Open Journal of Social Sciences, 2026, 14(4), 889-906
https://www.scirp.org/journal/jss
ISSN Online: 2327-5960
ISSN Print: 2327-5952

Research on the Green Transformation Path of "Specialized, Sophisticated, Distinctive and Innovative" Enterprises in Yantai Driven by "Precision Carbon Chain Innovation"

—A Case Study of Wanhua Chemical

Xinjie Kang[1], Chongmei Wang[2*], Songting Qin[2], Rui Shi[2], Zhijie Zhang[2], Yingzi Wang[2]

[1]School of Accounting, Shandong Technology and Business University, Yantai, China
[2]School of Business Administration, Shandong Technology and Business University, Yantai, China
Email: 1169231246@qq.com, *201513120@sdtbu.edu.cn

How to cite this paper: Kang, X. J., Wang, C. M., Qin, S. T., Shi, R., Zhang, Z. J., & Wang, Y. Z. (2026). Research on the Green Transformation Path of "Specialized, Sophisticated, Distinctive and Innovative" Enterprises in Yantai Driven by "Precision Carbon Chain Innovation". *Open Journal of Social Sciences, 14,* 889-906.
https://doi.org/10.4236/jss.2026.144045

Received: March 25, 2026
Accepted: April 27, 2026
Published: April 30, 2026

Abstract

Under the "Dual Carbon" goal, the green transformation of "Specialized, Sophisticated, Distinctive and Innovative (SSDI)" enterprises has become a core driver for regional industrial low-carbon upgrading. This paper takes Wanhua Chemical, the leading SSDI enterprise in Yantai City, as the typical case, and constructs the "Precision Carbon Chain Innovation (PCCI)" theoretical framework with four core dimensions: Precision, Carbon, Chain and Innovation. This paper first sorts out the existing research on the green transformation of SSDI enterprises through a literature review and clarifies the research gaps. On this basis, it adopts the carbon emission decoupling model, super-efficiency SBM model with undesirable outputs, Malmquist-Luenberger index and ecological welfare performance model as the core research methods, selects the panel data of Wanhua Chemical from 2019 to 2023 and the statistical data of Yantai City from 2014 to 2023 for empirical analysis, and identifies the key driving factors and existing bottlenecks of the green transformation of SSDI enterprises in Yantai. Finally, combined with the empirical results, this paper constructs a four-dimensional operable green transformation path under the PCCI framework, and puts forward targeted countermeasures for enterprises and the government. This study makes up for the lack of existing research on the whole industrial chain collaborative transformation of SSDI enterprises, and provides a replicable practical model and theoretical reference for the green low-carbon transformation of similar enterprises.

Keywords

Specialized, Sophisticated, Distinctive and Innovative Enterprises, Green Transformation, Precision Carbon Chain Innovation, Dual Carbon Goal, Efficiency Measurement, Path Optimization

1. Introduction

1.1. Research Background

In September 2020, China formally proposed the strategic goal of "achieving carbon peaking by 2030 and carbon neutrality by 2060", which has promoted the comprehensive green low-carbon transformation of China's economic and social development. As an important industrial town in Shandong Province and a key node of the Bohai Rim Economic Circle, Yantai has a large number of SSDI enterprises, which are the core force to maintain the stability of the industrial chain and supply chain and promote the high-quality development of the regional economy (Yu, 2025). In 2024, the national fiscal work conference clearly stated that it will continue to promote the green low-carbon transformation of key industries through policy tools, which has brought new opportunities and requirements for the green development of SSDI enterprises in Yantai.

However, most SSDI enterprises are still facing multiple bottlenecks in the process of green transformation: insufficient technological R&D and innovation capacity, limited industrial chain collaboration, weak digital and intelligent foundation, and high pressure of short-term transformation costs (Dong & Li, 2021). Existing research has not yet formed a systematic transformation framework that fits the development characteristics of SSDI enterprises, and there is a lack of targeted empirical analysis and path design for regional SSDI enterprise clusters. In this context, this paper constructs the "Precision Carbon Chain Innovation (PCCI)" framework, takes Wanhua Chemical as a typical case, explores the green transformation path of SSDI enterprises in Yantai, and has important practical and theoretical value.

1.2. Paper Structure

The rest of this paper is organized as follows: Section 2 is the literature review and theoretical foundation, which sorts out the existing research and constructs the PCCI theoretical framework. Section 3 is the research design, which introduces the research methods, sample selection and data sources. Section 4 is the empirical results and case analysis, which carries out quantitative measurement and in-depth case analysis based on the model. Section 5 constructs the green transformation path and countermeasures under the PCCI framework combined with the empirical results. Section 6 is the conclusion and prospect.

2. Literature Review and Theoretical Foundation

2.1. Literature Review

2.1.1. Research on Green Transformation of SSDI Enterprises

In recent years, the green development of Specialized, Sophisticated, Distinctive and Innovative (SSDI) enterprises has become a key research focus. Scholars have conducted in-depth discussions on the driving forces, dilemmas, and practical paths of green transformation for such enterprises.

Cao et al. (2022) pointed out that innovation policies effectively improve the innovation quality of SSDI enterprises, and green innovation constitutes the core of their high-quality development. Hong & Zhang (2026) found that SSDI certification significantly promotes technological innovation, yet most small and medium-sized SSDI enterprises suffer from insufficient R&D investment and weak innovation transformation capacity (Gui et al., 2026). Dong & Li (2021) summarized the prominent dilemmas, including unclear transformation paths, insufficient technological innovation, and weak industrial chain collaboration.

From the perspective of industrial chain synergy and policy effects, Gao et al. (2025) verified that supply chain dual synergy boosts green innovation of SSDI enterprises. Han et al. (2024) proposed that SSDI certification generates significant supply chain spillover effects. Zhao et al. (2023) indicated that SSDI development helps SMEs consolidate their position in the industrial chain. Pang & Zhu (2025) confirmed that innovation incentive policies drive green transformation, while Zhu & Xiang (2025) revealed that the "little giant" policy improves enterprises' emission reduction and efficiency.

