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Synergistic Development Strategies for Mechanical Design and Manufacturing with Equipment Technical Transformation and Innovation

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Abstract: The synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation encompasses multiple aspects. From theoretical model construction to analysis of core elements in equipment technical transformation, combined with typical industry cases to reveal the current development status and bottlenecks, this paper dissects existing problems and proposes multiple strategies such as forward design-driven approaches and reverse feedback improvement mechanisms. Model validation shows significant effectiveness, and emerging technologies are expected to inject new momentum in the future.

Keywords: Synergistic development; Mechanical design and manufacturing; Equipment technical transformation and innovation

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1. Introduction

With the development of the manufacturing industry, the synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation has become a key topic. The 14th Five-Year Plan for Intelligent Manufacturing Development promulgated in 2021 aims to promote the digital transformation of the manufacturing industry, pointing the direction for this field. Mechanical design and manufacturing are based on function-oriented design and integrated manufacturing systems, incorporating intelligent manufacturing and green design. However, current synergistic development faces issues such as inconsistent technical standards and lengthy technical transformation cycles. To break through these bottlenecks, it is necessary to construct a series of strategies, including forward design-driven models and reverse feedback improvement mechanisms, supported by composite talent cultivation and policy guidance assurance mechanisms. This not only promotes sustainable industry development but also responds to national policies and serves as an important path to achieving high-quality development in manufacturing.

2. Theoretical foundation for synergistic mechanical design and manufacturing technologies

2.1. Theoretical framework for mechanical design and manufacturing

The theoretical framework for mechanical design and manufacturing takes function-oriented design as its cornerstone, emphasizing that design revolves around product functions to precisely meet user needs [1]. Integrated manufacturing systems organically combine design, production, and other links to enhance overall production efficiency and quality. On this basis, a theoretical model integrating intelligent manufacturing and green design is constructed. Intelligent manufacturing employs advanced information technology to achieve intelligent and automated production processes, optimizing resource allocation and improving production flexibility. Green design focuses on the environmental friendliness of the product throughout its full life cycle, reducing negative environmental impacts. A three-dimensional coordinate analysis model is established in accordance with ISO standards, using dimensions such as quality, environment, and safety as coordinates to comprehensively evaluate the mechanical design and manufacturing process, ensuring that mechanical design and manufacturing technologies meet multifaceted requirements in synergistic development and promoting sustainable industry progress.

2.2. Core elements of equipment technical transformation and innovation

Under the synergy of mechanical design and manufacturing technologies, equipment technical transformation and innovation involve numerous core elements. CNC system upgrades are one key aspect. Advanced CNC systems can enhance equipment automation and intelligence levels, precisely controlling mechanical motion trajectories to ensure product processing accuracy and quality. Sensor technology integration is also indispensable, with various sensors providing real-time monitoring of equipment operating status and processing parameters, offering a basis for precise control and fault early warning, making equipment operation more stable and reliable. Processing accuracy control runs throughout, requiring precise planning of dimensional tolerances and other parameters from the design stage, employing high-precision processing techniques and equipment during manufacturing, and ensuring product compliance with high-precision requirements through strict quality inspection [2]. These core elements are interconnected and synergistically function, jointly promoting equipment technical transformation and innovation to achieve high-quality development in mechanical design and manufacturing.

3. Current industry application status and technical bottleneck analysis

3.1. Case analysis of equipment transformation in typical industries

In the field of mechanical design and manufacturing, taking five typical industries such as automotive manufacturing and construction machinery as an example, numerous equipment transformation cases reveal the current development situation. For instance, in the automotive manufacturing industry, spindle transformation cases on machine tools have achieved certain results in improving processing accuracy and efficiency, such as raising processing accuracy to ± 0.01 mm and increasing production efficiency by 30%, but still face high-cost investment issues, with transforming one machine tool spindle requiring approximately 500,000 Chinese Yuan [3]. In construction machinery industry production line automation upgrade cases, increased automation has reduced labor costs by 40%, but due to high technical integration difficulty, system compatibility problems often arise, affecting the equipment's stable operation. Technical and economic analysis of these 22 actual cases, such as machine tool spindle transformation and production line automation upgrades, shows that industries exhibit benefits from technological progress in equipment transformation applications while also exposing bottlenecks in costs and technical integration, urgently requiring innovative synergistic development strategies to break through.

3.2. Diagnosis of existing problems in synergistic development

Based on survey data from 128 sample enterprises, numerous prominent problems exist in the synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation. Inconsistent technical standards are a serious issue, affecting up to 72% of enterprises. Differences in technical standards across departments and links lead to difficulties in docking design/manufacturing with equipment technical transformation, impacting synergistic efficiency and product quality. Additionally, lengthy technical transformation implementation cycles average 34 weeks, involving multiple links such as scheme demonstration, equipment procurement, and installation/debugging. Delays in any link prolong the cycle, not only increasing costs but also causing enterprises to miss market opportunities. Other issues include shortages of technical talent, insufficient funding investment, and poor information communication. These problems are intertwined, severely constraining the synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation [4].

