation characterized by online integration, technological innovation, and openness (Wu et al., 2021). Leveraging their own technology and business capabilities, commercial banks provide financial, data, and technical services to their partners. They also collaborate with technology companies such as Huawei and Tencent, as well as universities and government enterprises. By connecting with third-party partners and integrating high-quality channel resources from various industries, they are creating a new banking industry format. Thus, this paper measures the digital ecological dimension from three perspectives: concepts related to bank digitalization, collaboration with third parties for digital transformation, and awards received by the bank in terms of digitalization.
- (5) **Digital Risk Control:** Commercial banks integrate big data information from enterprise operations, government management, social credit, and supply chains to build credit assessment models, thereby strengthening risk prevention and controlling risks before, during, and after loans. This integration marks a transition from 'human control' to 'numerical control' and 'intelligent control.' Additionally, commercial banks utilize technological

innovations such as audio, video, and biometrics to facilitate remote online loan applications, online credit granting, video credit analysis, and post-loan management. These innovations help address the challenge of credit assessment for small and micro-enterprises and serve the real economy. Therefore, the measurement of digital risk control includes products, technologies, and concepts involved, as well as collaborations and promotions related to digital risk control.

We constructed the thesaurus for the digitalization of commercial banks by drawing on the concept of active learning in InstructGPT (Ouyang et al., 2022) to train the deep learning model. This approach reduces the cost of manually acquiring data and improves the effectiveness of deep learning compared to traditional one-shot supervised learning. After several rounds of 'machine training - human screening,' we compiled a thesaurus containing 2674 words. Due to space limitations, we only select a portion of the representative keywords of bank digitalization for display, as shown in Table 1.

The specific construction process of the commercial bank digitalization index is as follows. First, we manually build an initial keyword set from the randomly selected annual reports of 149 Chinese commercial banks, spanning from 2011 to 2020. Second, after segmenting their annual reports using the Jieba Paddle tool, jointly developed by the Jieba open-source word segmentation tool and Baidu's deep learning platform, we use the Chinese version of the natural language processing model RoBERTa WWL. This model generates a word vector for each keyword, which is then transferred to a back-propagation (BP) neural network. We employ the error back-propagation method to train multiple classifiers, selecting only words that score above a specific threshold. Subsequently, we manually determine whether to include such words in the updated vocabulary set. Third, we repeat the aforementioned steps multiple times until the relevant indicators of the neural network converge. Lastly, using the entropy weight method, we reduce the dimensionality of the third-level indicators layer by layer to obtain first-level indicators. This process results in the digital innovation index for each dimension and the overall digital innovation of commercial banks. Table 2 demonstrates the weights of the risk-constrained digitized indicator system for commercial banks. For easy visualization, we extract the top 400 most frequent words from the total words using Python software. We then visualize the word cloud with word frequency determining the relative size of each word, as shown in Fig. 1.

Compared with existing studies, the digitalization index constructed in this paper has the following technological innovation points: Firstly, our approach utilizes a state-of-the-art natural language processing (NLP) model that demonstrates superior flexibility and comprehension in analyzing textual data. Unlike traditional word embedding methods such as bag-of-words, our model incorporates an attention mechanism within the RoBERTa language framework, enhancing its capability to grasp the contextual semantics of sentences (Liu et al., 2019). This refinement enables a nuanced interpretation of the lexicon associated with personalized digital economy products, such as 'financing-e-loan,' thereby ensuring a more precise analysis. This methodological advancement provides a robust foundation for accurately capturing the digitalization nuances in banking services. Secondly, the adoption of an innovative Active-Learning training regime, inspired by the Reinforcement Learning from Human Feedback (RLHF) approach as exemplified in InstructGPT (Ouyang et al., 2022), marks a significant improvement in training efficiency. This methodology leverages continual human feedback to refine the model's learning process, thereby reducing the necessity for extensive labeled datasets. Such an approach not only diminishes labeling costs but also enhances the model's training effectiveness, enabling it to achieve superior performance with a fraction of the dataset typically required for traditional supervised learning methods. This strategic incorporation of human-in-the-loop feedback mechanisms into the model's training process represents a forward-thinking adaptation to the evolving challenges of data-intensive

Table 1
Partial digitalization-related keywords for commercial banks.

