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The Heterogeneity of Financing Efficiency for Small and Medium-sized Enterprises in the Context of Digital Finance

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Abstract. This article examines the heterogeneity of small and medium-sized enterprise (SME) financing in the context of digital finance, based on the state of SME financing in China at the moment. Using the Super-Efficiency Data Envelopment Analysis (DEA) model, 3,000 Chinese businesses' data was assessed between 2014 and 2020.This paper uses dual machine learning models to explore the causal effect of digital transformation on financing efficiency. Later, the method of fractional regression is used to analyze the heterogeneity of enterprise financing. The results showed. The impact of digital finance on corporate financing costs is more pronounced in eastern China and higher Environmental, Social and Governance (ESG) ratings. The paper concludes that whether the impact of digital transformation on enterprise financing efficiency is positive depends on the combined effect of internal and external factors of enterprises. When the internal factors of the enterprise can be recognized by the market and the external can give the enterprise a good financial environment, the role of digital transformation in the financing efficiency of the enterprise will be greatly exerted.

Keywords: Digital finance, small and medium-sized enterprise, super-efficiency DEA model.

1. Introduction

The current engine of China's economic growth is small and medium-sized enterprises (SMEs), which are essential for regulating industrial structure, stabilizing economic growth, enhancing people's quality of life, and reducing business risks [1]. However, the traditional financial system is not conducive to the financing of SMEs, mainly because SMEs' financing is characterized by "difficulty in financing" and "expensive financing." The emergence of digital finance has effectively alleviated this difficult situation. Digital finance, relying on technologies such as big data, blockchain, and mobile payment supply chain finance, has brought new options for SMEs' financing. Although digital finance is developing rapidly, there are still significant differences in financing efficiency and other aspects among SMEs in different regions and industries.

There are substantial regional variances in the growth of digital finance in China as a result of the variations in how digital finance is constructed and how financial resources are distributed across Chinese regions. The degree to which digital finance fosters the growth of the real economy varies

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significantly among regions as a result of these factors [2]. With the guidance of current policies, issues of green environmental protection and social welfare are increasingly being emphasized, and sustainable development is gradually becoming a key theme of China's economic development. Related enterprises are facing greater transformation pressure than non-polluting enterprises [3]. This can be reflected in the increasingly cautious credit approval by banks and financial institutions for high-pollution industries. However, despite digital finance bringing new financing options, there are still many issues with the financing efficiency of small and medium-sized enterprises, which has prompted an in-depth study of related problems.

The current research is focused on the role of digital finance in alleviating the financing constraints of SMEs. This is mainly reflected in optimizing resource allocation, reducing credit risk, and mitigating information asymmetry [4]. The main research question of this paper is whether digital transformation inevitably improves SMEs' financing efficiency. This paper precisely measures financing efficiency using the super-efficiency Data Envelopment Analysis (DEA) model and combines DML (double machine learning) with segmented regression methods to reveal the heterogeneity of financing efficiency of SMEs in the context of digital finance. The potential contributions of this paper are as follows. Firstly, the article verifies that the financing efficiency of SMEs has regional heterogeneity. Secondly, the article verifies that in the context of digital finance, the financing difficulty for companies with lower Environmental, Social and Governance (ESG) ratings is greater than that for companies with higher ESG ratings, enriching the discussion on the factors affecting the financing of SMEs.

2. Methodology

2.1. Sample selection and data sources

This study employs a firm-level panel dataset of Chinese small and medium-sized enterprises (SMEs) spanning the period from 2014 to 2020. The initial sample comprises over 3,000 enterprises. After comprehensive data cleaning and processing, the final unbalanced panel consists of 31,998 firm-year observations. This substantial increase in observations is primarily attributable to two factors: first, the application of multiple imputation techniques that effectively handle missing values while preserving sample size; second, the inclusion of all available firm-year observations that meet our selection criteria across the entire study period, thus maximizing the utilization of available data.

The primary data sources are the China Stock Market & Accounting Research (CSMAR) database and the Wind Economic Database, which are widely recognized for their comprehensive coverage of Chinese listed firms [5]. To ensure the relevance and quality of the data, the sample selection adhered to the following criteria: (1) inclusion of only non-financial SMEs, as defined by the National Bureau of Statistics of China; (2) exclusion of firms with missing data for key variables; and (3) winsorization of all continuous variables at the 1st and 99th percentiles to mitigate the influence of outliers. Data on digital finance development at the provincial level were sourced from the Peking University Digital Financial Inclusion Index [6].