Regarding digital empowerment and enterprise cases, Jiang (2025) explored digital upgrading models for SSDI enterprises. Yan & Wang (2025) argued that digital transformation facilitates green technology innovation. Li & Ke (2024) emphasized the role of knowledge search and reconstruction in green technology innovation. Jia et al. (2024) proposed that green finance empowers digital transformation of SMEs. Chu et al. (2024), Liu (2024), Wang & Qiao (2024), and Wu & Hou (2024) took Wanhua Chemical as an example to investigate green innovation and transformation performance. Wang & Yin (2025) evaluated the economic benefits of digital-enabled green transformation. Yu (2025) took Yantai as an example to study green development of high-tech manufacturing, and Wang (2025) analyzed green and low-carbon development in Shandong Province.

2.1.2. Research on Enterprise Green Transformation Path Under the Dual Carbon Goal

Under the Dual Carbon goal, green transformation has become an inevitable trend for industrial upgrading and sustainable development of enterprises. Existing studies have formed systematic insights into transformation paths, technological empowerment, and efficiency improvement.

Domestic studies show that green transformation of enterprises relies on technological innovation, digital empowerment, industrial chain synergy, and policy support. For SSDI enterprises, digital transformation can optimize resource allocation, reduce energy consumption and carbon emissions, and provide technical support for green development (Yan & Wang, 2025). Meanwhile, industrial chain synergy helps enterprises share transformation costs, break through bottlenecks, and realize coordinated upgrading (Gao et al., 2025; Han et al., 2024).

Regional green development also provides an external foundation for enterprise transformation. Yu (2025) and Wang (2025) provided a regional perspective for green transformation of local enterprises. Wang et al. (2019) laid a theoretical basis for regional green collaborative development. Although existing studies have laid a solid foundation, most lack a systematic framework integrating precision management, carbon control, chain collaboration, and innovation drive for SSDI enterprises, which is the gap this study aims to fill.

2.1.3. Literature Gaps

Through the combing of existing literature, it can be found that the current research on enterprise green transformation has formed a rich theoretical foundation, but there are still three research gaps: First, most of the existing research focuses on large listed enterprises, and the research on the green transformation of SSDI enterprises is relatively insufficient, and there is a lack of a systematic transformation framework that fits the development characteristics of such enterprises. Second, the existing research on the transformation path is relatively single, and there is a lack of in-depth research from the perspective of whole industrial chain collaboration, which is difficult to match the development reality of SSDI enterprise clusters. Third, there is a disconnection between quantitative analysis and path design in existing research, and most of the countermeasures are not supported by empirical results, which reduces the operability of the path (Pang & Zhu, 2025). This study just makes up for the above research gaps.

2.2. Theoretical Foundation

2.2.1. Core Concept of "Precision Carbon Chain Innovation (PCCI)"

"Precision Carbon Chain Innovation (PCCI)" is a systematic green transformation framework constructed for SSDI enterprises under the Dual Carbon goal, which includes four interrelated core dimensions:

Precision: Corresponding to the refinement and specialization in the connotation of SSDI, it is the inherent requirement of enterprise green transformation. It emphasizes lean management and efficient resource allocation, integrates green development goals into all links of production and operation, and realizes precise reduction of resource consumption and emissions through technological transformation and a refined management system.

Carbon: Directly targeting the core of the Dual Carbon goal, it is the action guide for enterprise green transformation. It promotes enterprises to carry out full-cycle carbon emission management and clean energy structure optimization, makes breakthroughs in carbon reduction and carbon sequestration technologies, establishes a carbon footprint management system, and strictly monitors the carbon emissions of the whole life cycle from raw material procurement to product recycling.

Chain: Reflecting the whole link collaboration of the supply chain, it is the ecosystem of enterprise green transformation. It focuses on building a green supply chain, realizing upstream and downstream collaborative emission reduction, and building a closed-loop industrial ecology from R&D, production to recycling with chain-leading enterprises as the core, so as to share transformation costs and realize the overall green upgrading of the industrial chain.

Innovation: Highlighting innovation leadership, it is the power source of enterprise green transformation. It drives green transformation through technological, model and management innovation, carries out industry-university-research cooperation to develop green process technologies, and tries new business models to activate the endogenous power of transformation.

2.2.2. Basic Theories

This study is supported by three core theories:

Innovation-Driven Theory: This theory holds that technological innovation and institutional innovation are the core drivers of economic growth and industrial upgrading (Wang et al., 2019). For SSDI enterprises, innovation is their core competitive advantage, and green technological innovation, management model innovation and industrial chain collaboration innovation are the fundamental driving forces to achieve green transformation.

Circular Economy Theory: This theory emphasizes the construction of a closed-loop economic system of "resource-product-recycled resource", which requires enterprises to reduce resource consumption and pollutant emissions in the whole production process, and realize the efficient recycling of resources. This is consistent with the core connotation of the "Chain" dimension in the PCCI framework, and provides a theoretical basis for the construction of industrial chain collaborative transformation path.

Stakeholder Theory: This theory holds that the development of enterprises is affected by multiple stakeholders including the government, customers, suppliers, financial institutions and the public. The green transformation of SSDI enterprises is driven by the combined effect of external stakeholders such as government regulation, green credit and market demand, and internal stakeholders such as enterprise management and employees, which provides a theoretical basis for the analysis of transformation driving factors in this study.

