KEY TECHNOLOGIES FOR LOW-CARBON PRODUCTION TOWARDS SUSTAINABLE DEVELOPMENT

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Abstract

To mitigate resource waste and environmental pollution in the manufacturing process, a new production model of Low-Carbon production is proposed and examined. Building upon green production principles and aiming to balance resource efficiency with environmental impact, this research advances theories concerning resource utilization and other critical aspects of the production process.

1 Introduction

Within the context of a Low-Carbon production economy, a critical challenge facing modern manufacturing enterprises during their transformation and development is achieving maximal socio-economic benefits with minimal resource consumption and minimal ecological and environmental impact[1]. Addressing this challenge necessitates the study and application of relevant Low-Carbon manufacturing theories and technical methodologies. There is an urgent need to shift from the traditional resource-intensive model characterized by high consumption, low utilization, and high emissions towards a Low-Carbon, high-energy-efficiency production paradigm. This study initiates from an examination of Low-Carbon emissions and comprehensive resource-energy efficiency in mechanical manufacturing. It investigates the connotation and characteristics of Low-Carbon production and proposes a research framework for key technologies, encompassing theoretical foundations, core content, and enabling technologies. The relevant content is elaborated upon, and implementation strategies along with future prospects for Low-Carbon production are discussed.

2. Connotation and characteristics of Low-Carbon production

2.1 The meaning of Low-Carbon production

Low-Carbon production represents a sustainable enterprise organizational model guided by green environmental protection principles. It integrates principles of efficient and sustainable energy/resource use and stringent environmental emission standards into enterprise production activities, rendering them clean, energy-efficient, safe, highly productive, sustainable, and environmentally benign[2]. It aims to achieve the global common vision of sustainable development of resources, energy, social needs and natural environment. Its core objectives are to minimize environmental impact throughout the production process and to manufacture environmentally sound products that fulfill societal needs using minimal energy and resources[3]. The essence of Low-Carbon production lies in enhancing manufacturing process energy efficiency and reducing greenhouse gas emissions.

2.2 Characteristics of Low-Carbon production

Low-Carbon production strives to maximize value output relative to resource input during production while minimizing environmental impact. This approach safeguards the ecological environment and fosters sustainable socio-economic development. The characteristics are mainly reflected in:

- It coordinates and promotes the sustainable development of resources, ecology, and economy.
- It seeks coordinated and balanced development that optimizes resource utility while minimizing environmental and ecological impacts.
- It contributes to climate change mitigation and advances the global development of Low-Carbon production.

3. Some Key technologies for Low-Carbon Production

Achieving Low-Carbon production involves evaluating carbon emissions and resource utilization at each product lifecycle stage, followed by optimization efforts targeting equipment, processes, and management. Equipment optimization primarily focuses on improving the structural design and manufacturing processes of equipment exhibiting low resource utilization. Process optimization, undertaken at the operational level, aims to enhance production process resource utilization through effective production planning and scheduling. Management optimization, on one hand, enhances resource utilization by optimizing resource scheduling within the production process and streamlining internal resource storage, transportation, and distribution. On the other hand, adopting the value chain perspective, it employs whole-lifecycle cost accounting to enable effective planning and management of upstream, midstream, and downstream resources. This facilitates resource supply-demand balance, significantly reduces resource idle time, operational changeover time, and inventory levels, thereby contributing to Low-Carbon production. (Figure 1 illustrates the framework of these key technologies.)

