Digital transformation and total factor productivity in oil and gas enterprise - Mediating effects based on innovation performance

Mingxin Cui*, Xinyu Xing, Luxia Ma

College of Economics and Management, Northeast Petroleum University, Daqing 163318, China

Abstract. The research sample for this study consists of oil and gas enterprise listed on the Shanghai and Shenzhen A-shares in China from 2013-2022. The results of this study empirically examine the impact of digital transformation (DT) on total factor productivity (TFP) of oil and gas enterprise and its internal mechanisms using stepwise regression analysis. Additionally, innovation performance (IP) partially mediates this effect. After a series of tests, the above conclusion still holds true.

1. Introduction

China's economy has shifted from rapid growth to high-quality development. Economists emphasize the significance of total factor productivity (TFP) in this transition[1]. Oil and gas enterprises, vital to the national industrial system, face challenges due to rising costs and environmental changes. Over-dependence on traditional resources leads to low TFP. To enhance productivity, exploring new resources and adopting innovative technologies is crucial. Many enterprises in China have leveraged digital technology to improve efficiency, productivity, and management, thereby boosting their competitiveness. Oil and gas enterprises are also embracing this trend. Given their unique challenges in geological conditions and resource dependency, digital technology's implementation in resource management and exploration decisions is more extensive. The question remains: can oil and gas enterprises leverage digital technology to boost TFP and production? What are the underlying mechanisms and logic?

2. Theoretical assumptions

2.1 DT and TFP

Utilizing data analysis and intelligent decision-making systems to optimize resource allocation and utilization can address the low TFP in oil and gas enterprises. DT enhances exploration accuracy, reduces risks, and optimizes resource allocation during exploration. In processing and refining, DT manages and monitors production, reducing human error and boosting productivity[2]. DT also facilitates intelligent supply chain creation, improving coordination. Hypothesis H1: DT can enhance TFP in oil and gas enterprises.

2.2 DT and IP

IP is the achievement and effect of the adoption of a new technology. DT has a catalytic effect on enterprise technological innovation, particularly in the areas of resource integration, information acquisition, and analysis [3]. To implement the digital economy strategy, enterprise will increase their investment in R&D to enhance their innovation performance. Based on previous studies, IP is measured by both quality and quantity of innovation [4]. Therefore, this paper presents the following hypotheses: H2a: DT has the potential to increase the quantity of innovation in oil and gas enterprise; H2b: DT also has the potential to improve the quality of innovation in oil and gas enterprise.

2.3 DT, IP and TFP

Enhancing an enterprise's innovation capacity can boost its productivity. Innovation patent protection offers enterprises unique advantages[4], enabling them to raise product value and output, expand market share, achieve economies of scale, reduce costs, and improve technical efficiency, ultimately enhancing total factor productivity (TFP). In the context of the digital economy era, DT ultimately affects the performance of enterprises by influencing their strategies, and relying on DT and upgrading to enhance innovation is an effective way to change the mode of economic growth. This paper proposes: H3a: DT raises oil and gas enterprise TFP by increasing innovation quantity; H3b: DT raises oil and gas enterprise TFP by improving innovation quality.

*Corresponding author's e-mail: 957464075@qq.com

3. Research design

3.1 Data source

Combined with the availability of data, 84 listed oil and gas enterprise in China's A-share market were finally selected to study the relationship between DT and TFP. The period from 2013 to 2022 was chosen as the research scope of this paper, and all data except the DT indicators were obtained from the Cathay Pacific database and the Wind database.

3.2 Modelling

In this paper, in order to test all the hypotheses, the mediation effect test was chosen and equation (1), equation (2) and equation (3) was constructed for regression analysis.

$$TFP_{i,t} = \alpha_0 + \alpha_i DCG_{i,t} + \alpha_x X_{i,t} + \mu_i + \sigma_t + \theta_{i,t} \quad (1)$$

$$Patent_{i,t} = \beta_0 + \beta_i DCG_{i,t} + \beta_x X_{i,t} + \mu_i + \sigma_t + \theta_{i,t} \quad (2)$$

$$TFP_{i,t} = \gamma_0 + \gamma_i DCG_{i,t} + \gamma_1 Patent_{i,t} + \gamma_x X_{i,t} + \mu_i + \sigma_t + \theta_{i,t} \quad (3)$$

In the formula: $TFP_{i,t}$ is the total factor productivity of oil and gas enterprise i in period t; $DCG_{i,t}$ is the degree of digital transformation for oil and gas enterprise i in period t; $Patent_{i,t}$ is the innovation performance of oil and gas enterprise i in period t; α_0, β_0 and γ_0 are the interception conditions; $X_{i,t}$ is the set of all control variables; $\mu i_{,t}$ is controlling for individual fixed effects; σ_t is a control time fixed effect; $\theta_{i,t}$ is a random disturbance term.