3. Research Design

3.1. Research Methods

This paper adopts a combination of quantitative empirical analysis and case study, and the core research methods (Wang & Yin, 2025) are as follows:

3.1.1. Carbon Emission Decoupling Model

This paper combines the OECD decoupling index model and Tapio model to construct a decoupling elasticity model to examine the relationship between economic growth and carbon emissions in Yantai City and sample enterprises, and judge the decoupling state between economic development and carbon emissions. The core formula is:

$$t(C,G)=\frac{\Delta C/C_0}{\Delta G/G_0} \tag{1}$$

where $t(C,G)$ is the decoupling elasticity index of carbon emissions and regional GDP (or enterprise operating income); ΔC and ΔG are the changes in carbon emissions and GDP (operating income) during the study period; C_0 and G_0 are the base-period values of carbon emissions and GDP (operating income), respectively. Before the analysis, the data are standardized to eliminate the dimensional difference between variables. According to the value of the decoupling elasticity index, the decoupling state is divided into three categories: negative decoupling, decoupling and coupling, and eight sub-levels.

3.1.2. Super-Efficiency SBM Model with Undesirable Outputs and Malmquist-Luenberger (ML) Index

This paper adopts the super-efficiency SBM model with undesirable outputs to measure the static green development efficiency of sample enterprises, which can effectively solve the problem of input-output slack and include undesirable outputs (such as pollutant emissions and carbon emissions) into the evaluation system, so as to more accurately reflect the actual green transformation efficiency of enterprises. On this basis, the ML index is used to decompose the dynamic change of enterprise total factor productivity, which is decomposed into green technology efficiency change (EC) and green technology progress change (TC) so as to identify the core drivers of enterprise green efficiency change.

3.1.3. Ecological Welfare Performance Model

This paper uses the ecological welfare performance model to quantify the comprehensive effectiveness of the sample enterprises' green transformation, which measures the ratio of economic and social output brought by unit ecological input, and can effectively reflect the decoupling degree between enterprise development and ecological environment pressure. The formula is:

$$SD=\frac{F}{E} \tag{2}$$

where SD denotes ecological welfare performance, F denotes the economic and social function output of the enterprise (measured by operating income, tax payment and employment scale), and E denotes the ecological environmental footprint of the enterprise (measured by total carbon emissions, energy consumption and water consumption).

3.1.4. Case Study Method

This paper takes Wanhua Chemical, the leading SSDI enterprise in Yantai, as a typical case, conducts an in-depth analysis of its green transformation practice under the PCCI framework, summarizes its successful experience, and verifies the applicability of the PCCI framework, so as to provide a practical reference for other SSDI enterprises.

3.2. Sample Selection and Data Sources

3.2.1. Sample Selection

This paper selects two levels of samples for research:

Regional level: Yantai City, Shandong Province, with the research period from 2014 to 2023, to analyze the overall decoupling state between economic growth and carbon emissions in the region, and clarify the macro background of enterprise green transformation.

Enterprise level: Wanhua Chemical Group Co., Ltd., the leading SSDI "little giant" enterprise in Yantai, with the research period from 2019 to 2023, to conduct in-depth empirical measurement and case analysis of its green transformation efficiency and practice.

3.2.2. Data Sources

The data used in this paper mainly come from the following channels:

Regional statistical data: *Shandong Statistical Yearbook* (2015-2024), *Yantai Statistical Yearbook* (2015-2024), the official website of Shandong Provincial Bureau of Statistics and Yantai Municipal Bureau of Statistics.

Enterprise data: Wanhua Chemical's annual reports, ESG reports, social responsibility reports and official announcements from 2019 to 2023, as well as the first-hand data obtained from the team's field research on the enterprise.

Literature data: Relevant research results at home and abroad collected from CNKI, Web of Science and other academic databases.

3.3. Variable Setting

For the super-efficiency SBM model, this paper sets the input, expected output and undesirable output variables as follows:

Input variables: Total assets (million yuan), total energy consumption (10,000 tons of standard coal), number of employees (person), total fresh water consumption (10,000 m^3).

Expected output variables: Operating income (million yuan), net profit (million yuan).

Undesirable output variables: Total carbon emissions (10,000 tons of CO_2e), solid waste generation (10,000 tons).

4. Empirical Results and Case Analysis

4.1. Decoupling Analysis of Economic Growth and Carbon Emissions in Yantai City

Based on the carbon emission decoupling model, this paper calculates the decoupling elasticity index between GDP and carbon emissions in Yantai City from 2014 to 2023, and the results are shown in **Table 1**.

It can be seen from the results that the economic growth of Yantai City has basically achieved decoupling from carbon emissions during the study period.

Since 2017, it has entered a state of strong decoupling for many years, which indicates that the green low-carbon transformation of the regional economy has achieved remarkable results, and the industrial development has gradually got rid of the dependence on high carbon emissions (Zhu & Xiang, 2025). This provides a good macro environment for the green transformation of SSDI enterprises in Yantai, and also puts forward higher requirements for the low-carbon development of enterprises.

Table 1. Decoupling state between economic growth and carbon emissions in Yantai city (2014-2023).

Year	GDP Growth Rate (%)	Carbon Emission Growth Rate (%)	Decoupling Elasticity Index	Decoupling State
2014-2015	8.4	3.2	0.38	Weak Decoupling
2015-2016	8.1	1.7	0.21	Weak Decoupling
2016-2017	7.2	0.9	0.13	Weak Decoupling
2017-2018	6.6	−0.5	−0.08	Strong Decoupling
2018-2019	5.5	−1.2	−0.22	Strong Decoupling
2019-2020	3.6	−2.1	−0.58	Strong Decoupling
2020-2021	8.0	1.1	0.14	Weak Decoupling
2021-2022	5.1	−0.8	−0.16	Strong Decoupling
2022-2023	5.5	−1.4	−0.25	Strong Decoupling

4.2. Green Transformation Efficiency Measurement of Wanhua Chemical

4.2.1. Static Efficiency Measurement Based on Super-Efficiency SBM Model

This paper uses MaxDEA software to calculate the green transformation efficiency of Wanhua Chemical from 2019 to 2023 based on the super-efficiency SBM model with undesirable outputs, and the results are shown in **Table 2**.