Data cleaning involved handling missing values using Multiple Imputation by Chained Equations (MICE) and standardizing all continuous variables. Fixed effects for year, industry, and region are included to control for unobserved heterogeneity. All analyses were conducted using Python with appropriate robustness checks to ensure the validity of our findings.

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2.2. Variable definition

The dependent variable is financing efficiency, measured using a Super-Efficiency Data Envelopment Analysis (DEA) model. Return on assets (ROA) and revenue growth rate are examples of output variables, whereas financing cost, total assets, and asset-liability ratio are examples of input variables. The Digital Transformation Index, a composite metric derived from firm-level statistics on IT investment, digital patents, and online transaction volume, is the main independent variable.To account for geographical differences in the development of digital finance, Peking University created the Digital Financial Inclusion Index [6]. Control variables include firm size (natural logarithm of total assets), profitability (ROA), growth opportunity (revenue growth rate), leverage (asset-liability ratio), region (categorized into eastern, central, and western China), and ESG rating (categorized based on Wind ESG ratings).

2.3. Model construction and data cleaning

The empirical analysis consists of three main components: efficiency measurement, causal inference, and heterogeneity analysis.

2.3.1. Measurement of financing efficiency (Super-Efficiency DEA model)

Financing efficiency scores are calculated using the Super-Efficiency DEA model. A more nuanced ranking of efficient decision-making units (DMUs) is made possible by this model's extension of the conventional DEA technique, which permits efficiency ratings to be greater than 1.The linear programming formulation for each DMU *k* is as follows: $\min$, subject to

$$\sum_{j\neq k}\lambda_j x_{ij} \leq \theta x_{ik}, \forall_i \tag{1}$$

$$\sum_{j\neq k}\lambda_j y_{rj} \leq y_{rk}, \forall r \tag{2}$$

$$\lambda_j \geq 0, \forall_j \tag{3}$$

where x_{ij} and y_{rj} represent inputs and outputs, respectively, and θ denotes the efficiency score. The average efficiency score across all firms and years is 0.9976, indicating high overall financing efficiency. As illustrated in Figure 2, the efficiency score shows a steady upward trend from 2014 to 2022, with a slight decline during 2018–2020. This decline may be attributed to macroeconomic fluctuations and regulatory adjustments in the financial industry, which temporarily increased the financing pressure on SMEs.

2.3.2. Causal inference of digital transformation (Double Machine Learning model)

To estimate the causal effect of digital transformation on financing efficiency, a Double Machine Learning (DML) model is employed. This approach controls for potential confounders and provides robust average treatment effects (ATEs). The model specification is:

$$Y = \tau T + g(W) + \epsilon \ , \ T = m(W) + \eta \tag{4}$$

where Y represents financing cost, T denotes the digital transformation index, W encompasses control variables, and g(W) and m(W) are machine learning models (Random Forest in this case).

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The estimated ATE is 0.0004, suggesting a small but statistically significant positive effect of digital transformation on financing cost, possibly reflecting initial investment costs or operational disruptions during the digital transition.

As shown in Table 1, this research summarizes the main empirical approaches and their key findings. The Super-Efficiency DEA model reveals an average efficiency score of 0.9976, indicating generally high financing efficiency among Chinese SMEs. The Double Machine Learning approach yields an Average Treatment Effect of 0.0004, suggesting a modest but statistically significant impact of digital transformation on financing costs. The quantile regression analysis demonstrates substantial heterogeneity across regions and ESG ratings, with the most pronounced effects observed in eastern regions and among firms with higher ESG ratings.

As shown in Figure 1, this research observes the temporal evolution of financing efficiency scores derived from the Super-Efficiency DEA model. The graph demonstrates a consistent upward trajectory from 2014 to 2022, with a noticeable deviation during the 2018-2020 period. This pattern suggests generally improving financing efficiency among Chinese SMEs, with the temporary decline potentially corresponding to broader economic uncertainties during those years. The average efficiency score of 0.9976 indicates that most firms operate near the efficiency frontier, though meaningful variations exist beneath this aggregate measure.