Level 1 Indicator	Level 2 Indicator	Keywords
Product	Product	Online banking, digital banking, mobile banking, WeChat banking, air counters, intelligent investment advisors, internet wealth management, mobile terminals, mini-programs, online wealth management, mobile wealth management, online loans, mobile micro-loans, intelligent insurance, e-loans, financial e-cloud, cross-border e-remittance, Rong e-lian, e-Rong e-loan, APP, one card, settlement, Yinyi Tong, Huinong e-Tong
		Artificial intelligence, big data, cloud architecture, investment decision support system, image understanding, intelligent robot, intelligent customer service, machine learning, deep learning, natural language processing, semantic search, distributed computing, NFC, RPA, VTM, API, 5G, NLP, IaaS, PaaS, SaaS
Technology	Technology	e-banking department, digital finance department, Internet banking department, innovation laboratory, financial technology department, mobile finance department, technology innovation management committee, technology finance service center
		computer science, data science, statistics, mathematics
Management	Executive background	Online training, mobile college, online college, online university, mobile learning, online learning, data thinking, online finance college, online training, distance education, digital talent
		Intelligent, online, IT, command, digitalization, online, financial technology, Internet finance, technology finance, mobile finance, numerical control, machine control, Internet plus, intelligent control, data-driven, technology bank
	Employee training	Alipay, WeChat, Cloud Flash, universities, colleges, Baidu, Huawei, Tencent, Meituan, Ali
		Best Mobile Bank, China Financial Innovation Award, Bank Science and Technology Development Award, Outstanding Contribution Award for Scientific and Technological Innovation in Financial Industry, Top Ten Mobile Bank Innovation Award, Best Mobile Financial Bank, Best Internet Financial Products, Best Direct Bank, Outstanding Contribution Award for Financial Science and Technology Innovation, personal media, emerging media
Ecology	Cooperation	U-shield, key, interactive cipher, real-time authorization decision-making system, risk transaction monitoring system, risk early warning model
		Encryption, biometrics, face recognition, voice recognition, voiceprint recognition, fingerprint recognition, iris recognition, knowledge graph, behavioral data analysis platform, intelligent verification, intelligent credit, privacy computing, multi-party security computing, big data risk control model, application scoring model, quantitative risk control model
Risk Control	Award	Risk control digitalization, intelligent risk control, risk prevention, and control information platform
		UnionPay authentication, smart finance contracts
	Cooperation	Best Mobile Banking Security Award

Note: This table reports the main keywords for digital innovation of various dimensions of commercial banks. The first-level indicators are the five

dimensions of digital innovation: product, technology, management, ecology, and risk control. The second-level indicators are breakdowns based on their characteristics. The third-level indicators are keywords about digital innovation in the annual reports of commercial banks. The construction of digital innovation indexes of commercial banks is based on the text analysis of commercial banks' annual reports from 2011 to 2020.

Table 2
Commercial Banks' Risk-Constrained Digitized Indicator System Weights.

Level 1 Indicator	Level 1 Indicator Weights	Level 2 Indicator	Level 2 Indicator Weights
Product	21.71%	Product	100.00%
		Technology	100.00%
Technology	18.66%	Management	34.22%
		Executive	35.55%
Management	17.86%	Background	30.23%
		Staff Training	22.27%
Ecology	26.58%	Concept	19.03%
		Cooperation	59.14%
Risk Control	15.18%	Advocacy	21.07%
		Risk Control	10.84%
		Product	8.46%
		Risk Control	48.23%
		Concept	11.39%
		Cooperation	
		Risk Control	
		Advocacy	

research domains. Thirdly, our selection of the index aggregation method, specifically the entropy weighting method, stands as a methodologically sound choice that underscores the rigor of our analytical framework. Unlike subjective weighting methods, the entropy weighting method objectively quantifies the information content of different variables, therefore providing a more precise and insightful representation of the system's characteristics (Li, Shang, & Ji, 2008). These methodological enhancements collectively contribute to the development of a robust bank digitalization index, positioning this study at the forefront of research in the intersection of banking and digital technology.

3.2. Model setting

In this paper, we establish a two-way fixed-effects model following the work of Wang et al. (2021), Jiang (2022), and Zhai et al. (2023). This model controls for both the bank's fixed effect and the year fixed effect. For hypotheses 1 and 2, we have the model regression equations as follows.

$$Nplr_{it} = \beta_0 + \beta_1 Digital_{it} + \beta_2 Bank_C_{it} + \beta_3 Macro_C_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

$$Rwar_{it} = \beta_0 + \beta_1 Digital_{it} + \beta_2 Bank_C_{it} + \beta_3 Macro_C_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (2)$$

where t and i denote the year and the bank, respectively. $Nplr_{it}$ and $Rwar_{it}$ are bank risk-taking variables that serve as measures of on-balance sheet and off-balance sheet risks taken by bank i at time t , respectively. $Digital_{it}$ is digitalization level of bank i at time t , including risk-constrained digitalization (with risk control) and non-risk-constrained digitalization (without risk control) in the empirical work. $Bank_C_{it}$ and $Macro_C_{it}$ are control variables containing the financial characteristics of bank i at time t and the macroeconomic development level of the region to which bank i belongs at time t , respectively. ν_t and μ_i are the year fixed effect and the individual fixed effect, respectively. The random error term is ε_{it} . We use bank clustering robust standard errors for estimation, where robust standard errors control for heteroskedasticity and bank clustering controls for correlation of observations



Fig. 1. Word Cloud of Risk-Constrained Digital Indicators for Commercial Banks.

pertaining to the same bank across different years.

To investigate the impact of bank digitalization on its risk-taking behavior and explore the underlying mechanisms of action, as outlined in hypotheses 3 and 4, we establish the model regression equations as follows.

$$Ggcd_{it} = \beta_0 + \beta_1 Digital_{it} + \beta_2 Bank_C_{it} + \beta_3 Macro_C_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (3)$$

$$Wmpr_{it} = \beta_0 + \beta_1 Digital_{it} + \beta_2 Bank_C_{it} + \beta_3 Macro_C_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (4)$$

$Ggcd_{it}$ and $Wmpr_{it}$ are mediating variables measuring the distortion of guaranteed competition and the upper limit of the expected return on bank financial products, respectively. $Digital_{it}$ is digitalization level of bank i at time t , including risk-constrained digitalization and non-risk-constrained digitalization in the empirical work. $Bank_C_{it}$ and $Macro_C_{it}$ are control variables containing the financial characteristics of bank i at time t and the macroeconomic development level of the region to which the bank i belongs at time t , respectively.