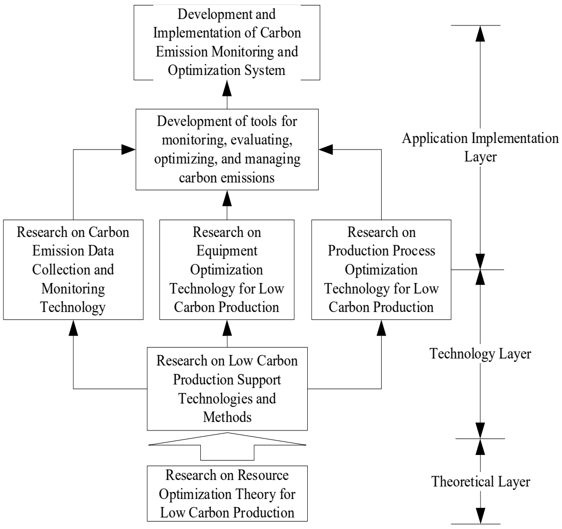

Fig. 1 Framework of Key Technologies for Low-Carbon Production

3.1 Research on the resource utility management theory for Low-Carbon production

Resource utilization management entails the effective oversight of resources throughout the entire production process. Leveraging green manufacturing theory, lean management principles, and value chain theory, and integrating the characteristics of resource management in high-efficiency manufacturing, a theoretical system for resource utilization management is established. This system is developed from perspectives encompassing the resource utilization environment, underlying values, and methodological approaches. Research on resource utilization management within the production process focuses on the efficient use of resources in both production and operational contexts, and seeks to re-engineer enterprise-wide resource utilization. This involves examining and redesigning structures, policies, procedures, processes, management practices, incentive mechanisms, and external relationships with customers and suppliers. The goal is to minimize waste throughout resource utilization and to maximize profitability efficiently and effectively. Research on resource utilization methodology, grounded in the perspectives of the resource utilization environment and core values, analyzes the means for improving resource utilization. Its core encompasses advancements in technology, organizational structures, management models, and methods aimed at enhancing resource utilization. Currently, the widely used theories include SCM (supply chain management), ERP (enterprise resource management), MES (manufacturing execution system), etc.

3.2 Research on technologies and methods supporting comprehensive resource utilization

3.2.1 Resource Utility Data Collection and Monitoring: The collection and monitoring of resource utilization data play a decisive role in enabling high-efficiency production. Data quality directly influences the analysis results, consequently impacting the effectiveness of optimization and proposed solutions[4]. Given the critical importance of data quality, the following requirements are established:

- Data must be collected in real-time.
- Data collection should be performed comprehensively in a single pass.
- Data collection points must be strategically located at critical nodes that significantly influence resource effectiveness.
- Collected data must be accurate, while also meeting requirements for high flexibility and cost-effectiveness.

Analyzing the resource and environmental attributes of manufacturing production processes involves diverse resource types, rendering data collection both critically important and inherently challenging. Research on evaluation data collection methodologies prioritizes leveraging existing mature methods, tools, and devices. Where necessary, novel data collection methods or tools are developed to align with specific evaluation model requirements. Based on analyzing the characteristics of resource consumption information flow and considering requirements for information importance, real-time availability, and reliability, data collection, processing, and storage are categorized into three methodologies: process imaging, short-term archiving (e.g., X/ISAM), and long-term archiving (e.g., relational databases).

3.2.2 Carbon emission analysis and modeling simulation of production process: The analysis of carbon emissions within production processes has long been recognized as both critically important and highly complex. Driven by advancements in green manufacturing research and global energy scarcity concerns, research focused on reducing machining process energy consumption has progressively emerged as a primary focus area[5]. This encompasses studies on power transmission, energy consumption analysis, and the optimized operation and control of machining processes.

3.2.3 Low-Carbon production process evaluation system and evaluation methods:

- Low-Carbon production process evaluation system framework

The structure of the evaluation index system must satisfy two key criteria: (1) comprehensiveness balanced with a focus on critical factors, and (2) adaptability to enable continuous refinement and enhancement of the index system as design activities evolve. The production process evaluation system incorporates both qualitative and quantitative indicators. Quantitative indicators are selected and refined based on three dimensions: resource consumption, comprehensive utilization, and waste discharge. These indicators are designed to be readily comparable and to systematically reflect the mechanical production process. Qualitative indicators are derived from three aspects: compliance with state-encouraged key technologies, implementation of environmental management systems and clean production audits, and establishment of waste treatment systems.

- Evaluation Methods for Low Carbon Production Process

The assessment of carbon emissions and analysis of environmental characteristics associated with manufacturing resources during production have garnered significant attention in both domestic and international academia, leading to the development of various evaluation methods[6]. Life Cycle Assessment (LCA) is a widely researched method for evaluating the environmental impact across a product's entire lifecycle. However, the complexity, lengthy duration, and high cost of conducting LCA constrain its broader application. Additionally, numerous comprehensive evaluation methods exist both domestically and internationally. These methods possess distinct characteristics but can be broadly categorized into two types. The primary distinction lies in the approach used to determine indicator weights. One category employs subjective weighting, predominantly utilizing expert consultation or scoring to assign weights, followed by the integration of normalized data. Examples include the comprehensive index method, fuzzy comprehensive evaluation, Analytic Hierarchy Process (AHP), and the efficacy coefficient method. The other category utilizes objective weighting, where weights are determined based on the inter-correlation between indicators or the degree of variation in their values. Examples encompass principal component analysis, factor analysis, and the TOPSIS method.