2.3.3. Heterogeneity analysis (Quantile Regression model)

To thoroughly investigate the heterogeneous effects of digital transformation on financing efficiency across different firm characteristics and regional contexts, this study employs Quantile Regression (QR) methodology. While conventional ordinary least squares (OLS) regression examines the conditional mean of the dependent variable, QR provides a more comprehensive analysis by estimating effects across the entire conditional distribution of financing costs [7]. This approach is particularly valuable for research objectives for several reasons.

First, the distribution of financing costs among Chinese SMEs exhibits significant heterogeneity, with firms experiencing varying degrees of financial constraints. QR allows us to examine whether digital transformation affects high-cost firms differently from low-cost firms, capturing potentially non-linear relationships that would be obscured in mean-based approaches. Second, this method enables us to identify threshold effects and differential impacts across the financing cost spectrum, providing nuanced insights into how digital transformation benefits or challenges firms with different initial financial conditions.

As shown in Figure 2, the quantile regression results reveal substantial regional heterogeneity in how digital transformation affects financing costs across different quantiles of the cost distribution. In eastern China (Region 1), it observe a generally negative relationship between digital transformation and financing costs, with the strongest effects evident in the lower quantiles (0.1-0.3). This pattern suggests that digitally advanced firms in developed regions achieve greater cost reductions, particularly those already operating with relatively efficient financing structures. The diminishing effect in higher quantiles may indicate capacity constraints or diminishing returns for firms with initially higher financing costs.

The central region (Region 2) demonstrates a distinctive non-linear pattern where the effect of digital transformation initially strengthens through medium quantiles (0.4-0.6) before weakening again in higher quantiles. This inverted U-shaped relationship suggests that moderate-cost firms in central China may benefit most from digital transformation, while both low-cost and high-cost firms experience more modest effects. Western China (Region 3) shows a positive relationship throughout

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the distribution, indicating that digital transformation may increase financing costs in less developed regions, particularly for firms in higher cost quantiles.

Similarly, Figure 3 illustrates how the relationship between digital transformation and financing costs varies across ESG performance categories at different quantiles. Firms with excellent (A) and good (BBB) ESG ratings show strong negative relationships throughout the distribution, with particularly pronounced effects in middle and upper quantiles. This suggests that high-ESG firms experience substantial financing cost reductions from digital transformation regardless of their initial cost position, though the benefits are most dramatic for firms facing moderate to high financing costs.

For firms with moderate ESG ratings (B, BB), it observe more variable effects across the distribution. The relationship is strongest in middle quantiles, suggesting that digital transformation provides the greatest benefits for firms with average financing costs and middling ESG performance. Enterprises with poor ESG ratings (CCC, CC, C) show minimal benefits from digital transformation across most quantiles, with some evidence of adverse effects in the highest cost quantiles, indicating that digital transformation may exacerbate financing challenges for firms with both weak sustainability performance and high existing financing costs.

The quantile regression approach thus provides valuable insights beyond what conventional mean-based methods could offer. By examining effects across the entire distribution of financing costs, it can identify: (1) differential impacts of digital transformation on firms with varying initial financial conditions; (2) threshold effects where the relationship changes significantly at certain points in the distribution; and (3) heterogeneous responses that would be averaged out in conventional analyses. These findings substantially enrich our understanding of how digital transformation affects SME financing efficiency in different contexts and conditions.

3. Result

3.1. General trends

Table 1. Summary of empirical methods and main findings

Method	Main Findings
Super-Efficiency DEA	Average super-efficiency score: 0.9976, yearly changes visualized
Double Machine Learning	Average Treatment Effect: 0.0004
Quantile Regression	Quantile regression results visualized by region and ESG rating

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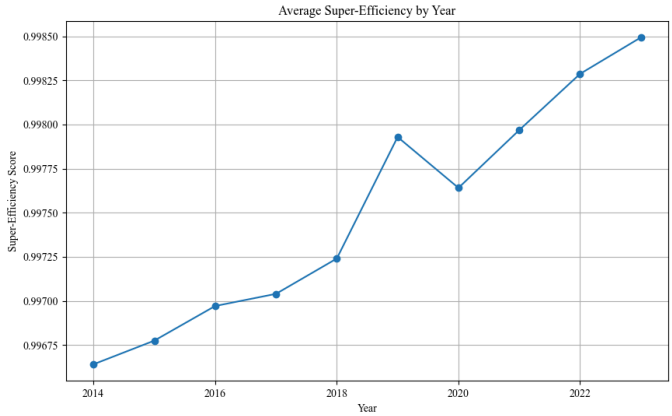