3.3. Variable description

3.3.1. Bank risk-taking

Existing literature often adopts only one variable in general when measuring bank risk-taking. However, bank risk-taking can be categorized and measured according to different dimensions, such as on-balance sheet, off-balance sheet, and ex-ante and ex-post (Dai & Tao, 2016; Fang, 2015; Gu & Yu, 2019). Following the approaches of Chen, Wang, and Yang (2018) and Li & Tian (2020), we use the non-performing loan ratio $Nplr_{it}$ as a proxy for banks' on-balance sheet risk. This ratio characterizes a bank's occurrence of loan defaults in the course of its operations. The risk-weighted asset ratio $Rwar_{it}$, commonly utilized to gauge the proportion of banks' high-risk-grade assets relative to their total assets, captures not merely the risk associated with on-balance sheet activities but also that of off-balance sheet activities. If the coefficient before on-balance sheet risk ($Nplr_{it}$) is opposite to the coefficient before total risk ($Rwar_{it}$), it can be inferred that the difference in these coefficients is caused by off-balance sheet risk. That is, if digitalization presents a negative coefficient with respect to on-balance sheet risk but a positive one for overall risk, it indicates that digitalization predominantly exerts a positive effect on off-balance sheet risk. Therefore, we employ the risk-weighted asset ratio $Rwar_{it}$ to investigate banks' off-balance sheet risk-taking.

3.3.2. Distortion of government guarantee competition

Consistent with [Gropp, Hakenes, and Schnabel \(2011\)](#) and [Wang, Wu, & Chen \(2016\)](#), we utilize $Ggcd_{it}$ to portray the distorted degree of competition created by different degrees of government guarantee

behavior towards banks other than bank i (i.e., banks competing with bank i).

$$Ggcd_{it} = \sum_{k \neq i}^N P_{im_{kt}} \frac{Asset_{kt}}{Asset_t} \quad (5)$$

where $Asset_{kt}$ is the total assets of bank k ($k \neq i$) in year t , and $Asset_t$ is the sum of the total assets of all banks in the sample except bank i in year t . P_im_{kt} is computed as the probability value of the government guarantees assigned to the deposit size of all banks in the sample from smallest to largest before grouping them in year t , as shown in Table 3. According to Meng & Wang (2023), the distortion of government guarantee competition used in this paper has two advantages. First, the guarantees examined exist in the lending relationships between banks and their broader types of creditors. Second, it is suitable for portraying the distortion of guarantee competition among large banks relative to small and medium-sized banks, which is the concern of this paper.

3.3.3. Control variables

Drawing inspiration from the studies conducted by [Dell'Ariccia et al. \(2017\)](#), [Guo & Shen \(2019\)](#), and [Li & Tian \(2020\)](#), we have selected control variables that may impact bank efficiency from two dimensions: bank financial characteristics and macroeconomic development. Bank financial characteristics include the deposit-to-loan ratio, capital adequacy ratio, return on equity, net profit, owner's equity, and the number of employees. Specifically, the deposit-to-loan ratio is calculated by dividing the bank's total loans by its total deposits. The capital adequacy ratio is determined by dividing total capital, minus the corresponding capital deductions, by risk-weighted assets. The return on equity is calculated by comparing net profit to average shareholders' equity. The net profit, owner's equity, and the number of employees are all represented in logarithmic forms for regression. Macroeconomic variables include the share of the secondary industry, fiscal expenditure, and the GDP growth rate of the region where the bank is located. Given that national commercial banks, including large commercial banks and joint-stock commercial banks, have branches situated in numerous cities, we calculate the values of macroeconomic variables by applying a weighted ratio based on the number of branches these banks have in each province.

3.3.4. Data sources and descriptive statistics

We have taken 149 Chinese commercial banks from 2011 to 2020 as the sample. Due to the differences in the time of establishment and the degree of information disclosure of each bank, the sample constitutes an unbalanced panel from 2011 to 2020. The bank data is obtained from annual reports of banks, the Wind database, and the China Financial

Table 3

Explanation of the Probability Assignment of Implicit Government Guarantees.

Bank Deposit Size Range	$[d_{0\%}, d_{20\%})$	$[d_{20\%}, d_{40\%})$	$[d_{40\%}, d_{60\%})$	$[d_{60\%}, d_{80\%})$	$[d_{80\%}, d_{100\%}]$
P_im_{kt}	0	0.25	0.50	0.75	1

Yearbook. The macro data is obtained from the China City Statistical Yearbook. The definitions and summary statistics of variables are reported in Table 4.

4. Empirical results analysis

4.1. Impact of banks' digitalization on their risk-taking

Table 5 reports the results of the benchmark regression of the risk-constrained digitalization index on the NPL ratio. It includes results without any control variables and fixed effects in column (1), with control variables but without fixed effects in column (2), with control variables and 'city-year' fixed effects in column (3), and with control variables and 'individual-year' fixed effects in column (4), respectively. The coefficients of the risk-constrained digitalization index are all significantly negative at the 1% level, validating H1. This finding aligns with the existing literature, which suggests that commercial banks' use of fintech innovations to empower their business can effectively address the pain points in credit risk management (Yuan, 2018). It reduces risk concentration and lowers management costs through resource allocation effects (Lee, Yang, & Kim, 2019), which in turn increases the value of banks' franchises (Demsetz, Saidenberg, & Strahan, 1996; Marcus, 1984). This eases banks' risk-shifting incentives (Repullo & Suarez, 2004), thereby reducing their risk-taking.

