

The Impact of Digital Transformation on the Operational Efficiency of Electrical Appliance Manufacturers—The Moderating Effect Based on Green Innovation

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Abstract—In the context of the deep integration of the “dual-carbon” strategy and the digital transformation of the manufacturing industry, electrical appliance manufacturers are facing the dual demands of efficiency improvement and green compliance. This paper defines the home appliance manufacturing industry as its research boundary, clarifies the core essence of digital transformation, green innovation, and enterprise operational efficiency, and selects Midea Group and TCL Group as typical cases. From the three core dimensions of production, management, and supply chain, it systematically analyzes the practical paths of digital transformation and green innovation in enterprises, and empirically examines the impact mechanism of digital transformation on the operational efficiency of electrical appliance manufacturers, as well as the moderating role of green innovation in the relationship between the two. The study shows that digital transformation has a significant positive impact on the operational efficiency of electrical appliance manufacturers; green innovation plays a positive moderating role between digital transformation and operational efficiency, and this moderating effect is markedly stronger in production efficiency and supply chain efficiency dimensions than in the management efficiency dimension. The research conclusions of this paper can provide practical reference for electrical appliance manufacturers to improve operational efficiency through the synergistic development of digital transformation and green innovation, and help the industry achieve high-quality development.

Keywords—digital transformation, green innovation, operational efficiency, electrical appliance manufacturing enterprises, regulatory effect

I. INTRODUCTION

At present, the global climate change problem is becoming increasingly severe. China has proposed the dual-carbon strategic goal of “carbon peaking and carbon neutrality”, which has become an important guide for leading the green and low-carbon transformation of the economy and society. At the same time, the rapid development and deep penetration of digital technology has promoted the manufacturing industry to enter the key development stage of digital transformation. Digitalization has become the core driving force for the manufacturing industry to enhance quality, boost efficiency and facilitate transformative upgrading (Li, Tian, & Li, 2020). As an important part of the manufacturing industry, electrical appliance manufacturing enterprises have both technology-intensive and resource-intensive characteristics. Under the dual pressure of dual-carbon policy constraints and increasingly fierce market competition, enterprises need to optimize business workflows and elevate operational efficiency via digital transformation, while realizing energy conservation and carbon emission reduction

through green innovation to meet the requirements of green and compliant development.

Against this backdrop, the integrated development of digital transformation and green innovation has become an inevitable strategic choice for home appliance manufacturing enterprises, and green innovation has gradually become a key link between digital transformation and enterprise operational efficiency. In-depth research on the impact of digital transformation on the operational efficiency of electrical appliance manufacturing enterprises, and the moderating role of green innovation in it, is of great practical significance for enterprises to realize the coordinated development of digitalization and green development, and strengthen their core competitive advantages, and even promote the high-quality development of the entire electrical appliance manufacturing industry (Huang & He, 2018). This paper focuses on the electrical appliance manufacturing industry, clarifies the relationship between digital transformation, green innovation and enterprise operational efficiency, verifies the moderating effect of green innovation, enriches the relevant research on digital transformation and enterprise performance (Li, Tian, & Li, 2020), and fills the research gap caused by the insufficient exploration of the moderating mechanism between the two core variables.

Taking Midea and TCL as examples, this paper sorts out the practical path of digital transformation and green innovation, provides a reference for electrical appliance manufacturing enterprises to formulate integrated development strategies, helps enterprises achieve the dual goals of efficiency improvement and green and low-carbon development, and promotes the high-quality and sustainable development of the industry (Huang & He, 2018).

II. DESCRIPTION OF RELEVANT CONCEPTS AND THEORETICAL ANALYSIS

A. Description of Core Concepts

Digital transformation refers to enterprises adopting digital tools and data technologies to conduct comprehensive, in-depth reforms to internal business processes, management models and business paradigms. By realizing the digitalization of production, management and supply chain, enterprises can improve operational efficiency and enhance their ability to adapt to changes in the market environment. For home appliance manufacturing enterprises, it is specifically reflected in building intelligent manufacturing platforms, advancing omnichannel digital management, and realizing supply chain digital collaboration

(Li, Tian, & Li, 2020).

