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Innovation Path of Pollution Reduction in Manufacturing Enterprises Driven by Digital Transformation

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ABSTRACT
In recent years, artificial intelligence technology has made major breakthroughs, showing strong capabilities in image recognition, speech processing, natural language understanding and other fields. Its rapid development has brought new opportunities and challenges to various industries, and the manufacturing industry is no exception. AI technology is capable of processing large amounts of data, making complex analyses and decisions, and providing manufacturing companies with more efficient and precise solutions. As an important pillar of the national economy, the manufacturing industry has also brought serious environmental pollution problems while promoting economic development. Facing dual pressure from both policies and the market, manufacturing enterprises need to actively explore innovative pollution reduction paths to meet environmental protection requirements and enhance corporate competitiveness.

KEYWORDS
Digital transformation; Manufacturing enterprises; Pollution reduction; Innovation path; Empirical analysis

1 Introduction

In recent years, artificial intelligence is developing vigorously, and manufacturing industry, as an important pillar of national economy, promotes economic development, but also brings serious environmental pollution problems. Manufacturing enterprises in the production process will produce a large number of waste gas, waste water, waste residue and other pollutants, causing great pressure on the ecological environment. With the continuous improvement of people's awareness of environmental protection, the requirements for pollution reduction of manufacturing enterprises are becoming more and more stringent. Manufacturing enterprises need to take effective measures to reduce the emission of pollutants and achieve sustainable development. Governments around the world have issued a series of policies and regulations to strengthen the environmental supervision of manufacturing enterprises and promote enterprises to reduce pollution. At the same time, the public's attention to environmental protection has been increasing, and higher requirements have been put forward for the environmental performance of manufacturing enterprises. Facing the dual pressure from both the policy and the market, manufacturing enterprises need to actively explore innovative pollution reduction paths to meet environmental protection requirements and enhance corporate competitiveness. This study focuses on the impact of digital transformation on pollution reduction of manufacturing enterprises, and through integrating theoretical analysis and empirical research, explores the innovation path and mechanism in depth. Using multi-dimensional data from manufacturing enterprises, the correlation between digital technology application and pollution reduction indicators was analyzed, and relevant hypotheses were verified with the help of econometric models. The research results provide theoretical support and practical guidance for manufacturing enterprises to achieve sustainable development, and reveal the potential and direction of digital transformation in pollution reduction. Under the background of increasing global environmental awareness and booming digital wave, manufacturing enterprises are faced with severe pollution reduction challenges and digital transformation opportunities. The production mode of traditional manufacturing industry is often accompanied by a large amount of pollutant emissions, causing a heavy burden on the ecological environment, while the rapid development of digital technology has brought new opportunities for enterprises to control pollution. The application of technologies such as artificial intelligence, big data and cloud computing is expected to reshape manufacturing production and management processes, improve resource utilization efficiency and reduce pollution emissions. The purpose of this study is to deeply analyze the innovation path of pollution reduction of manufacturing enterprises driven by digital transformation, and provide strong support for the sustainable development of enterprises through the combination of theory and demonstration, and help the manufacturing industry to find a new balance between environmental protection and development, and realize green transformation.

2 Literature Review

Digital transformation has become the focus of academic and industrial attention. Many studies have shown that digital technology can deeply penetrate all aspects of enterprise operations, from the intelligent upgrading of

manufacturing to the optimization and integration of supply chain management, showing significant efficiency improvement potential. At the production end, intelligent manufacturing technology can realize accurate control of the production process, reduce resource waste and energy consumption; In the supply chain, digital platforms promote information sharing and collaboration, reduce logistics costs and inventory overstocking, and enhance the overall competitiveness of enterprises.

2.1 Research on factors affecting pollution reduction

Past studies have explored factors affecting pollution reduction from multiple dimensions. At the macro level, the mode of economic growth, the intensity of environmental regulations, and the degree of industrial agglomeration have a key impact on environmental pollution. At the micro level, an enterprise's financial performance and financing constraints are directly related to its environmental protection input and pollution control ability. With the deepening of research, technological innovation plays an increasingly prominent role in pollution reduction, which can promote enterprises to adopt cleaner production technologies, improve energy utilization efficiency, and fundamentally reduce the generation of pollutants.

2.2 Research on the correlation between digitalization and pollution reduction

Some studies have been involved in the field of the relationship between digitalization and pollution reduction, but there are still certain limitations. Most of the studies focus on the macro region or industry level, and the analysis on the micro enterprise level is relatively insufficient, and it is difficult to accurately reflect the differences of individual enterprises. In terms of mechanism discussion, most of them focus on a single technology or link, and lack a systematic analysis of the multi-path collaborative emission reduction mechanism of digital transformation.