Table 2. Green transformation efficiency of Wanhua chemical (2019-2023).

Year	Super-Efficiency SBM Value	Efficiency Ranking
2019	0.782	5
2020	0.845	4
2021	0.913	3
2022	1.056	2
2023	1.124	1

The results show that the green transformation efficiency of Wanhua Chemical has shown a continuous upward trend from 2019 to 2023, and the efficiency value exceeded 1 for the first time in 2022, reaching the effective frontier of production (Wu & Hou, 2024). This indicates that the green transformation measures of Wanhua Chemical under the PCCI framework have achieved significant results, and the enterprise has realized the coordinated improvement of economic benefits and environmental benefits.

4.2.2. Dynamic Efficiency Decomposition Based on ML Index

This paper further decomposes the ML index of Wanhua Chemical's green total factor productivity, and the results are shown in **Table 3**.

Table 3. ML index and its decomposition of Wanhua chemical (2019-2023).

Year	ML Index	Technology Efficiency Change (EC)	Technology Progress Change (TC)
2019-2020	1.087	1.032	1.053
2020-2021	1.102	1.041	1.059
2021-2022	1.135	1.058	1.073
2022-2023	1.152	1.064	1.083
Annual Average	1.119	1.049	1.067

The results show that the average annual ML index of Wanhua Chemical from 2019 to 2023 is 1.119, which means that the green total factor productivity of the enterprise has increased by an average of 11.9% per year. From the decomposition results, both the technology efficiency change and technology progress change have maintained a growth trend, and the contribution rate of technology progress change (6.7%) is slightly higher than that of technology efficiency change (4.9%). This indicates that the improvement of Wanhua Chemical's green transformation efficiency is driven by both the improvement of resource allocation and management efficiency, and the breakthrough of green technology, among which technological innovation is the core driver (Liu, 2024).

4.3. Ecological Welfare Performance Evaluation of Wanhua Chemical

Based on the ecological welfare performance model, this paper calculates the ecological welfare performance of Wanhua Chemical from 2019 to 2023, and the results are shown in **Table 4**.

Table 4. Ecological welfare performance of Wanhua chemical (2019-2023).

Year	Ecological Welfare Performance (SD)	Year-on-Year Growth Rate (%)
2019	0.652	-
2020	0.718	10.12
2021	0.795	10.72
2022	0.883	11.07
2023	0.976	10.53

The results show that the ecological welfare performance of Wanhua Chemical has maintained a steady growth during the study period, with an average annual growth rate of more than 10%. This indicates that the enterprise has realized the continuous improvement of economic and social output under the premise of controlling the ecological environment footprint, and the green transformation has realized the win-win of economic benefits, social benefits and ecological benefits.

4.4. In-Depth Case Analysis of Wanhua Chemical's Green Transformation Practice

Combined with the empirical results, this paper conducts an in-depth analysis of Wanhua Chemical's green transformation practice under the PCCI framework, and summarizes its core experience as follows:

Precision: Lean management to achieve precise emission reduction: Wanhua Chemical integrates green development goals into all links of production and operation, optimizes the production process through refined management, and realizes the precise control of energy consumption and emissions. For example, the company has built an intelligent energy consumption monitoring system, which reduces the unit product energy consumption by 20% compared with the base year through process optimization and new catalyst application, and the water cycle utilization rate has reached more than 98% (Wang & Qiao, 2024).

Carbon: Full-cycle carbon management to anchor the Dual Carbon goal: Wanhua Chemical has set the goal of "carbon peaking no later than 2030 and carbon neutrality by 2048", which is 12 years ahead of the national goal. The company has built a full life cycle carbon footprint management system, actively laid out new energy projects such as offshore wind power and photovoltaic, and is expected to achieve 100% clean power coverage in Chinese parks by 2030. At the same time, it has built a CCUS platform to promote the resource utilization of carbon dioxide, with an annual carbon dioxide recovery of 150,000 tons.

Chain: Industrial chain collaboration to build a green ecological closed loop: As the "chain leader" of Yantai's green chemical industry chain, Wanhua Chemical gives full play to its innovation advantages, outputs low-carbon process packages to 30 downstream enterprises, and drives the carbon intensity per unit output value of supporting enterprises to decrease by 18%. At the same time, it has established a collaborative hazardous waste disposal center for the industrial chain, with a resource recycling rate of 90%, realizing the collaborative emission reduction of the whole industrial chain.

Innovation: Technological innovation to activate the endogenous power of transformation: Wanhua Chemical has always taken technological innovation as its core competitiveness, with a R&D team of more than 2,800 people, and has made a number of breakthroughs in green chemical technology. For example, the MDI waste brine circulation technology developed by the company reduces carbon emissions by about 700,000 tons per year, and the chlorination hydrogen oxidation cycle technology saves 710 million kWh of electricity per year. The company has also established a "school-enterprise 4 + 1 model" with a number of universities to cultivate professional technical talents for the whole industrial chain (Chu et al., 2024).

4.5. Bottlenecks of Green Transformation of SSDI Enterprises in Yantai

Combined with the empirical results and field research, this paper summarizes the core bottlenecks faced by SSDI enterprises in Yantai in the process of green transformation:

Insufficient technological innovation transformation capacity: Most small and medium-sized SSDI enterprises have limited R&D investment, and it is difficult to break through the core green technology bottleneck. Compared with leading enterprises such as Wanhua Chemical, the contribution rate of technological progress to green efficiency is low, and the innovation achievements are difficult to transform into actual emission reduction benefits.

High pressure of transformation cost and financing constraints: The green transformation of enterprises requires a large amount of upfront investment in equipment renewal and technological transformation, and the return cycle is long. Most SSDI enterprises have limited financing channels, and it is difficult to obtain sufficient green financial support, which restricts the implementation of transformation measures.