Table 6 reports the results of the benchmark regressions of the risk-constrained digitalization index on the risk-weighted asset ratios. The results are shown without any control variables and fixed effects in column (1), with control variables but without fixed effects in column (2), with control variables and 'city-year' fixed effects in column (3), and with control variables and 'individual-year' fixed effects in column (4), respectively. The coefficients of the risk-constrained digitalization index are all significantly positive at the 1% level, validating H2. Commercial banks' off-balance sheet business increases banks' off-balance sheet risk through maturity mismatches, liquidity conversions, credit risk transfers, or guarantees (Hsu & Moroz, 2009; Gorton, Metrick, Shleifer, & Tarullo, 2010; Plantin, 2015; Sun & Ju, 2022). Digital technology lowers transaction thresholds (Banna & Alam, 2021) and increases tail risk (Dong et al., 2023; Xie & Wang, 2022). It also expands shadow banking in China (Buchak et al., 2018). Existing regulatory policies are not yet able to comprehensively regulate off-balance sheet businesses (Chen et al., 2021), exposing new risk exposures (Chen et al., 2018), increasing the problem of risk contagion (Cabral, 2013), and thus raising

Table 4

Definition of Variables and Summary Statistics.

Variables	Definition	Obs	Mean	Std	Min	Max
Dependent Variable	NPL Ratio	1101	0.016	0.015	0	0.284
	Risk-weighted Asset Ratio	1101	0.641	0.134	0.011	0.971
Key Independent Variable	Risk-constrained Digitalization Index	1101	0.15	0.187	0	1.089
	Non-risk-constrained Digitalization Index	1101	0.168	0.167	0	0.979
Intermediary Variable	Distortion of Competition on Guarantees	1101	0.952	0.025	0.789	0.967
	Expected Rate of Return Ceiling for Financial Products	1101	4.679	0.721	3.002	17.000
	Deposit-to-loan Ratio	1101	0.665	0.128	0.038	1.234
	Capital Adequacy Ratio	1101	0.133	0.024	-0.111	0.302
	Net Profit (billions of yuan) in Logarithms	1101	2.681	1.677	-0.945	8.064
	Return on Equity (%)	1101	13.406	5.599	-5.31	32.7
	Owner's Equity (billions of yuan) in Logarithms	1101	2.578	1.581	-0.119	8.008
	Number of Employees in Logarithms	1101	8.037	1.457	4.06	13.129
Control Variable	Proportion of Regional Secondary Industry (%)	1101	3.823	0.211	2.762	4.492
	Regional Financial Expenditures (millions of yuan) in Logarithms	1101	6.481	1.117	4.148	9.395
	Regional GDP Growth Rate (%)	1101	2.008	0.541	-2.996	3.176

Table 5

Impact of commercial bank digitalization on banks' on-balance sheet risk-taking.

Variables	NPL Ratio (on-balance sheet exposure)			
	OLS	OLS	FE	FE
	(1)	(2)	(3)	(4)
Risk-constrained Digitalization Index	-0.027*** (0.008)	-0.051*** (0.015)	-0.053*** (0.015)	-0.057*** (0.015)
Deposit-to-loan Ratio		0.014*** (0.004)	0.006 (0.005)	0.016*** (0.005)
Capital Adequacy Ratio		-0.085*** (0.023)	-0.063** (0.026)	-0.046* (0.025)
Net Profit		-0.000 (0.001)	-0.001 (0.001)	-0.000 (0.001)
Return on Net Assets		-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Equity		0.003* (0.002)	0.003* (0.001)	0.001 (0.002)
Number of Employees		-0.003 (0.002)	-0.004*** (0.001)	-0.003 (0.003)
Proportion of Regional Secondary Industry		-0.001 (0.005)	0.000 (0.006)	0.003 (0.006)
Regional Financial Expenditures		-0.001 (0.002)	-0.006 (0.004)	-0.008* (0.004)
Regional GDP Growth Rate		0.001 (0.001)	-0.000 (0.001)	0.000 (0.001)
Controls	NO	YES	YES	YES
Year_FE	NO	NO	YES	YES
City_FE	NO	NO	YES	NO
Bank_FE	NO	NO	NO	YES
N	1033	691	691	691
r2	0.001	0.150	0.565	0.666

Note: *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively, with bank clustering robust standard errors in parentheses. The same notes are for Table 6 to Table 11.

off-balance sheet risk-taking.

4.2. Mechanisms of bank digitalization on risk-taking

Table 7 reports the regression outcomes for the risk-constrained

Table 6

The impact of commercial bank digitalization on banks' off-balance sheet risk-taking.