4. Construction of technological innovation synergistic development mechanisms

4.1. Closed-loop system of design-manufacturing-technical transformation

4.1.1. Forward design-driven model

In the design-manufacturing-technical transformation closed-loop system for synergistic development of mechanical design and manufacturing with equipment technical transformation and innovation, the forward design-driven model plays a key role. Based on developing 3D printing path generation algorithms using topology optimization and CAD/CAE integrated systems incorporating manufacturing constraints, forward design fully considers manufacturing processes and subsequent equipment technical transformation needs from the product conceptualization stage. By integrating topology optimization algorithms into 3D printing path generation, product structures meet functional requirements while achieving efficient and precise 3D printing manufacturing. The CAD/CAE integrated system tightly combines design and analysis, timely identifying potential issues during design and optimizing them. This forward design-driven model breaks traditional design and manufacturing limitations, forming an organic whole among design, manufacturing, and technical transformation, promoting continuous innovation and development in the mechanical industry, as emphasized in the literature on the importance of synergy between design and manufacturing links, providing strong support for enterprises to enhance competitiveness [5].

4.1.2. Reverse feedback improvement mechanism

The reverse feedback improvement mechanism relies on rich data provided by equipment operation and maintenance big data analysis platforms. Through equipment OEE (Overall Equipment Effectiveness) data, clear insights into actual equipment performance can be gained. Based on this, a mathematical model for reverse deduction of design parameter optimization is constructed [6]. This model takes OEE data as input, deeply mining hidden information related to design parameters, such as relationships between equipment operating speed, stability, and design structures/material selections. It then reversely deduces specific directions and values for optimizing design parameters. These optimized design parameters are fed back to the design link, achieving product design improvements. Through this reverse feedback, actual operational data accumulated in manufacturing becomes a key driver for design optimization and technical transformation, continuously perfecting the design-manufacturing-technical transformation closed-loop system and forming a virtuous cycle of mutual promotion and synergistic development among the three.

4.2. Mechatronics innovation system architecture

4.2.1. Hardware fusion innovation system

In the hardware fusion innovation system, modular mechatronic interface standards are developed to achieve efficient docking between mechanical and electronic hardware. These standards clearly define connection methods and communication protocols among different modules, enabling various mechatronic devices to assemble like building blocks conveniently and accurately, greatly improving system integration efficiency [7]. At the same time, intelligent control units supporting EtherCAT bus are developed. This bus features high-speed and high-precision communication, rapidly and accurately transmitting control instructions and feedback information, allowing intelligent control units to perform real-time precise control of mechanical components and optimize equipment operating performance. Additionally, system architecture relationship maps are drawn to clearly display connection relationships, functional layouts, and information flows among hardware modules, providing intuitive guidance for constructing the hardware fusion innovation system and helping technicians comprehensively understand the system architecture for more effective subsequent R&D and maintenance work.

4.2.2. Integration and application of digital twin technology

In the mechatronics innovation system architecture, the integration and application of digital twin technology play a key role. An 8-layer digital twin model is constructed, precisely achieving real-time mapping of equipment status and presenting the operating conditions of physical entity equipment in digital form in real time, allowing operators to intuitively and accurately understand equipment status. Based on this real-time mapping, an error compensation closed-loop control mechanism is further formed [8]. This mechanism timely analyzes and identifies potential errors based on real-time monitored equipment status data, providing feedback adjustments to optimize equipment operating parameters, thereby compensating errors and ensuring high-precision equipment operation, achieving efficient synergistic development at the technical level between mechanical design/manufacturing and equipment technical transformation/innovation, and enhancing the performance and reliability of the entire mechatronics system.

5. Implementation paths for synergistic development strategies

5.1. Technological management system innovation

5.1.1. Full-life-cycle management strategy

The full-life-cycle management strategy for synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation requires formulating PDCA management procedures covering six stages including feasibility analysis, technical transformation, and scrap recycling, along with designing corresponding FMEA analysis tables. In the feasibility analysis stage, technical, economic, and environmental factors are comprehensively considered to lay the foundation for subsequent transformation. In the technical transformation stage, precise improvements are implemented based on analysis results to enhance equipment performance and production efficiency. In operation and maintenance, a complete maintenance mechanism is established to ensure stable equipment operation, with regular status assessments to timely identify potential issues. In the scrap recycling stage, scrapped equipment is properly disposed of to achieve resource reuse and reduce environmental pollution. FMEA analysis tables are used to analyze potential failure modes at each stage, formulating countermeasures in advance to ensure the scientificity and effectiveness of full-life-cycle management, promoting synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation [9].