3.3 Variable definition

Explained variable: Total factor productivity (TFP) of oil and gas companies. In this paper, TFP of enterprises is estimated using the LP method[5], where the output indicator is operating income and the input indicators are fixed capital formation, the number of persons employed in the enterprise and intermediate inputs.

Core explanatory variables: Digital transformation (DT) for oil and gas companies. The annual reports of listed oil and gas enterprise were textually analysed and the total word frequency was obtained by summarizing the statistics of digitally related word frequencies and processing them logarithmically[6].

Intermediate variable: Innovation performance (IP) is measured in two dimensions. The first is the quantity of innovation(IP1), measured by the total number of patent applications in the 3 categories of inventions, utility models and designs. The second is the quality of innovation(IP3), which is measured by the number of patents granted in the 3 categories of inventions, utility models and designs. Some scholars believe that invention patents contain a high innovation component, which is one of the most important outcomes of enterprise’s basic innovation activities. There, this paper continues to use the number of invention patents filed and granted as proxies for the quantity and quality of innovation, denoted by IP2 and IP4 respectively.

Control variable: With reference to previous scholars' studies, leverage (Lev), current ratio (Cr), equity concentration (Lhr), book-to-market ratio (BM), cash flow ratio (CF) and two jobs in one (Dual) are selected as control variables.

4. Empirical testing and analysis of results

4.1 Analysis of baseline regression results

In order to select the appropriate regression method, F-test and Hausman test were conducted for all models, and the results of the test indicated that it was more appropriate to select the fixed effects model. The results of the benchmark regression are presented in Table 1, where column (1) and (2) reports the results of the regression between DT and TFP of oil and gas enterprise. The results of the study show that DT has a significant incentive effect on the TFP of oil and gas companies, controlling for other variables, and hypothesis H1 is valid.

Table 1. Analysis of baseline regression results.

Variable name	TFP (1)	TFP (2)
DCG	0.1034*** (3.80)	0.0939*** (3.20)
Lev	—	0.1298 (0.07)
Cr	—	-0.0170 (-0.66)
Lhr	—	0.0112*** (4.35)
BM	—	-0.0435 (-0.33)
CF	—	1.3690*** (4.57)
Dual	—	0.02686 (0.55)
_cons	8.7937*** (18.65)	8.4439*** (31.98)
Controls	—	YES
id FE	YES	YES
year FE	YES	YES
R^2_a	0.8454	0.8658

Note. *,**,*** denote p<0.1, p<0.05, p<0.01 respectively.

4.2 Mechanism of action analysis

Through the above research hypotheses, this paper analyses the relationship between IP, DT and TFP, and the results are presented in Table 2. From columns (1) and (2) of Table 2, the regression results of DT of oil and gas enterprise on the innovation quantity are significantly positive at the 1% level, and hypothesis H2a is valid. Similarly, columns (3) and (4) of Table 1 show that the regression results of DT of oil and gas enterprise on innovation quality are significantly positive at the 1% level, testing hypothesis H2b.

Finally, the mediating effect of IP on the relationship between DT and TFP was tested. The results in columns (5) and (6) of Table 1 show that the coefficients of both DT and the quantity of innovations are significantly positive at the 1% level, and that the regression coefficients of DT are smaller than the coefficients of DT in the baseline regression model, confirming hypothesis H3a. The results in columns (7) and (8) of Table 1 show that the regression coefficients for DT and innovation quality are both significantly positive at the 1 per cent level, and that the regression coefficient for DT is smaller than the coefficient for DT in the baseline regression, confirming hypothesis H3b.

Table 2. Mechanism of action analysis.

Variable name	innovation quantity		innovation quality		innovation performance			
	Patent1 (1)	Patent2 (2)	Patent3 (3)	Patent4 (4)	TFP (5)	TFP (6)	TFP (7)	TFP (8)
DCG	0.2836*** (4.94)	0.2207*** (4.40)	0.3091*** (5.95)	0.1668*** (3.97)	0.0756*** (2.55)	0.0768*** (2.60)	0.0837*** (2.86)	0.0747*** (2.68)
Patent1					0.0646*** (3.27)			
Patent2						0.0772*** (3.42)		
Patent3							0.0777*** (3.64)	
Patent4								0.1287*** (5.07)
_cons	1.1269*** (2.18)	1.3625*** (3.01)	0.7757*** (1.69)	-0.1984*** (-0.51)	8.3583*** (32.86)	8.3386*** (31.62)	8.5058*** (33.65)	8.6196*** (33.75)
controls	YES	YES	YES	YES	YES	YES	YES	YES
id FE	YES	YES	YES	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES	YES	YES	YES
R^2_a	0.8298	0.8306	0.8261	0.8354	0.8679	0.8479	0.8576	0.8556

4.3 Robustness check

Replacement of Explanatory Variables: In order to demonstrate the robustness of the empirical results of this paper, this section uses the OP method instead of the LP method in the benchmark regression to regress TFP of oil and gas firms, and the results are shown in column (1) of Table 3. the coefficient of DT remains significantly positive, and thus the conclusion of the contribution of DT to the total factor productivity of oil and gas firms remains unchanged.