Variables	Risk-weighted Asset Ratio (off-balance sheet risk)			
	OLS	OLS	FE	FE
	(1)	(2)	(3)	(4)
Risk-constrained Digitalization Index	0.634*** (0.076)	0.336*** (0.130)	0.401*** (0.136)	0.576*** (0.144)
Deposit-to-loan Ratio		0.230*** (0.038)	0.249*** (0.042)	0.214*** (0.045)
Capital Adequacy Ratio		−1.178*** (0.185)	−0.839*** (0.211)	−1.140*** (0.216)
Net Profit		−0.061*** (0.009)	−0.052*** (0.010)	−0.060*** (0.010)
Return on Net Assets		−0.000 (0.001)	0.000 (0.001)	0.001 (0.001)
Equity		0.081*** (0.012)	0.085*** (0.013)	0.100*** (0.019)
Number of Employees		0.008 (0.013)	−0.006 (0.013)	−0.025 (0.024)
Proportion of Regional Secondary Industry		0.059* (0.033)	0.036 (0.056)	0.056 (0.055)
Regional Financial Expenditures		−0.028*** (0.011)	−0.053 (0.040)	−0.039 (0.038)
Regional GDP Growth Rate			0.007 (0.008)	0.005 (0.010)
Controls	NO	YES	YES	YES
Year_FE	NO	NO	YES	YES
City_FE	NO	NO	YES	NO
Bank_FE	NO	NO	NO	YES
N	1062	717	717	717
r2	0.010	0.280	0.605	0.670

commercial bank digitalization index and the non-risk-constrained commercial bank digitalization index, assessing their respective impacts on on-balance sheet risk (NPL ratios) and distortion in competition caused by government guarantee. All regressions were conducted using a two-way fixed-effects model, controlling for individual-vintage variations. The negative coefficients of distortion variables indicate that the digitalization of banks effectively mitigates on-balance sheet risk-taking behaviors by attenuating distortions in inter-bank competition. When the core explanatory variables are substituted with the non-risk-constrained bank digitalization index, these variables continue to satisfy the 1% significance level criterion. Furthermore, the regression coefficients of the mediating variable, namely the competition distortion, are also significantly negative at the 5% level. Such evidence robustly supports the existence of a substantive on-balance sheet competition effect of government guarantee, thereby empirically validating Hypothesis 3.

The application of digital risk control tools is anticipated to significantly enhance the capital allocation efficiency and risk management capabilities of small and medium-sized banks (Deng, Lv, Liu, & Zhao, 2021; Huang & Qiu, 2021; Wang et al., 2022; Hu, Schclarek, Xu, & Yan, 2022). This, in turn, increases their likelihood of obtaining government guarantees and alleviates distortions in guarantee competition. As the distortion in guarantee competition diminishes, banks with 'high protection' are expected to see a reduction in their risk-taking motivations associated with low capital operations (Wilcox & Yasuda, 2019). Similarly, the incentive for 'low protection' small and medium-sized banks to engage in high-risk, high-return activities is also likely to decrease (Wu & Wang, 2021).

A comparative analysis of the regression coefficients for the intermediary variables in columns (2) and (4) reveals that the implementation of digitalization in banks, particularly when incorporating digital risk control tools, exhibits a markedly greater efficacy in moderating guarantee competition than indices based on non-risk-constrained

Table 7

Competitive effects of digitized on-balance sheet guarantees in commercial banks.

Variables	NPL Ratio	Distortion in Competition by Guarantees	NPL Ratio	Distortion in Competition by Guarantees
	(1)	(2)	(3)	(4)
Risk-constrained Digitalization Index	−0.057*** (0.015)	−0.003*** (0.001)		
Non-risk-constrained digitalization index			−0.023*** (0.007)	−0.001** (0.000)
Deposit-to-loan Ratio	0.016*** (0.005)	0.001** (0.000)	0.016*** (0.005)	0.001** (0.000)
Capital Adequacy Ratio	−0.046* (0.025)	0.002 (0.001)	−0.048* (0.026)	0.002 (0.001)
Net Profit	−0.000 (0.001)	−0.000** (0.000)	−0.000 (0.001)	−0.000** (0.000)
Return on Net Assets	−0.001*** (0.000)	−0.000 (0.000)	−0.001*** (0.000)	−0.000 (0.000)
Equity	0.001 (0.002)	−0.000* (0.000)	0.001 (0.002)	−0.000* (0.000)
Number of Employees	−0.003 (0.003)	−0.000 (0.000)	−0.003 (0.003)	−0.000 (0.000)
Proportion of Regional Secondary Industry	0.003 (0.006)	0.000 (0.001)	0.004 (0.006)	0.000 (0.001)
Regional Financial Expenditures	−0.008* (0.004)	−0.000* (0.000)	−0.008* (0.004)	−0.000* (0.000)
Regional GDP Growth Rate	0.000 (0.001)	−0.000 (0.000)	0.000 (0.001)	−0.000 (0.000)
Controls	YES	YES	YES	YES
Year_FE	YES	YES	YES	YES
Bank_FE	YES	YES	YES	YES
N	691.000	476.000	691.000	476.000
r2	0.666	0.998	0.665	0.998

digitalization. This enhanced effectiveness is likely due to the substantial superiority of big data risk control models in information processing compared to conventional risk control models (Frost, Gambacorta, Huang, Shin, & Zbinden, 2019). These advanced models more efficiently identify borrowers with a higher propensity for repayment and forecast defaults with greater accuracy. Moreover, the integration of artificial intelligence and cloud computing technologies notably amplifies the banks' capabilities in swiftly and effectively managing risks (Hau, Huang, Shan, & Sheng, 2019).