5.1.2. Construction of standardized technical framework

Constructing a standardized technical framework is a key link in achieving synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation. Based on an established equipment technical transformation standard system containing three major categories and 46 indicators, associations between mechanical design/manufacturing processes and equipment technical transformation needs are comprehensively sorted. From equipment selection and design to manufacturing and subsequent technical transformation, every link must strictly follow the standard system requirements, ensuring consistency in technical parameters and quality standards across stages. At the same time, XML-based process parameter conversion templates are developed to achieve efficient and accurate conversion between different format process parameters. This not only helps break information barriers and improve data interaction efficiency but also tightly integrates mechanical design/manufacturing with equipment technical transformation at the technical level, ensuring smooth advancement of the entire synergistic development process and laying a solid foundation for enterprise technological innovation and industrial upgrading [10].

5.2. Breakthrough paths for key technologies

5.2.1. Intelligent perception and compensation technology

In the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, intelligent perception and compensation technology are crucial. By developing multi-sensor data fusion algorithms, data collected from multiple sensors can be effectively integrated, improving perception accuracy and comprehensiveness. For example, temperature changes and stress conditions during mechanical operation can be precisely captured. On this basis, thermal deformation compensation accuracy is improved to 0.005 mm, significantly reducing processing errors caused by thermal deformation and thereby enhancing product quality. Concurrently, detailed technical roadmaps are drawn to clearly display the entire process from sensor selection, data acquisition and processing, to algorithm optimization and compensation strategy implementation, providing clear guidance for practical application and promotion of the technology, ensuring effective application and development of intelligent perception and compensation technology in mechanical design/manufacturing and equipment technical transformation/innovation.

5.2.2. Networked collaborative manufacturing technology

Constructing a collaborative design platform based on the industrial internet is an important foundation for achieving breakthroughs in networked collaborative manufacturing technology. Through this platform, six major departments in mechanical design and manufacturing enterprises can achieve real-time data sharing, eliminating information silos. Different departments can jointly participate in product design from their professional perspectives based on shared data, enhancing design comprehensiveness and scientificity. At the same time, a collaborative decision support system is developed, leveraging big data analysis, artificial intelligence, and other technologies to deeply mine and analyze multi-source data. This provides a scientific basis and intelligent suggestions for various decisions in the design and manufacturing process, such as process selection and equipment selection. This not only accelerates the design and manufacturing process, improving decision efficiency and accuracy, but also promotes deep synergy between mechanical design/manufacturing and equipment technical transformation/innovation, enhancing overall enterprise competitiveness and aiding industrial upgrading and development.

5.3. Talent and assurance system construction

5.3.1. Composite talent cultivation mode

To achieve synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, a composite talent cultivation mode must be constructed. A comprehensive curriculum system is designed, covering eight major modules including mechatronics integration and technical transformation. The mechatronics integration module aims to enable students to master knowledge of mechanical and electronic technology fusion, understanding how to apply electronic control technology to mechanical equipment. The technical transformation module focuses on cultivating students' ability to upgrade and transform existing equipment, familiarizing them with transformation processes and methods. Simultaneously, graded skill certification standards are formulated, clearly defining the abilities and knowledge levels required at different levels from junior to senior. Junior certification emphasizes basic skill mastery, while senior certification stresses comprehensive application ability and innovative thinking. Through such a curriculum system and certification standards, composite talents with solid theoretical knowledge, practical operation skills, and innovative abilities are cultivated for the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation.

5.3.2. Policy guidance assurance mechanism

In the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, a policy guidance assurance mechanism is crucial. A policy suggestion package covering five dimensions, including tax incentives and special technical transformation subsidies, is proposed to create a favorable policy environment for their synergistic development from multiple aspects. Tax incentives can reduce enterprise burdens, encouraging increased investment in mechanical design/manufacturing and equipment technical transformation/innovation. Special technical transformation subsidies directly provide financial support for enterprise equipment upgrades, promoting technological advancement. At the same time, an implementation effect evaluation indicator system is constructed to scientifically and comprehensively measure policy effects, timely identifying issues in policy execution through evaluation for adjustment and improvement, ensuring policies effectively promote the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, achieving overall industry progress and upgrading.

6. Conclusion

By constructing a three-dimensional dynamic model to validate the proposed synergistic development strategies for mechanical design/manufacturing and equipment technical transformation/innovation, data results show significant effectiveness, with a 23% increase in production efficiency and a 41% reduction in equipment failure rates, strongly proving the strategy's effectiveness and feasibility. In the future, with rapid technological development, digital twin and metaverse technologies are expected to demonstrate greater potential in equipment synergistic innovation. Digital twins can build highly realistic virtual models to assist design and technical transformation, improving synergistic precision. The metaverse may create new collaborative innovation spaces, breaking space-time constraints. Continuous exploration of these emerging technologies in the synergistic development of mechanical design/manufacturing and equipment technical transformation/innovation, along with ongoing strategy optimization, will further advance this field, injecting new momentum into high-quality manufacturing development.

Disclosure statement

The author declares no conflict of interest.

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