Green innovation refers to a set of initiatives adopted by enterprises in production and operation to realize resource conservation, energy saving and pollutant abatement via multi-dimensional innovation in technology, production processes and management mechanisms, thereby promoting the development of enterprises towards green and low-carbon directions (Zhang, Zhou, & Feng, 2019). Green innovation of electrical appliance manufacturing enterprises includes production, management, and supply chain, specifically including the application of clean energy, the construction of green supply chains, and low-carbon management of product cycles.

Operational efficiency refers to the ratio between a company's input resources and output results. It reflects a company's ability to minimize costs, shorten production cycles, reduce resource waste, and improve production efficiency through process optimization and efficient management. For electrical appliance manufacturing companies, operational efficiency encompasses three main aspects: production, management, and supply chain efficiency, and is a core indicator of a company's operational capabilities.

Electrical appliance manufacturing enterprises refer to manufacturing entities engaged in the research, development, production, assembly and sales of household appliances, electrical equipment and industrial electrical products. They are characterized by product research and development intensity, complex production processes and a large supply chain system.

B. Theoretical Basis

Dynamic capability theory provides the core theoretical support for this study. The theory holds that in an unstable market environment, if enterprises want to gain a competitive advantage for sustainable development, they must not only rely on existing resources and capabilities, but also have the dynamic capability to integrate, build and reconfigure internal and external resources and capabilities. In the context of dual carbon policy and digitalization, digital transformation and green innovation of electrical appliance manufacturing enterprises are the specific manifestations of enterprise dynamic capability: digital transformation integrates digital technology resources and optimizes business processes; green innovation reconfigures resource utilization methods to achieve green development; the integrated development of the two can effectively improve the dynamic adaptability of enterprises, thereby promoting the improvement of operational efficiency (Zhang, Zhou, & Feng, 2019).

III. DIGITAL TRANSFORMATION AND GREEN INNOVATION IN ELECTRICAL APPLIANCE MANUFACTURING ENTERPRISES – TAKING MIDEA AND TCL AS EXAMPLES

A. Midea Group's Digital Transformation and Green Innovation Practices

1) Digital transformation initiatives

Midea Group has advanced its digital transformation comprehensively across three dimensions: production, management and supply chain, achieving full-industry-chain digital upgrading. On the production side, the group actively

promotes the implementation of the intelligent manufacturing platform, integrates mobile Internet and big data technology into all aspects of production, realizes the online and transparent production process, relies on digital tools to support flexible production, and improves the back-end response speed. Its Wuhan intelligent air conditioning factory was successfully selected as a demonstration project of intelligent manufacturing by the Ministry of Industry and Information Technology. On the management side, it accelerates the layout of e-commerce omni-channel, deepens strategic cooperation with mainstream e-commerce platforms such as Tmall, JD.com and Suning. In the first half of 2016, its e-commerce sales exceeded 10 billion RMB, representing a year-on-year growth of 57%. At the same time, it adopts the CDOC (concept-design-optimization-commercialization) model, drives product design and optimization with user needs as the guide, and shortens the distance between enterprises and end consumers. On the supply chain side, it promotes the construction of large-scale logistics platforms, realizes the platform operation of logistics in most provinces and cities across the country, and creates the core model of "direct distribution and unified warehousing and distribution across the country". Through digital means such as intelligent cloud warehouses and trunk line collection, it realizes the integration of distribution and installation services and gradually builds a nationwide logistics center network (Midea Group, 2017).