Figure 1. Super efficiency trend (picture credit: original)

The general trend of financing efficiency for small and medium-sized businesses in the context of digital finance is measured in this research using the super-efficiency DEA model.The research results are shown in Figure 1. In Figure 1, the trend of the average financing efficiency scores of the sample enterprises from 2014 to 2022 is presented. Overall, the trend is steadily rising, with a significant fluctuation between 2018 and 2020. The mean financing efficiency of the sample enterprises from 2014 to 2022 is 0.9976, close to 1, indicating that the overall financing efficiency of the sample enterprises is relatively high. It is noteworthy that, although the overall performance of financing efficiency is good, there are still certain differences among enterprises. To study the causal effect of digital transformation on financing efficiency, this paper adopts a dual machine learning model (DML) for analysis. The research results are shown in Table 1. The average treatment effect (ATE) of digital transformation is 0.0004. Although digital transformation is considered an important means to improve corporate financing efficiency, the data shows that digital transformation may have a certain inhibitory effect on corporate financing. The possible reasons for this may be cost adjustments or resource losses during the process of digital transformation.

3.2. Heterogeneity analysis

3.2.1. The impact of regional differences on the financing efficiency of enterprises

To explore the factors affected by corporate financing, this paper further starts from a regional perspective. The rapid development of China's economy and the good results of rapid urban construction have produced a series of related negative effects, and spatial imbalance is one of the negative effects [8]. The result is shown in the figure. Here, China is divided into three parts: Region 1, Region 2, and Region 3. The results of the study are shown in Figure 2, Figure 3 and Figure 4. As can be seen in Figure 2, Figure 3 and Figure 4, the research data in the eastern region shows that the negative impact of digital transformation on financing costs gradually decreases as the score increases. This proves that the cost reduction effect of enterprises with relatively low financing costs will be more obvious than that of enterprises with high financing costs. Compared with other regions, the financial market in the eastern region is more developed and the construction of technical facilities is more perfect. In such a good economic environment, enterprises with low financing costs will gain greater marginal benefits through digital transformation. With peaks around the 0.5th percentile and all coefficients positive, research data from the central region demonstrates

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that the effect of digital transformation on financing costs initially gets stronger and then gets less as the score rises. This shows that in the central region, digital transformation will increase the financing costs of enterprises. Digital transformation significantly lowers firm financing expenses, according to research data from the western area. This effect is especially noteworthy for businesses with high financing prices. This demonstrates how finance expenses may rise because of digital transformation. Businesses' financing costs will rise because of digital transformation in both the central and western regions, which are in comparable states.