3 Theoretical mechanism

3.1 Production process optimization

digital technology enables intelligent transformation of production process, and realizes real-time monitoring and precise regulation of production process through the integration of sensors, automation equipment and intelligent control system. In chemical production, raw material input and reaction conditions can be dynamically adjusted according to the reaction process to ensure efficient reaction, reduce by-product generation, and thus reduce pollutant emissions. Machinery manufacturing enterprises use the digital process to optimize the processing path, improve the utilization rate of materials, reduce the amount of waste and waste generation.

3.2 Intelligent energy management

With the help of big data and artificial intelligence technology, enterprises can conduct fine management of energy consumption. By analyzing the energy consumption data of production equipment, we can tap the energy saving potential and formulate personalized energy saving strategies. At the same time, the use of energy monitoring data feedback, guide enterprises to upgrade equipment and process improvement, improve energy efficiency, reduce pollution emissions caused by energy consumption.

3.3 Indirect effects of digitalization in promoting pollution reduction

3.3.1 Incentives for green technology innovation

The digital environment creates favorable conditions for enterprises to innovate in green technology. On the one hand, digital platforms broaden the channels for enterprises to obtain external technical knowledge, and enterprises can carry out remote collaborative innovation with scientific research institutions and upstream and downstream enterprises to accelerate the process of green technology research and development; On the other hand, big data analysis helps enterprises gain accurate insight into market demand and technology trends, and guides innovation resources to focus on green technologies.

3.3.2 Supply chain collaborative emission reduction

The digital supply chain system enhances the depth and breadth of cooperation between enterprises. Enterprises share production planning, inventory, logistics and other information with suppliers and distributors to achieve the

overall optimization of the supply chain. In the green procurement process, enterprises can select partners based on suppliers' environmental performance data, and promote upstream enterprises to improve production processes and reduce pollution emissions.

4 Research Design

4.1 Data sources

The data in this study mainly come from the field investigation of manufacturing enterprises and the collection of professional databases. The field survey covers manufacturing enterprises of different sizes and industries to ensure the diversity and representativeness of samples; At the same time, multi-channel data such as CSMAR database, corporate annual reports, social responsibility reports and official environmental protection data platform were integrated to obtain information on enterprises' financial status, production and operation, pollution emission and digital technology application, etc., and to build a panel data set covering 2007-2022 to provide a solid data foundation for empirical research.

4.2 Explained variables

Chemical oxygen demand (COD), sulfur dioxide (SO_2), nitrogen oxide (NO_x) and other pollutant emissions are selected as the key indicators to measure the pollution level of enterprises, and the comprehensive pollution equivalent logarithm is calculated by a specific method to comprehensively reflect the pollution emission intensity and the overall situation of enterprises.

4.3 Explanatory variables

Construct the digital transformation index system from multiple dimensions. Through the text analysis of enterprise annual reports, the word frequency of technical keywords such as artificial intelligence, blockchain, cloud computing and big data was counted, and the weight was determined by entropy method to synthesize the digital transformation index; At the same time, set the proportion of enterprise information technology investment, equipment numerical control rate and other indicators to reflect the digitalization degree from the level of investment and equipment; In addition, whether the enterprise implements the digital management system (such as ERP, MES, etc.) dummy variables are introduced to consider the application status of digital management.

4.4 Control variables

Variables such as enterprise size (total assets and number of employees), financial status (asset-liability ratio, return on net assets), industry category, regional economic development level (per capita GDP) were included to control the potential impact of individual characteristics of enterprises, financial health, industry differences and external economic environment on pollution reduction, so as to ensure the accuracy and reliability of research results.

5 Analysis of pollutant emission trends

Through the line chart, we can more intuitively observe the change trend of the total emission of each pollutant with the year. As can be seen from the chart, the total emission of most pollutants shows a fluctuating upward trend, which may reflect the expansion of production scale of enterprises over time, or there are still some areas for improvement in

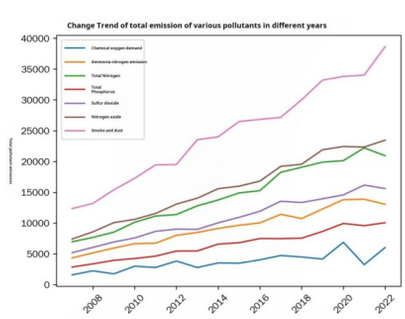

Figure 1 Line chart of the change trend of total pollutant discharge

pollution control. These emissions also do great harm to our lives and health.

Table 1 Correlation coefficient matrix calculation

	The number of AI uses	Number of uses of blockchain technology	The number of uses of cloud computing technology	Usage of big data technology	Number of digital technology applications used
The number of times artificial intelligence technology was used	1.00000	0.215406	0.641942	0.770468	0.702427
Number of use of blockchain technology	0.215406	1.000000	0.255962	0.329815	0.255579
The number of uses of cloud computing technology	0.641942	0.255962	1.000000	0.796624	0.845356
Usage of big data technology	0.770468	0.329815	0.796624	1.000000	0.795942
Number of digital technology applications used	0.702427	0.255579	0.845356	0.795942	1.000000

Calculate its correlation coefficient matrix. The results are shown in the table above, where the correlation coefficient between the number of uses of artificial intelligence technology and the number of uses of big data technology is 0.770468, the correlation coefficient between the number of uses of cloud computing technology is 0.641942, while the correlation coefficient between the number of uses of blockchain technology is only 0.215406, indicating that different digital technologies have different degrees of correlation in their applications. However, the number of uses of artificial intelligence technology and big data technology are the most frequently used, which indicates the indispensability of data transformation for enterprises' pollution reduction.