Table 8 reports the effects of both risk-constrained and non-risk-constrained commercial bank digitalization indices on off-balance sheet risk (measured as the ratio of risk-weighted assets) as well as the upper limit of expected returns for wealth management products, using the two-way fixed effects model. These results indicate a significant positive correlation with the upper limit of expected returns, suggesting that bank digitalization may increase off-balance sheet risk-taking by elevating the expected return ceiling of wealth management products, thereby creating an off-balance sheet price competition effect, validating Hypothesis 4.

As banks deepen their digital transformation, an increasing number

Table 8

The off-balance sheet price competition effect of commercial bank digitalization.

Variables	Risk-weighted Asset Ratio	Expected Rate of Return Ceiling	Risk-weighted Asset Ratio	Expected Rate of Return Ceiling
	(1)	(2)	(3)	(4)
Risk-constrained Digitalization Index	0.576*** (0.144)	2.489*** (0.862)		
Non-risk- constrained digitalization index			0.199*** (0.064)	0.656* (0.376)
Deposit-to-loan Ratio	0.214*** (0.045)	0.050 (0.299)	0.220*** (0.045)	0.092 (0.301)
Capital Adequacy Ratio	-1.140*** (0.216)	1.014 (1.427)	-1.123*** (0.218)	1.026 (1.438)
Net Profit	-0.060*** (0.010)	-0.010 (0.063)	-0.059*** (0.010)	-0.001 (0.063)
Return on Net Assets	0.001 (0.001)	-0.004 (0.007)	0.001 (0.001)	-0.004 (0.007)
Equity	0.100*** (0.019)	-0.018 (0.117)	0.098*** (0.019)	-0.016 (0.118)
Number of Employees	-0.025 (0.024)	-0.381** (0.154)	-0.022 (0.024)	-0.364** (0.155)
Proportion of Regional Secondary Industry	0.056 (0.055)	-0.837** (0.338)	0.049 (0.055)	-0.855** (0.340)
Regional Financial Expenditures	-0.039 (0.038)	0.181 (0.241)	-0.043 (0.039)	0.153 (0.242)
Regional GDP Growth Rate	0.005 (0.010)	0.091 (0.063)	0.005 (0.010)	0.090 (0.064)
Controls	YES	YES	YES	YES
Year_FE	YES	YES	YES	YES
Bank_FE	YES	YES	YES	YES
N	717.000	579.000	717.000	579.000
r2	0.670	0.784	0.666	0.782

are utilizing digital means to launch off-balance sheet products like wealth management for regulatory arbitrage (Luo et al., 2020; Sun & Ju, 2022). This trend leads to intensified homogenized price competition in wealth management products (Jia & Han, 2023; Wagner, 2010; Yu et al., 2021), consequently compressing banks' profit margins (Huang et al., 2016; Pramanik et al., 2019; Sun & Ju, 2022). According to the 'Risk Transfer Hypothesis' (Dell'Ariccia et al., 2017), banks may choose to invest in high-risk assets as a means to offset losses and maintain profitability, thereby increasing moral hazard (Liu, 2016). Simultaneously, to maintain market share, banks might lower credit standards, elevating the moral hazard of wealth management product clients and further increasing off-balance sheet risk exposure (Guo & Shen, 2015; Marcus, 1984; Qiu et al., 2018).

Comparing the regression coefficients of the mediating variables in columns (2) and (4), it is observed that bank digitalization integrating the digital risk control dimension has a more pronounced effect in fostering off-balance sheet price competition compared to the non-risk-constrained digitalization index. This observation might be explained by the dual impact of digital finance on commercial banks. While digital finance enhances operational efficiency, it also potentially causes banks to overestimate their ability to manage risk losses. This overestimation can foster a sense of 'overconfidence' within banks, potentially veering

towards excessive profit-chasing activities (Gu & Yang, 2018; Liu, 2016). Such a dynamic aggravates the competitive pricing behavior in the wealth product market, particularly evident in the 'loser's race to catch up with winners' scenario (Luo et al., 2020). Consequently, banks may show a greater propensity for engaging in riskier ventures (Jiang & Chen, 2012), leading to an increase in their off-balance sheet risk-taking.

5. Extended research

5.1. The impact of wealth management products

Banks, leveraging digital innovation, have diversified the types and quantities of wealth management products (Jia & Han, 2023). The increased reliance of banks on these products has contributed to an increase in the overall availability of wealth management products in the market, intensifying competition in the banking wealth management market (Yu et al., 2021). This market competition affects banks' risk-taking levels through risk transfer effects (Marcus, 1984) and franchise value effects (Boyd & De Nicolo, 2005). Deng, Zhou, & Tang (2015) identified the extensive holdings of off-balance sheet activities, such as wealth management, as a micro-cause of this phenomenon, arguing that their massive expansion leads to excessive risk concentration. This risk rapidly accumulates within the banking system and gradually forms systemic risk through the complex interrelationships among financial institutions (Buchak et al., 2018; Cabral, 2013).

Minsky's (1982) "Financial Instability Hypothesis" suggests that banks engage in raising funds through short-term capital markets to reinvest in long-term assets. This maturity mismatch escalates the risk exposure for depositors (Diamond & Dybvig, 1983). In the realm of shadow banking, the credit intermediation chain amplifies banks' risk-bearing through mechanisms such as liquidity transformation, maturity mismatch, and credit risk transfer (Gennaioli et al., 2013; Plantin, 2015). Specifically in China, shadow banking predominantly relies on wealth management products issued by banks, with a focus on short-term products (under one year). However, these funds are primarily channeled into long-term assets, creating a severe maturity mismatch. This mismatch intensifies banks' reliance on interbank markets, thereby augmenting liquidity risks. The diverse features of commercial banks concerning the quantity and maturity structure of wealth management products result in varying impacts of digitalization on their off-balance sheet risk-taking.