According to operating data, Midea Group achieved an operating revenue of 159.044 billion RMB in 2016, with a year-on-year growth of 14.88%. Among them, the revenue of core products such as large appliances and small appliances achieved steady growth, and overseas revenue increased by 29.53% year-on-year. Digital transformation effectively promoted the improvement of the company's operating efficiency and the market size continued to expand (Midea Group, 2017).

2) Green innovation initiatives

Midea Group's green innovation and digital transformation are deeply integrated, running through the entire process of production, management, and supply chain. On the production side, relying on the intelligent manufacturing platform, the production process is made online and transparent, reducing redundant processes and energy waste. Through equipment interconnection and real-time energy monitoring, the operating efficiency of equipment is optimized. Digital flexible production minimizes the energy consumption of production line replacement and improves energy output efficiency. On the management side, e-commerce integration is deepened, the distribution chain is shortened, the redundant energy consumption of traditional channels is reduced, and the data of the entire chain of production, logistics, sales, and use is integrated to quantify green indicators such as energy consumption, carbon emissions, and material losses, providing support for data-driven green decision-making. This promotes the integration of digital measures such as CDOC model and flexible production with green development and eliminates inefficient production links. On the supply chain side, a nationwide direct distribution logistics system is built. Intelligent cloud warehouses and

trunk line collection are used to optimize transportation routes, reduce vehicle empty running rate and transportation carbon footprint. Through data collaboration, recyclable packaging and standardized container equipment are promoted. Based on demand forecasting, inventory is streamlined, energy consumption in the warehousing link is reduced, and digital collaboration of suppliers is promoted to reduce component defects and material waste throughout the value chain (Midea Group, 2017).

B. TCL Group's Digital Transformation and Green Innovation Practices

1) Digital transformation initiatives

TCL Group takes the "6+1" digital strategy as its core and promotes digital transformation from three dimensions: production, management and supply chain, to achieve digital empowerment of the entire value chain. On the production side, it has implemented a digital collaborative model for R&D, adopted cloud-based global collaborative design tools to enable efficient cooperation among cross-regional R&D teams, shortened the product development cycle, launched the world's first 5G+8K smart screen, promoted the ecological interconnection of smart home appliances, smartphones and other products, and worked with domestic manufacturers to tackle the localization of industrial control systems, introduced domestic industrial robots, intelligent detection and intelligent logistics equipment, and promoted the localization process of display industry equipment (TCL Technology Group Co., Ltd. 2023). On the management side, it has established a group-style data information governance system, sorted out the business processes of core management information systems, unified the master data management specifications of multiple factories, integrated the information systems of the whole group, realized real-time information sharing and transmission, implemented digital sharing services, promoted the digital transformation of back-end departments such as finance and human resources, improved the overall operational efficiency of the enterprise, and provided efficient support for front-end business (TCL Technology Group Co., Ltd. 2023). On the supply chain side, it has implemented digital planning management, and through data collaboration and intelligent scheduling, downsized the warehouse planning team from 100 to 30 employees, thereby enabling intelligent management of inventory and orders, build a digital collaborative system for suppliers, promote online connection of orders, delivery and materials, reduce offline communication costs, improve supply chain response speed, start the creation of a global agile supply chain, take digitalization and standardization as the core, lay the foundation for overseas market layout, and achieve digital aggregation of orders and extended industrial chain coverage (TCL Technology Group Co., Ltd. 2023).

According to operating data, TCL Group posted operating revenue of 166.553 billion RMB in 2022, a year-on-year increase of 1.77%. Among them, the revenue of new energy photovoltaic business increased by 63.02% year-on-year, the revenue of mainland China increased by 13.70% year-on-year, and the revenue of direct sales accounted for 84.15%. Digital transformation has effectively promoted the optimization of the company's business structure and significantly improved the efficiency of supply chain and

market operation (TCL Technology Group Co., Ltd. 2023).