Insufficient industrial chain collaborative capacity: Most SSDI enterprises are in the middle and lower reaches of the industrial chain, and it is difficult to participate in the collaborative emission reduction of the whole industrial chain. The green supply chain system has not been fully constructed (Han et al., 2024), and the transformation cost cannot be shared through industrial chain collaboration, resulting in a high single transformation cost of enterprises.

Weak digital and refined management foundation: Many small and medium-sized SSDI enterprises have not yet built a complete intelligent energy consumption and carbon emission monitoring system, and the refined management level is insufficient. It is difficult to achieve precise control of the whole process of emissions, and the management efficiency of green transformation needs to be improved.

5. Optimization Paths and Countermeasures of Green Transformation Under the PCCI Framework

Combined with the empirical results and the identified transformation bottlenecks, this paper constructs a four-dimensional green transformation path under the PCCI framework for SSDI enterprises in Yantai, and puts forward targeted countermeasures for enterprises and the government.

5.1. Green Transformation Paths Under the PCCI Framework

5.1.1. Technological Innovation Drive: Opening up the Green Track with "Innovation"

Technological innovation is the core engine of green transformation, which is the key to solving the bottleneck of insufficient innovation capacity of SSDI enterprises. First, enterprises should increase R&D investment in green technologies, focus on key areas such as low-carbon materials, energy-saving technology and CCUS, and break through technical bottlenecks through industry-university-research collaborative research with universities and research institutions. Second, enterprises should learn from the experience of Wanhua Chemical, establish a sound talent training and incentive mechanism, introduce professional technical talents, and cultivate the internal innovation team. Third, enterprises should actively carry out technological transformation around the key links of energy conservation and emission reduction, promote the application of mature green technologies, and transform technological innovation achievements into actual emission reduction benefits (Li & Ke, 2024).

5.1.2. Industrial Upgrading Leadership: Building a Symbiotic Ecology with "Chain"

Industrial chain collaboration is an effective way for SSDI enterprises to share transformation costs and achieve collaborative emission reduction (Gao et al., 2025). First, give full play to the leading role of chain-leading enterprises such as Wanhua Chemical, build a green supply chain standard system, drive the green upgrading of upstream and downstream supporting enterprises through green procurement, technology output and resource sharing, and form a "PCCI industry community". Second, SSDI enterprises should actively integrate into the green industrial chain, strengthen the collaborative cooperation with upstream and downstream enterprises, jointly build environmental protection infrastructure such as hazardous waste disposal and energy sharing, and reduce the single transformation cost. Third, promote the construction of low-carbon circular industrial parks, realize the sharing of green technology and environmental protection facilities among enterprises in the park, and build a closed-loop industrial ecology of "R&D-production-recycling" (Zhao et al., 2023).

5.1.3. Energy Structure Optimization: Navigating the Low-Carbon Revolution with "Carbon"

Optimizing the energy structure is the core measure to achieve the Dual Carbon goal and reduce the carbon emission intensity of enterprises. First, enterprises should accelerate the replacement of clean energy, expand the application proportion of renewable energy such as wind power and photovoltaic, and build a diversified clean energy system of "nuclear, wind, solar and energy storage" by combining the regional advantages of Yantai as a northern clean energy center. Second, enterprises should carry out energy-saving transformation of high-energy-consuming equipment, eliminate backward production capacity, optimize the production process, and reduce energy consumption per unit product. Third, enterprises should establish a full life cycle carbon footprint management system, realize the precise monitoring and accounting of carbon emissions in all links, and incorporate carbon emission control into the whole process of production and operation.

5.1.4. Green Responsibility Commitment: Building the Ecological Bottom Line with "Precision"

Refined management is the foundation to ensure the effective implementation of green transformation measures. First, enterprises should elevate green development to the core strategic level, incorporate green transformation goals into the medium and long-term development planning, and establish a sound green performance evaluation system. Second, enterprises should accelerate the digital transformation, introduce intelligent monitoring systems such as the Internet of Things and AI, build an intelligent energy consumption and carbon emission management platform, and realize the precise control of resource consumption and emissions in all links. Third, enterprises should actively assume social responsibility for environmental protection, strengthen the disclosure of ESG information, enhance the brand image through green development, and transform environmental protection costs into economic benefits through carbon sink trading and other models.

5.2. Targeted Countermeasures

5.2.1. For Enterprises: Building Core Capabilities for Green Transformation

Strengthen the strategic leadership of green development, integrate the PCCI framework into the enterprise's development strategy, clarify the phased carbon emission reduction targets and transformation roadmap, and balance the short-term cost and long-term benefit of transformation.

Increase R&D investment in green technologies, establish industry-university-research cooperation alliances, accelerate the transformation of innovation achievements, and take technological innovation as the core driver of green transformation.

Actively integrate into the green industrial chain, strengthen the collaborative cooperation with upstream and downstream enterprises, participate in the construction of green supply chain standards, and share transformation costs through industrial chain collaboration.

Accelerate digital transformation, improve the level of refined management, build an intelligent carbon emission monitoring system, and realize the precise control of the whole process of emissions.

5.2.2. For the Government: Improving the Supporting System for Transformation

Strengthen policy guidance and incentives, formulate targeted special support policies for the green transformation of SSDI enterprises, set up special subsidies and green transformation risk pools, and reduce the upfront investment pressure of enterprises.

Improve the green financial service system, encourage financial institutions to innovate green financial products such as green credit and green bonds, establish a credit evaluation system for the green transformation (Jia et al., 2024) of enterprises, and reduce the financing threshold for SSDI enterprises.

Build a public service platform for green transformation, provide integrated services such as technical consultation, carbon footprint accounting and achievement transformation for SSDI enterprises, and promote the popularization and application of mature green technologies.

Promote the construction of industrial collaborative ecology, support leading enterprises to drive the collaborative transformation of the industrial chain, promote the construction of low-carbon circular industrial parks, and create a good external environment for the green transformation of SSDI enterprises.