Excluding municipalities:Considering that municipalities directly under the central government have greater economic and political peculiarities, and that the characteristics of DT and TFP of oil and gas enterprises may also be quite different, this paper re-examines the test after excluding the sample of municipalities directly under the central government, and the results are shown in column (2) of Table 3. The regression results remain unchanged, demonstrating the robustness of the underlying conclusions.

Excluding exceptional years: During the sample period of this paper, both the stock market crash in China in 2015 and the outbreak of a novel corona virus infection epidemic in 2020 will affect companies' DT upgrade plans. Therefore, in this paper, the 2015 and 2020 samples are again excluded from the regression and the results are shown in column (3) of Table 3. The coefficient on DT is still positive, again demonstrating the robustness of the benchmark regression results in this paper.

Table 3. Robustness test results.

Variable name	TFP_OP （1）	TFP （2）	TFP （3）
DT	0.0775*** （2.88）	0.0574** （2.23）	0.0711*** （2.66）
_cons	11.1409*** （38.84）	8.5445*** （32.01）	8.5445*** （32.01）
controls	YES	YES	YES
id FE	YES	YES	YES
year FE	YES	YES	YES
R^2_a	0.8733	0.8226	0.8386

4.4 Endogeneity test

This paper employs an instrumental variables method to assess endogeneity in empirical analysis. We selected first-order and second-order lagged DT variables as instrumental variables for two-stage least squares regression[7]. Table 4 summarizes the regression outcomes. The first stage indicates significant positive relationships between IV1 and IV2 at the 1% level, satisfying correlation conditions. The second stage results reveal that the Kleibergen-Paap rk LM statistic rejects the under-identification hypothesis at the 10% significance level. Additionally, the Kleibergen-Paap rk Wald F statistic surpasses the Stock-Yogo weak instrumental variable identification F test's critical value of 1993, rejecting the weak instrumental variables hypothesis. The DT coefficient remains significantly positive at the 10% level, indicating that our core findings are robust against endogeneity concerns.

Table 4. Instrumental variable regression results.

Variable name	IV1 DT	IV2 TFP
DT	—	0.2621*** (6.67)
IV1	0.7490*** (20.23)	—
IV2	0.0948*** (2.54)	—
_cons	0.4980*** (3.71)	6.0529*** (30.55)
id FE	YES	YES
year FE	YES	YES
N	672	672
R^2_a	0.6969	—
Kleibergen－Paap rk LM	—	449.123
Kleibergen－Paap rk Wald F	—	668.010

5. Conclusions and management lessons

5.1 Conclusion

This paper empirically analyses the mechanism and path of DT to promote enterprises' TFP through innovation performance, selecting the data of A-share oil and gas enterprises in Shanghai and Shenzhen. The conclusions of the study are set out below: (1) DT can increase the TFP of oil and gas companies; (2) DT can promote the IP of oil and gas enterprise; (3)Innovation performance plays a mediating role between DT and the TFP of oil and gas enterprise. The results still hold after a series of endogeneity tests.

5.2 Management insights

(1) Enterprises should continue to increase investment in research and development, develop industry-specific digital technology, and enhance the level of exploration and development intelligence; in addition, strengthen talent training, improve staff digital literacy, and build a professional team, and finally, deepen cooperation with the upstream and downstream of the industry chain to jointly promote DT, and form a synergistic advantage of the industry to enhance TFP.

(2) Oil and gas enterprises should pay attention to the importance of innovation ability, borrow the positive effect of DT on innovation ability to stimulate the innovation momentum of the enterprise, accelerate the promotion of the transformation of old and new kinetic energy, to achieve the goal of improving quality and efficiency, and drive the process of high-quality development with innovation.

Acknowledgements

This study was supported by the Philosophy and Social Science Research Planning Project of Heilongjiang Province (Project No. 21JYB141).

References

1. SOLOW R M. (1957) Technical change and the aggregate production function. Review of Economics and Statistics, 39 (3): 312-320.
2. MAKRIDAKIS S. (2017) The forthcoming artificial intelligence (AI) revolution:its impact on society and firms. Futures, 90: 46-60.
3. Yang J. (2020) Research on the impact of digital transformation on national innovation system and countermeasures. Research and Development Management, 32(6): 26-38.
4. Lai W, Cheng M. (2016) Substantive or strategic innovation: The impact of macro-industrial policy on micro-firm innovation. Economic Research, 51(4): 60-73.
5. Lu X, Lian Y. (2012) Estimation of total factor productivity of Chinese industrial enterprises:1999-2007. Economics (Quarterly), (2): 541-558.
6. Zhao C, Wang W, Li X. (2021) How does digital transformation affect the total factor productivity of enterprises. Financial and Trade Economics, 42(7): 114-129.
7. Fan H, Wu T, He S. (2022) How to optimise urban business environment through "Internet+Government Service" platform? Management World, 38(10): 26-153.