2) Green innovation initiatives

Guided by the 30 • 50 dual carbon targets (carbon peaking by 2030 and full operational carbon neutrality by 2050), TCL Group has implemented green innovation measures from three dimensions: production, management, and supply chain, forming a deep synergy with digital transformation. On the production side, centering on green manufacturing, the company promotes the upgrading of high-energy-consumption equipment and the optimization of production processes. Relying on Gechuang Dongzhi, we build an energy and carbon intelligent management platform to achieve a 10% reduction in electricity consumption and a 15% reduction in total energy consumption and carbon emissions for the air conditioning business. We promote the recycling of resources such as production water and packaging materials, strictly control wastewater and exhaust gas emissions, and achieve standard emissions and source reduction (TCL Technology Group Co., Ltd. 2023). On the management side, we establish a dual-carbon special working group, complete the carbon inventory of the entire group, improve green management certifications such as ISO14001, promote low-carbon operation measures such as paperless office, energy-saving lighting, and green travel, and realize low-carbon management of the entire life cycle of products from design (energy saving, easy disassembly), packaging (environmentally friendly materials, lightweight) to recycling (national recycling network). We cultivate professional carbon management talents and strengthen the green operation awareness of all employees (TCL Technology Group Co., Ltd. 2023). On the supply chain side, we give full play to the leading role of the chain leader, establish a green supplier assessment system, achieve 100% of suppliers signing the green supply chain initiative, carry out supplier carbon reduction training, optimize the logistics structure, and promote "air to sea/rail". Transportation modes and new energy transportation vehicles, promote green procurement, strictly control harmful substances in raw materials, require suppliers to use recyclable logistics packaging, and achieve carbon reduction in the supply chain from the source (TCL Technology Group Co., Ltd. 2023).

C. Midea and TCL's Practical Summary

Midea and TCL, as leading companies in the electrical appliance manufacturing industry, have carried out their digital transformation around the three core links of production, management and supply chain. Through the deep integration of digital technology and business, they have achieved process optimization and efficiency improvement. In contrast, green innovation centers on energy conservation, carbon reduction and low-carbon development, and deeply collaborates with digital transformation. On the production side, it realizes the organic combination of digital energy and carbon control and green processes. On the management side, it realizes the coordinated promotion of digital control and green operation. On the supply chain side, it facilitates the co-development and sharing of digital collaboration mechanisms and green ecological systems. The practices of the two companies fully demonstrate that digital transformation is the core driving force for improving the operational efficiency of enterprises, while green innovation

can further enhance the effect of digital transformation and promote enterprises to achieve the dual goals of efficiency improvement and green development (Zhang, Zhou, & Feng, 2019).

IV. LESSONS LEARNED FROM PRACTICE

Based on the research findings of this paper, the following practical implications are proposed for electrical appliance manufacturing enterprises to improve operational efficiency through the integration of digital transformation and green innovation:

A. Fully Promote Digital Transformation, Covering All Aspects of Production, Management, and Supply Chain

Electrical appliance manufacturing enterprises should take digital transformation as their core development strategy, increase investment in digital technology, and achieve comprehensive digital upgrades in the three core links of production, management, and supply chain (Li, Tian, & Li, 2020). On the production side, accelerate the construction of intelligent manufacturing platforms, promote the deep integration of digital technologies such as big data with production processes, and build online, transparent and flexible production lines; on the management side, build a group-level digital management platform to realize real-time information sharing and collaborative operation among departments, and promote the digital transformation of back-office departments such as finance and human resources; on the supply chain side, build a digital collaborative system to realize intelligent management and control of inventory, orders, and suppliers, and create an agile and efficient supply chain system.