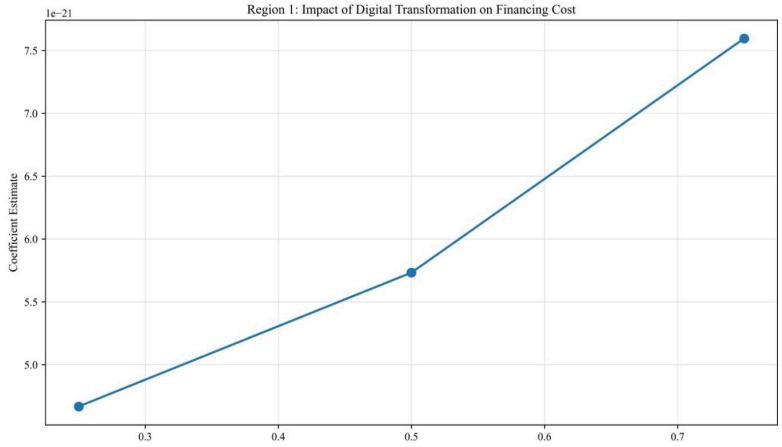

Figure 2. Quantile regression by region 1

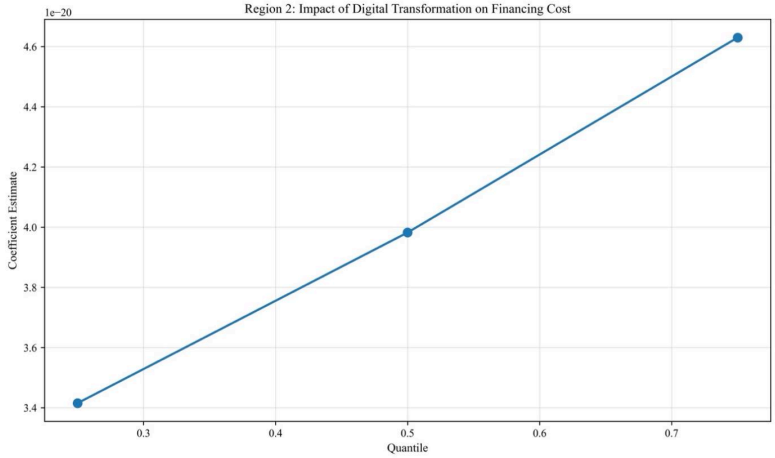

Figure 3. Quantile regression by region 2

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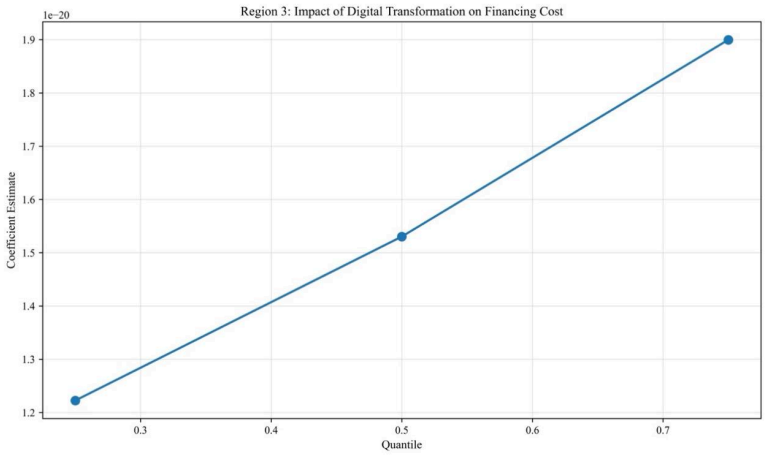

Figure 4. Quantile regression by region 3

The fact that the eastern area has the best digital finance development out of the three, the center region has better digital finance development than the western region, and the western region has the worst digital finance development is one of the key factors contributing to this outcome [2]. Midwestern companies will receive less support than developed eastern regions when they want to reduce financing costs through digital transformation.

3.2.2. The impact of different ESG performance on corporate financing efficiency

Climate warming has become a global problem, and enterprises, as important micro players in the economy, have exacerbated global environmental problems while promoting economic development [9]. Environmental, Social and Governance (ESG) is the value of sustainable development, and the goal is to achieve a good state of harmonious coexistence between man and nature. At present, this value has reached a consensus in all sectors of society, that is, enterprises need to strengthen their social responsibility. As of 2020, there are 600 institutions worldwide capable of providing ESG rating services, including about 20 in China [10]. This also proves that China attaches great importance to sustainable development. Under the premise of this environment, the ESG score of enterprises will also be paid attention to by all parties, including financial institutions. ESG performance is often linked to a company's credit rating, and companies with high ESG performance usually have higher credit ratings than those with poor ESG performance. Among Chinese listed companies, good ESG performance usually reduces financing costs and improves market valuations [11].

The research results are shown in Figure 5, Figure 6 and Figure 7. The figure shows the impact of digital transformation on financing costs and ESG ratings, which are classified as excellent (A), good (BBB), above moderate (BB), medium (B), moderately low (CCC), poor (CC), and poor (C). From the chart, can see that the general trend is that the higher the ESG rating, the greater the impact on corporate financing costs. It can be noted that when the ESG rating is good and the corporate rating is poor, the impact on corporate financing costs is the greatest. The coefficient range in the Table 1 with a good ESG rating is about 5.5-7.5. In the Table 1 with a poor ESG rating, the coefficient range is about 4.0-7.5. When the ESG rating is above or below average, digital transformation can play a huge role in reducing financing costs. The coefficient range in this Table 1 with a medium ESG rating is about 1.2-2.2. The coefficient range in this Table 1 with poor ESG ratings is about 1.0-1.8. When a company's ESG rating is moderate or poor, the role of digital

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transformation in reducing corporate financing costs is relatively weak or even close to failure. In summary, the better the ESG performance of enterprises, the greater the impact of digital transformation on corporate financing costs, but overall, the financing costs of enterprises with poor ESG performance will be higher than those of companies with good ESG performance.