The evaluation methodology for Low-Carbon production processes is grounded in efficiency assessment, ecological economics, clean production principles, and multi-objective comprehensive evaluation. It defines the concept of production process energy efficiency and establishes an evaluation analysis framework. This framework integrates considerations of the analysis boundary, evaluation object, evaluation objectives, and guiding principles relevant to assessing production process energy efficiency. Building upon this evaluation analysis framework, the product lifecycle method is combined with other comprehensive evaluation techniques to assess production process carbon emissions.

3.3 Research on equipment optimization technology for Low-Carbon production

Production equipment forms the foundational layer of production and processing activities. Its energy consumption typically constitutes the most significant portion of an enterprise's total energy use. Consequently, optimizing production equipment is paramount for achieving Low-Carbon production. Data indicates that during metal cutting, auxiliary systems account for approximately 85.2% of power consumption[2], significantly exceeding that of the core cutting process itself (see Figure 2). Furthermore, cutting fluid, acting as an intermediate medium in the cutting process, does not directly contribute value but represents a primary source of pollution. This highlights the considerable energy-saving potential inherent in auxiliary systems.

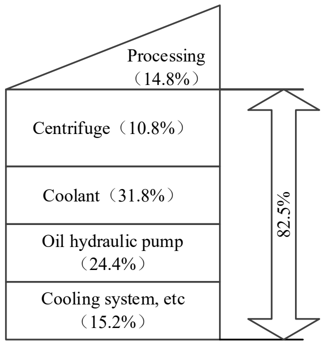

Fig. 2 Energy Consumption Distribution in the Metal Cutting Process[2]

The optimization and improvement of production equipment mainly focuses on the following aspects:

- Cutting Method Selection & Improvement: While traditional cutting fluids are costly (representing ~10-15% of processing costs) and improper use causes environmental pollution, adopting dry cutting or Minimum Quantity Lubrication (MQL) offers alternatives. These methods can reduce costs, protect the environment, and potentially extend tool life.
- Tool Efficiency Enhancement: Utilizing advanced tooling and selecting optimal tool geometry angles and cutting parameters can significantly enhance cutting efficiency, reduce cutting power requirements, and prolong tool life. This contributes to the goal of achieving higher output with reduced resource consumption.
- Energy Disconnection & Protection: Implementing online detection, intelligent control, and optimization technologies within the production process can enhance overall system efficiency and yield energy savings.
- Lightweight Materials: Employing lightweight materials in equipment redesign can substantially reduce equipment mass. This not only lowers transportation costs but, more critically, reduces operational energy consumption. However, while offering material and energy savings, lightweighting may introduce challenges like vibration and noise, necessitating complementary technological solutions.

3.4 Research on production process optimization technology for Low-Carbon production

Process-oriented production optimization involves selecting suitable methods and auxiliary equipment within the value-creation process to reduce costs and save time[7]. This approach offers significant advantages, including the effective elimination of redundant mechanisms or steps, leading to enhanced production efficiency and resource utilization. There are mainly three methods:

- Value Stream Mapping (VSM) is a process design and optimization method focused on value-added activities. It employs simple, visual diagrams to manually map each value-adding step in the product flow. Arrows connect these steps, illustrating their relationships, enabling the identification and elimination of non-value-adding (redundant) processes.
- Process Chain Control represents each process step using chain-like graphics and text, connected by lines to depict relationships. This visualization of inter-departmental workflow facilitates process optimization.
- ARIS (Architecture of Integrated Information Systems) is a framework for describing business processes using modeling methods, supported by computer software. Its purpose is to reduce modeling complexity and optimize the production structure. The core of ARIS lies in representing processes through sequences of events and process chain diagrams, effectively modeling the production workflow. Production-level data is stored in databases, integrated computationally, and monitored/controlled via visualization software.

3.5 Software support and system implementation for Low-Carbon production

In recent years, alongside internationally renowned ERP vendors like SAP and Oracle, numerous equipment system suppliers have developed proprietary production process control software. For instance, Germany's Bosch Rexroth developed IndraMotion MTX cta (cycle time analysis) and IndraMotion MTX ega (energy analysis) software. These tools optimize the analysis of machine tool working cycles and energy consumption, enabling real-time measurement, optimization, and monitoring of running time and energy consumption for CNC program blocks.

4. Summary

Low-Carbon production for sustainable development enhances resource utilization within processing, protects the ecological environment, and facilitates the achievement of low emissions.It represents a production model that fundamentally conserves resources and safeguards the environment[8]. This model signifies the future trajectory of manufacturing technology and production paradigms. This paper has analyzed the connotation and characteristics of Low-Carbon production from a product lifecycle technical perspective. Building on this analysis, it has proposed a theoretical research framework for Low-Carbon production and elaborated on the framework's key components.

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