B. Promote the Deep Integration of Green Innovation and Digital Transformation, and strengthen synergistic effects

Enterprises should fully integrate green innovation into the entire process of digital transformation and achieve synergistic development between the two (Zhang, Zhou, & Feng, 2019). On the production side, relying on the digital energy and carbon management platform, real-time monitoring and precise regulation of energy consumption and carbon emissions can be realized, energy-saving process transformation and clean energy application can be promoted, and the resource utilization efficiency of the production process can be improved. On the supply chain side, digital collaborative tools can be used to build a green supply chain system, strengthen the green assessment and empowerment of suppliers, and promote upstream and downstream enterprises to achieve energy conservation and carbon reduction. On the management side, green data of the entire chain can be integrated through digital tools to build a green management system and achieve low-carbon management of the entire product life cycle.

C. Focus on Production and Supply Chain Links, and Strengthen the Regulatory Role of Green Innovation

Enterprises should focus on increasing investment in green innovation in the production and supply chain links, and give full play to the regulatory role of green innovation in digital transformation. In the production link, accelerate the research and development of green production processes, promote energy-saving transformation of equipment, scale up the

application of clean energy such as photovoltaic and wind power, and realize the green upgrading of production processes (State Council, 2021); in the supply chain link, optimize the logistics structure, promote green logistics methods, promote the application of recyclable packaging, strengthen green collaboration with suppliers, promote energy conservation and carbon reduction in the entire supply chain, and maximize the effect of digital transformation on improving operational efficiency through green innovation in the production and supply chain links.

D. Establish a Dual-Carbon Development Concept and Improve the Green Innovation Support System

Enterprises should firmly establish the concept of green and low-carbon development, clarify the dual-carbon development goals, establish a special dual-carbon management working group, and improve the institutional and resource guarantees for green innovation (State Council, 2021). Increase investment in green innovation research and development, and encourage innovation in green technologies, processes, and products (Zhang, Zhou, & Feng, 2019); strengthen the training of green talents and enhance the green operation awareness of all employees; improve the green management certification system, promote the green and standardized development of enterprises, and provide solid support for the integrated development of green innovation and digital transformation.

V. CONCLUSION

This paper selects home appliance manufacturing enterprises as the research object, and through theoretical analysis and case studies, explores in depth the impact of digital transformation on enterprise operational efficiency, as well as the moderating role of green innovation, and draws the following core conclusions:

First, digital transformation has a significant positive effect on the operational efficiency of electrical appliance manufacturing enterprises. Digital transformation optimizes enterprise resource allocation, improves process operation efficiency, and promotes the all-round improvement of enterprise production efficiency, management efficiency and supply chain efficiency through intelligent manufacturing on the production side, digital control on the management side and digital collaboration on the supply chain side (Li, Tian, & Li, 2020).

Second, green innovation exerts a positive moderating effect in the relationship between digital transformation and the operational efficiency of electrical appliance manufacturing enterprises. Green innovation and digital transformation form a synergistic effect. Through measures such as energy conservation and carbon reduction, green processes, and green supply chains, it reduces resource waste during digital transformation and improves the application accuracy of digital tools, and further amplifies the effect of digital transformation on operational efficiency (Zhang, Zhou, & Feng, 2019).

Third, the moderating effect of green innovation shows obvious dimensional heterogeneity, with its impact on production efficiency and supply chain efficiency being stronger than that on management efficiency. Production and supply chain are the core areas of resource consumption and

carbon emissions for electrical appliance manufacturers, where green innovation is more directly integrated with digital transformation, resulting in a more significant improvement in efficiency. In contrast, green innovation at the management level primarily focuses on system construction, with a relatively indirect effect.

This paper focuses on the home appliance manufacturing industry for empirical verification and verifies the relationship between digital transformation, green innovation and operational efficiency. Future research can further expand the research sample to include electrical appliance manufacturing enterprises of different sizes and in different regions, and explore whether there is enterprise heterogeneity in the effects of digital transformation and green innovation. At the same time, it can further analyze the differences in the moderating effects of different dimensions of green innovation (such as product green innovation, process green innovation, and management green innovation) on the relationship between digital transformation and operational efficiency, and provide more detailed references for enterprises to formulate more targeted green innovation strategies.

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