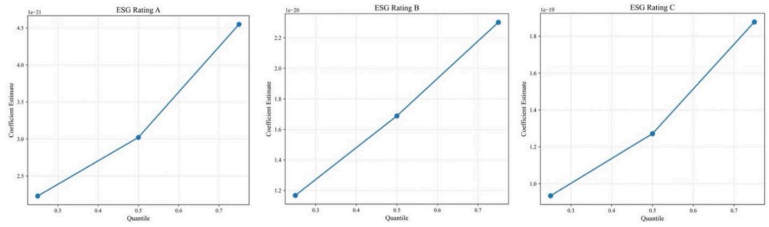

Figure 5. Quantile regression by ESG Rating A-C

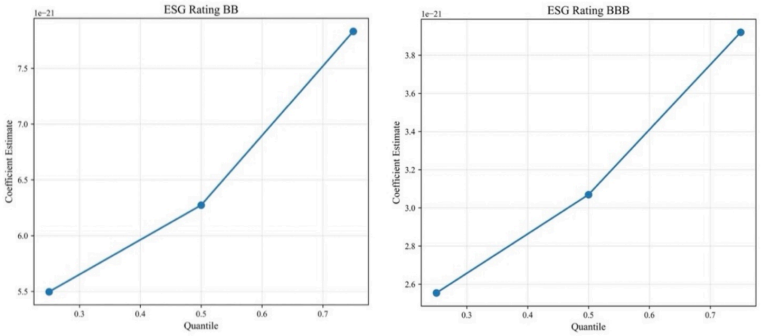

Figure 6. Quantile regression by ESG Rating BB-BBB

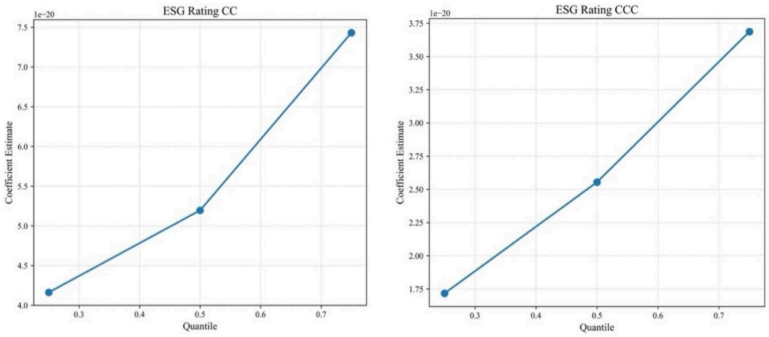

Figure 7. Quantile regression by ESG Rating C-CCC

4. Conclusion

This paper focuses on the core question of what factors affect the financing efficiency of small and medium-sized enterprises in the context of digital finance and conducts an empirical analysis of listed companies from 2014 to 2022 by combining the super-efficient DEA model, dual machine learning and fractional regression method. This analysis proves that digital transformation does not necessarily have a positive impact on enterprises. First, the average processing effect estimated by the dual-machine model is 0.0004, which indicates that digital transformation has a certain inhibitory effect on enterprise financing efficiency. The results of quantile regression show that the financing efficiency of enterprises is not only affected by a single factor, but also by internal and external factors. From a regional perspective, that is, from the perspective of external factors, the

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financing efficiency of enterprises is related to the maturity of regional digital financial development. The development of the financial ecology in the eastern region is in a relatively complete state, while the financial ecological development in the central and western regions is significantly different from the financial ecological development in the eastern region. From the perspective of ESG ratings, that is, from the perspective of internal factors, companies with high ESG ratings and companies with low ESG ratings have a certain negative effect on corporate financing efficiency, but companies with average ESG performance show a good response. In summary, this paper draws a conclusion that whether the impact of digital transformation on enterprise financing efficiency is positive depends on the combined effect of internal and external factors of the enterprise. When the internal factors of the enterprise can be recognized by the market and the external can give the enterprise a good financial environment, the role of digital transformation in the financing efficiency of the enterprise will be greatly exerted.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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