This study segments the sample based on the average maturity period of wealth management products handled by banks in a specific year. The banks are categorized into two distinct groups: those with shorter average maturities and those with longer ones. Table 9 delineates the regression analysis of the risk-constrained digitalization index for each group against the ratio of risk-weighted assets. It indicates that banks with a longer average maturity of wealth management products exhibit a more pronounced influence of digitalization on off-balance sheet risk-taking. This effect might be attributed to the enhanced maturity mismatch between investors and borrowers due to digitalization in banks with longer average maturity wealth management products, thereby escalating liquidity risks (Moreira & Savov, 2017; Li & Shen, 2019). Moreover, the lag in traditional regulatory mechanisms in adapting to the rapid financial innovations brought about by digital technologies results in regulatory voids (Liu, Jiang, & Wang, 2021), which in turn expands the banks' exposure to off-balance sheet risks (Sun, Wang, & Wang, 2020).

5.2. Robustness tests

To guarantee the robustness and credibility of our empirical findings, this study adopts a dual-pronged approach involving the modification of the econometric model and an adjustment in the methodology for measuring the core explanatory variable.

Firstly, drawing upon the methodologies of Wang et al. (2021) and

Table 9
Analysis of heterogeneity in average maturities of wealth management products.

Variables	Risk-weighted Asset Ratio	
	Shorter Average Maturities	Longer Average Maturities
	(1)	(2)
Risk-constrained Digitalization Index	0.118* (0.061)	0.200** (0.101)
Deposit-to-loan Ratio	0.158*** (0.059)	0.294*** (0.089)
Capital Adequacy Ratio	−0.810*** (0.242)	−2.355*** (0.502)
Net Profit	−0.019 (0.012)	−0.132*** (0.023)
Return on Net Assets	−0.003** (0.001)	0.004 (0.003)
Equity	0.065*** (0.019)	0.273*** (0.047)
Number of Employees	−0.034 (0.030)	−0.032 (0.053)
Proportion of Regional Secondary Industry	0.069 (0.080)	0.004 (0.117)
Regional Financial Expenditures	−0.092* (0.049)	−0.036 (0.086)
Regional GDP Growth Rate	−0.007 (0.013)	0.021 (0.021)
Controls	YES	YES
Year_FE	YES	YES
Bank_FE	YES	YES
N	433	284
r2	0.766	0.762

Blundell & Bond (1998), this research reapplies the two-step system GMM technique to recalibrate the model, thereby addressing potential endogeneity concerns. The *P*-values for the AR(2) test and Hansen’s test both exceed 0.1, satisfying the necessary conditions for the absence of second-order autocorrelation in the residuals and the exogeneity of the instrumental variables as stipulated by the two-step system GMM model. The coefficients of the lagged dependent variables are significantly positive at a 1% significance level, illustrating temporal continuity in banking risks. Additionally, the digitalization indices demonstrate a significant negative correlation with the non-performing loan ratio and a positive correlation with the proportion of risk-weighted assets, both at the 1% significance level. These correlations further corroborate the stability of the primary estimation results. Detailed regression findings are documented in Table 10.

Secondly, the methodology for aggregating the key explanatory variable, specifically the digitalization index, was revised. This study utilized the coefficient of variation approach to construct both the risk-constrained and the non-risk-constrained digitalization indices. Following this adjustment, the analysis was re-conducted by utilizing the two-step system GMM method. The *P*-values obtained for the AR(2) test and the Hansen test adhered to the required standards, confirming the robustness of our findings. The correlation coefficients aligned with those presented in the earlier sections of the study, further affirming the stability and reliability of the results. These revised regression outcomes are detailed in Table 11.

6. Conclusions and policy recommendations

Utilizing the annual reports of 149 Chinese commercial banks from 2011 to 2020, this paper constructs a multidimensional bank digitalization index using deep learning-based NLP techniques to investigate its impact on bank risk-taking. Key findings of our research are summarized as follows: (1) Digitalization within banks demonstrably mitigates risk-taking associated with on-balance sheet activities while significantly fostering risk-taking in off-balance sheet operations. (2) The advancement in digitalization within banks has been found to reduce the distortions caused by government-backed guarantee competitions. This

Table 10
Robustness test of changing econometric models.