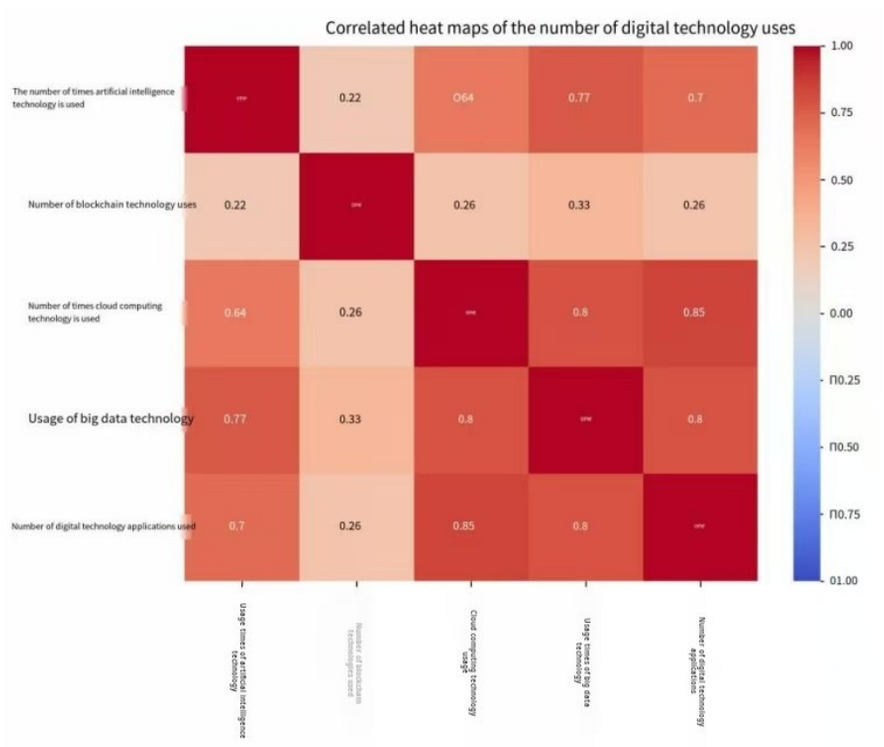

Figure 2 The number of uses of digital technology is correlated with heat map

The heat map visually shows the strength of the correlation between the number of digital technology uses (such as the number of artificial intelligence technology uses, the number of blockchain technology uses, the number of cloud computing technology uses, etc.). The depth of the color represents the size of the correlation coefficient, with warm colors indicating a stronger positive correlation and cool colors indicating a stronger negative correlation. We can significantly see a strong correlation between the number of AI uses and the number of big data technology uses. The emission reduction of pollutants requires the support of these technologies.

6 Conclusions and Suggestions

6.1 Research conclusions

Through theoretical and empirical analysis, this study systematically reveals the innovation path and mechanism of

pollution reduction of manufacturing enterprises driven by digital transformation. The research shows that by optimizing production process, intelligent energy management, stimulating green technology innovation and promoting supply chain collaboration, digital transformation can significantly reduce enterprise pollution emissions, and has a heterogeneous impact on enterprises of different sizes and industries, providing new theoretical support and practical guidance for the green development of manufacturing enterprises.

6.2 Policy Recommendations

At the enterprise level, manufacturing enterprises should actively embrace digital transformation and formulate digital plans that fit their own development strategies. Increase investment in the research and development and application of digital technology, and improve the digital and intelligent level of production equipment; Build an internal digital management system to promote information flow and collaborative decision-making; Strengthen cooperation with external innovation entities, accelerate green technology innovation with the help of digital platforms, and achieve a win-win situation of pollution reduction and competitiveness improvement. At the government level, the government should strengthen policy guidance and support, set up a special digital transformation support fund, and give incentives such as tax incentives and financial subsidies to digital projects that actively promote pollution reduction; Improve the construction of digital infrastructure, narrow the regional digital divide, and create a good external environment for enterprises' digital transformation; We will strengthen the formulation and promotion of industry digital standards, promote data sharing and experience exchange among enterprises, and promote the overall green upgrading of the manufacturing industry. In the future, the research can be extended to the fields of comparative analysis of multinational enterprises and dynamic impact assessment of emerging digital technologies, so as to continuously deepen the understanding of the relationship between digital transformation and sustainable development of manufacturing industry, and help the process of green and low-carbon transformation of global manufacturing industry.

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