6. Conclusion and Prospect

6.1. Research Conclusion

This paper takes SSDI enterprises in Yantai City as the research object, constructs the "Precision Carbon Chain Innovation (PCCI)" theoretical framework, takes Wanhua Chemical as a typical case, uses a variety of quantitative models to carry out empirical analysis, explores the green transformation path of SSDI enterprises under the PCCI framework, and draws the following main conclusions:

First, the PCCI framework integrating the four dimensions of "Precision, Carbon, Chain and Innovation" is highly compatible with the development characteristics of SSDI enterprises, and can provide a systematic theoretical guidance for the green transformation of such enterprises. The four dimensions are interrelated and mutually supportive, forming a complete closed-loop system of green transformation.

Second, the economic growth of Yantai City has basically achieved strong decoupling from carbon emissions, which provides a good macro environment for the green transformation of SSDI enterprises. The empirical results show that the green transformation efficiency, green total factor productivity and ecological welfare performance of Wanhua Chemical have maintained a continuous upward trend from 2019 to 2023, and its transformation practice under the PCCI framework has achieved remarkable results, which verifies the applicability of the PCCI framework.

Third, the green transformation of SSDI enterprises in Yantai is still facing four core bottlenecks: insufficient technological innovation transformation capacity, high financing constraints, insufficient industrial chain collaborative capacity, and weak refined management foundation. The four-dimensional transformation path constructed under the PCCI framework can effectively solve these bottlenecks, and has strong replicability and popularization value for similar SSDI enterprises.

6.2. Research Prospect

This study constructs the PCCI theoretical framework and carries out empirical analysis with typical cases, but there are still some limitations. In the future, further research can be carried out in the following aspects: First, expand the research sample, include more SSDI enterprises in different industries for comparative analysis, and explore the heterogeneity of green transformation paths of enterprises in different industries. Second, construct a long-term dynamic evaluation system for the effectiveness of green transformation, and conduct a follow-up study on the long-term transformation effect of enterprises. Third, further deepen the research on the industrial chain collaborative transformation mechanism, and explore the benefit distribution and risk sharing mechanism in the collaborative transformation of the industrial chain.

Acknowledgements

We would like to express our sincere gratitude to Professor Wang Chongmei for her professional guidance and strong support throughout the research process. We also thank the relevant departments of Yantai Municipal Government for their help in the field research, and the management and technical staff of Wanhua Chemical, Longgang Pump Industry and other enterprises for accepting our interviews and providing valuable practical materials. Finally, we thank all the team members for their hard work and collaboration in this research project.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Cao, H. J., Zhang, S., Ouyang, Y., & Xiong, J. (2022). Innovation Policy and Innovation Quality of Specialized, Sophisticated, Distinctive and Innovative SMEs. *China Industrial Economics, No. 11,* 135-154. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGHAz97XMaatW2K6U-JaWWz5-Ix-9KImvSMUfMe2KZNVpTe-4aEYCsv-gp5L7VaR_QlMBMvEebIEms0G9t-6deHY5Wp67Ul7m1WHm8sS7H40B_Xh71dGfOqChEupMCLTGYE72CMZQC7En-WgeRG1rR17MLt9Yg1AH1Mpbo6cbzPrJAg==&uniplatform=NZKPT&language=CHS

Chu, M. Y., Ma, Q., & Li, M. X. (2024). Research on Influencing Factors of Green Innovation in Shandong Advanced Manufacturing Industry: A Case Study of Wanhua Chemical. *Enterprise Science and Technology & Development, No. 7,* 42-46. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGFWU7l4opN-zuo11MeE1hFkFdLALaNJPvGJjk-LFqeoyxZh-Ap-pkhYyFDYwGJdx-HcBoQD8KVfFcc3LF-_osxBY8Fj2cin6VTl8Lb4EpferQvge-sUmVJyjEiVPtmLi6lsKPDoq71ta-ynfHqJGLuAfWt2NnkEzHPkBYA7umSJaYqPtjDaMmGiBj_f5hJ8ON-fk&uniplatform=NZKPT&captchaId=8f504657-abb1-4a35-bbfb-da3266729e0e

Dong, Z. Y., & Li, C. M. (2021). High-Quality Development Trend and Path Choice of Specialized, Sophisticated, Distinctive and Innovative SMEs. *Reform, No. 10,* 1-11. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGHKMQ8TzACQGnuh-wwcW3I0cOi5-4S28ips5E9Ju7iQOUFz7acT411PlWAMp2o2-wKHzfoyuNGQ3BUS7akwlG10XR-eIuS3QgkGBam2U_WNZC3U8fd5Uxe8mCHAh3RO38vs12S0AfYbn-YF9Va2-ZX7sPiW2ljFStPYSyRGyL-QTvA==&uniplatform=NZKPT&language=CHS

Gao, X. Y., Han, Z. X., & Dong, S. Y. (2025). Supply Chain Dual Synergy and Green Innovation of Specialized, Sophisticated, Distinctive and Innovative Enterprises: fsQCA

Analysis from a Collaborative Perspective. *Journal of Industrial Technological Economics, 44,* 13-21. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGGq8TtnVQno-1iUny8jovnWXj3sopqjhhLTd-O4X6Tb6GUSQS9OVq1K1CM4cVGK9oT-rPrzaamCvPmUQvBUsLPhK_S4a8Y8mtnqj_9otjDxUogCqklZNJhaDYJnPu-HYmIal1LtD5ry_SJ63_mfxSW1rn-aIbK_pn2_T4b3jlCjrYzQ==&uniplatform=NZKPT&language=CHS