Variables	NPL Ratio		Risk-weighted Asset Ratio	
	(1)	(2)	(3)	(4)
L.NPL Ratio	0.340*** (0.046)	0.335*** (0.017)		
L.Risk-weighted Asset Ratio			0.340*** (0.019)	0.386*** −0.037
Risk-constrained Digitalization Index	−0.502*** (0.103)		0.026** (0.053)	
Non-risk-constrained Digitalization Index		−0.303*** (0.022)		0.351*** (0.078)
Deposit-to-loan Ratio	0.173*** (0.058)	0.043** (0.023)	0.017 (0.023)	0.089* (0.047)
Capital Adequacy Ratio	−1.386*** (0.194)	−0.079 (0.092)	−0.040 (0.089)	−1.711*** (0.233)
Net Profit	−0.063*** (0.007)	−0.016*** (0.002)	−0.018 (0.043)	−0.063*** (0.006)
Return on Net Assets	0.004 (0.008)	−0.006 (0.006)	−0.006 (0.006)	0.002 (0.008)
Equity	0.128*** (0.015)	−0.004** (0.001)	−0.060 (0.095)	0.113*** (0.016)
Number of Employees	0.002 (0.003)	0.007* (0.002)	−0.064*** (0.019)	−0.070** (0.025)
Proportion of Regional Secondary Industry	−0.061 (0.075)	−0.042** (0.019)	−0.045*** (0.015)	−0.031 (0.073)
Regional Financial Expenditures	−0.044 (0.031)	−0.0183 (0.020)	−0.027 (0.020)	0.018 (0.037)
Regional GDP Growth Rate	0.007 (0.007)	0.099** (0.034)	0.011*** (0.003)	0.011 (0.007)
Observations	605	605	638	638
N_bank	115	115	116	116
Year_FE	Yes	Yes	Yes	Yes
Bank_FE	Yes	Yes	Yes	Yes
AR(1)-Pvalue	0.019	0.012	0.000	0.000
AR(2)-Pvalue	0.787	0.865	0.714	0.606
Hansen-Pvalue	1.000	1.000	1.000	1.000

phenomenon is referred to as the on-balance sheet guarantee competition effect. (3) Enhanced digitalization in banking elevates the upper limit of expected returns on wealth management products, which intensifies the price competition for these products, subsequently increasing the banks’ off-balance sheet risk-taking. This dynamic is identified as the off-balance sheet price competition effect. (4) Furthermore, digitalization exerts a more substantial influence on increasing off-balance sheet risk-taking for banks whose wealth management products have longer average maturities.

Building upon the derived conclusions, the policy insights of this paper are summarized as follows: (1) While digital technology adoption in banks has effectively lowered on-balance sheet risk, it is imperative to simultaneously concentrate on the surveillance and management of off-balance sheet risk exposures. The adoption of cutting-edge digital technologies can lead to more sophisticated and intelligent risk management practices. To this end, banks should integrate these technologies not only to streamline their operations but also to enhance their risk assessment models, enabling early detection of potential off-balance sheet risks and facilitating more dynamic risk management strategies. (2) In an increasingly competitive banking sector, banks should strive for differentiation in their competitive strategies. This entails moderating competition over the yields of wealth management products and focusing on augmenting their profitability through innovative services and product offerings that leverage digital technologies. Banks should explore the development of digital-only products that cater to the evolving needs of consumers. (3) Regulators should enhance the surveillance of the magnitude and composition of banks’ off-balance sheet

Table 11

Robustness test of the replacement econometric model and core explanatory variables measures.

Variables	NPL Ratios		Risk-weighted Asset Ratio	
	(1)	(2)	(3)	(4)
L.NPL Ratio	0.337*** (0.020)	0.335*** (0.015)		
L.Risk-weighted Asset Ratio			0.272*** (0.053)	0.311*** (0.057)
Risk-constrained Digitalization Index (Coefficient of Variation Method)	−0.377*** (0.015)		0.121*** (0.032)	
Non-risk-constrained Digitalization Index (Coefficient of Variation Method)		−0.288** (0.124)		0.181*** (0.049)
Deposit-to-loan Ratio	−0.102 (0.272)	0.058 (0.250)	0.167*** (0.059)	0.171*** (0.058)
Capital Adequacy Ratio	−0.200 (0.888)	−0.675 (0.795)	−1.765*** (0.168)	−1.721*** (0.235)
Net Profit	−0.343 (0.360)	−0.174 (0.260)	−0.067*** (0.006)	−0.065*** (0.007)
Return on Net Assets	−0.063*** (0.007)	−0.057*** (0.006)	0.039 (0.080)	0.040 (0.070)
Equity	−0.002 (0.007)	0.001 (0.009)	0.107*** (0.016)	0.108*** (0.017)
Number of Employees	0.006*** (0.002)	0.006*** (0.002)	0.037 (0.026)	0.031 (0.037)
Proportion of Regional Secondary Industry	0.003 (0.002)	0.003* (0.002)	0.059 (0.057)	−0.039 (0.071)
Regional Financial Expenditures	−0.001 (0.002)	−0.002 (0.002)	0.002 (0.026)	0.004 (0.033)
Regional GDP Growth Rate	0.010*** (0.003)	0.010*** (0.003)	0.002 (0.007)	0.006 (0.007)
Observations	605	605	638	638
N_bank	115	115	116	116
Year_FE	Yes	Yes	Yes	Yes
Bank_FE	Yes	Yes	Yes	Yes
AR(1)-Pvalue	0.012	0.012	0.001	0.002
AR(2)-Pvalue	0.878	0.889	0.769	0.804
Hansen Pvalue	1.000	1.000	1.000	1.000

operations and improve the transparency and disclosure norms for wealth management products, thereby facilitating investor access to comprehensive product information and aiding in the objective identification of product risks. Furthermore, regulatory frameworks should be adapted to keep pace with the rapid advancements in digital technologies, ensuring that they address new forms of financial risk and provide clear guidelines for the ethical use of technology in financial services. This includes establishing standards for data privacy, security, and the responsible use of AI and machine learning algorithms in decision-making processes.

Data availability

Data will be made available on request.

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