Gui, H. B., Li, S., Li, W. J., & Liu, H. L. (2026). Research on the Mechanism of Data Elements Empowering High-Quality Development of Specialized, Sophisticated, Distinctive and Innovative Enterprises. *Science Research Management, 47,* 25-34. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGHW18FayYoEtrx2MMULH1NHDy4qVLUKq0cIVw1XlDCb2UBpIDQ9CsmkElrlTB3dwaNwxd_fYBga7iDOmb_gii3YPc1dlVY-Wruk9xeJWrOy6uSY0dxEvymo8rua-cNiKwqDykp9Leb1_s7SqaJmsPNR_PEkRM-pZXb_z8olvFHWhreg==&uniplatform=NZKPT&language=CHS

Han, H. L., Peng, Y., Liu, Q., & Jiang, X. Y. (2024). Little Giant Big Effect: Specialized, Sophisticated, Distinctive and Innovative Certification, Supply Chain Spillover and Enterprise Productivity. *The Journal of Quantitative & Technical Economics, 41,* 177-198. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGG4jDi9DqEpNYbjbZ-Tetf6oF0cG4YjLPwPeKc8yn9WUJPFsdMKQ5XJB11lMflPY4reZkAlbQQWBio_kexo-aJdSpIO_qqp1qqQvOgeIxLGR864H3RP8d9gIOKCaDPpmLwjMaZ-BYy8BU8pvRfeVvjkQBhj2H10dcLNc9Rvi9D2noAcA==&uniplatform=NZKPT&language=CHS

Hong, T., & Zhang, Y. R. (2026). Research on the Impact of Specialized, Sophisticated, Distinctive and Innovative Certification on Enterprise Technological Innovation. *Science Research Management, 47,* 90-100. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGEXU8AMjV_ukYaTYVda-HuE8V-Dtl109GbPFca-OGam_AGtlHxthPcmHF78ujJFg44Hlvmho-Azdg_lF2mJiLai32gs-eQRB1AHz3YvxDsR2i3pSptV7MB2x8JXqW-dogz5OKiev2ZWMHi6gofKyZ2zYkbDFJrWTjVQZ2DKIsTjM1jew==&uniplatform=NZKPT&language=CHS

Jia, J. N., Zhang, R. H., & Zhao, B. Q. (2024). Research on Green Finance Empowering Digital Transformation of Specialized, Sophisticated, Distinctive and Innovative SMEs. *Modern Business, No. 10,* 113-116. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGGVs0k1Wny-PHNNggyX4AR3fnuOnhcIgPwC5RPZDLj4Zop8pELdptnK-waWPUv2wIq0pveq_DgUa9xJgLa7HjU0Wjphw8ytFg6KzeGv2d079-62asAWc7wwKRu1CpRHhvDMGZF5Rgm9SWguUvHg9wZCeZukqkG-zEL87AeewVe9b4hvA==&uniplatform=NZKPT&language=CHS

Jiang, W. (2025). Model Innovation and Path Optimization in Digital Upgrading of Specialized, Sophisticated, Distinctive and Innovative Enterprises. *Do Business and Trade Facilitation Journal, 5,* 103-117.
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGFLFed3fe9xAQGcl79AOplR04HtBBseMAEE69cKy6BHB1umBy-iLtM7f11xtrE5R8ItxIyEDdZXBk-P474bnjNCIZNuQbbqoAt-THKHePoukt5lFJdtzUZcAsbTNZkvv5sOQ5wcxL5JqTjjXGiAvUK6LRyLi-fxnjPGjSmO_ihUMo1k-0OvX86DHLCXkAH0E3wBnNCXjg3RxUWDQ==&uniplatform=NZKPT&language=CHS

Li, J. S., & Ke, W. (2024). How Knowledge Search and Reconstruction Promote Green Technology Innovation of Specialized, Sophisticated, Distinctive and Innovative SMEs.

Science & Technology Progress and Policy, 41, 111-121. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGHgrAg8kvLT-
fFuj5kPDMX_Gz48KuQoTyz2KFCormvsyhPOoOB1yZc8K9H5zVGrxv1URXRO_cvR
kD1IVrqXwn-
aoE8S5V21VjQEqb1bGfhPsZBU8gKAOJn1yFMDHD5Rdx7rKr_5DJm_EN6BMd1k7lB
cbWHTea1jqA6tfVjStQRQAwZQ==&uniplatform=NZKPT&language=CHS

Liu, X. T. (2024). Impact of Green Transformation on Corporate Financial Performance: A Case Study of Wanhua Chemical. *Accountant, No. 10,* 58-60. (In Chinese)
https://kns.cnki.net/kcms2/article/ab-
stract?v=BKa2HtjuZGHLmfBXOC79EjEv2EYeyDnV2ilyknOAy_bZSF5OHFbWjZ-
Teuaf42qkraeI9_lZ7-08yovMemzZ-t2ctmxUHOOmxdozUPLLNENjKkaM-
jbE7cZ85OJIMcosHIgBCsPJwftZuKQkK5tA9KY1ATx6jFxSB4p1G-
4Wbf7eO2NkQliuyvuA==&uniplatform=NZKPT&language=CHS

Pang, W. Y., & Zhu, J. H. (2025). Research on the Impact of Innovation Incentive Policies on Enterprise Green Transformation under Specialized, Sophisticated, Distinctive and Innovative Orientation: A Quasi-Natural Experiment Based on Little Giant Enterprises. *Frontiers of Engineering Management,* 1-12. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGFhn5QZ7Scd1KREY-
hfjEe8N6TIVS69QdovjaST5pZsmXDNM6OMkJVs5gIGZ49VT1-
jwYnnA3mY19Uw3_qbtfRX0geOEU5LVd78AMV5fNzY7s6JQCmWtufGL9qpSgems-
GXFVQpL4MmH_H0inMxEW0McQExyJHHVZd30uMcqNTmwt5w==&uniplat-
form=NZKPT&language=CHS

Wang, C. M. (2025). *Research on Green and Low-Carbon High-Quality Development in Shandong Province.* China Financial & Economic Publishing House. (In Chinese)

Wang, C. M., Wang, C. H., & Liu, C. G. (2019). Measurement and Evaluation of Regional Green Collaborative Development Capability Based on Systematic Innovation. *Science and Technology Management Research, 39,* 53-58. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGHu-
Jemh7Md_cpU8CQORg1K6qzzRr6IIhuQIgyXMNOj-
VtdJzVHCXwg7vsjWdFj0SwlUtFwvSEvRrFE97ADyWiLDETscrXuD-
MgKjyROEGYBw1Yt7vg2sLRIfN5h2oXD9DvoXDa0coQZxw1rpx16rvkw98lWh2xz3J
MOev8glL9fy9Aw==&uniplatform=NZKPT&language=CHS

Wang, M. H., & Yin, X. X. (2025). Research on Economic Benefit Evaluation of Digital-Intelligence Enabling Green Transformation of Specialized, Sophisticated, Distinctive and Innovative Enterprises. *Marketing Circle, No. 6,* 142-144. (In Chinese)
https://kns.cnki.net/kcms2/article/ab-
stract?v=BKa2HtjuZGHaJAADTQaIG78fv6Elb9yVlijr1FrRbmBkJVCs-
QyYbWPqtmm4jxuT_Xc6luObIADTJGJ2Mz-o7zqlvjSHK4kuGElz-YldkYJVoWDy-
pLU8EjB1CmOA1P0MOwvPYH15pKP9tyGfgmYMtBjVUKapSR7N08QLvXJcyh4m6R
_An3UHTg==&uniplatform=NZKPT&language=CHS

Wang, X. L., & Qiao, H. L. (2024). Mechanism and Path of Digitalization Enabling Green Transformation of Chemical Enterprises: A Case Study of Wanhua Chemical. *Finance and Accounting Monthly, 45,* 89-96. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGH34-Ghl_rKLO7xlPbwS-
SeYUk2k9fBKGjyVyteM8o-nkkTNRAaAxa-
OIpDcp4ZPUlr45XmQMWiVRay6T4qF5IQguceMsB0UY5qci_lT43EP5PdjX942_60T
AfJGbOfU9aBTPQhmjPVDYkkWcpnkAqWb7D3In-
wgCtOokF56ChMErhg==&uniplatform=NZKPT&language=CHS

Wu, S. C., & Hou, J. P. (2024). Low-Carbon Transformation Path and Performance Evaluation of Wanhua Chemical under Dual Carbon Goal. *Financial Management Research,*

No. 9, 73-78. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGEc1l-L0OvT69oEkbo1bPmONzxEtEiLwTCooNETEfHeyZagKwVorIOx-SLdBp1WSOK1nN18oR2J0uPNdAaPKSuQ5E-dWUMWWu1Nd0P1S1NU4x_dfRjR-FOzlk9LcaoMfznPK-2ZjJ8blglSwY1djk_kg3gPw1tqTzN--I57bvZPER6g==&uniplatform=NZKPT&language=CHS

Yan, Y. S., & Wang, R. X. (2025). Digital Transformation of Specialized, Sophisticated, Distinctive and Innovative SMEs and Green Technology Innovation. *Science Technology and Industry, 25,* 247-254. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGHVQ5Vku9hxjxSQVzk1OyU3zzADdj5Op5NhgMrNiY-xU5B8lGR7ihMZiqLyUKjXwMgFzANo2UWvcuZcUKHRgRFu9ZAkzmqvd-COQkDIKKzBz-3ROn70Tbkqb9rCKxwKdfz_N8ALd-faH9jM4clzF8zd8axnrZsbayRxt6z1rgO7pnnA==&uniplatform=NZKPT&language=CHS

Yu, Q. Y. (2025). Research on Green Development and Cost Control Strategy of High-Tech Manufacturing under Dual Carbon Goal: A Case Study of Yantai City. *Journal of Yantai Vocational College, 20,* 7-12. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGEIzYK6DD_5cLxE4Nzg-_9y88nzcN7dPhkMOqAv7Q_sRgH-NiZLfMOSXLbP4cFFkxKmA_TPkqCoUx0KUVPX_5iseLfttC9afOOiOw2sa7MV9ZNdo9O7jv_Dtt3Ozq5uejm8rFfEoYcAVSDTET_d57vofZZJQBT2NG7DLfWshsMr8Vw==&uniplatform=NZKPT&language=CHS

Zhao, J., Sun, Z. J., Cheng, Q. Y., & Zhou, B. (2023). How SMEs Strengthen Industrial Chain Relying on Specialized, Sophisticated, Distinctive and Innovative Development. *China Industrial Economics, No. 7,* 180-200. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGG8A_zY2Q14Q3Cx83lytqFydq2DUD-lUJMxI8tQWccYVg_cvO8IZcIlgSD-z0tr4LAtzUJ5pTeVuP1OBEPfaD9Ab7LbqHql-zolBo52z72AXJ2m18b9M9cy5G2YFMF3_-CcPm-z0HNOUCFQDj0VWPsSG1CF4CaRb0HiW-dZhqQ45r3A==&uniplatform=NZKPT&language=CHS

Zhu, Z. Q., & Xiang, X. H. (2025). Research on the Impact of Specialized, Sophisticated, Distinctive and Innovative "Little Giant" Policy on Enterprise Emission Reduction and Efficiency Improvement. *Coal Economic Research, 45,* 81-92. (In Chinese)
https://kns.cnki.net/kcms2/article/abstract?v=BKa2HtjuZGFVM6zOMgMFFW65cEYahnhM97urigoHFHsZFvSVh8l1yPFwYM8IAmewazgGceAEhlIO4yJ2DdR-Kg1ydw0pp9dqRcJtro91UzeCCn5Gy0CzPZhjP67JoqSB4pIAMYQorwDR_UP-cdZg9IFDSshcyZpZFdI7BNxOjf2Tlwv371tsA8Q==&uniplatform=NZKPT&language=CHS