Application of Dynamic Optimization and Carbon Efficiency Synergy Driven by QFD-TOC Model in Low-Carbon Aluminium Electrolysis

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Abstract

To address bottlenecks in the low-carbon transformation of the aluminium electrolysis industry, including the rough process optimization, lagging carbon efficiency management, and difficulty in multi-objective dynamic synergy, this paper innovatively proposes a QFD-TOC dual-drive dynamic optimization method. For the first time, the Quality Function Deployment (QFD) is deeply integrated with the Theory Of Constraints (TOC) to establish a low-carbon process optimization system that links “policy demand - process constraints- real-time regulation”. By using QFD to hierarchically analyse the dual-carbon policies, cost-reduction needs of enterprises, and technical characteristics of the process (e.g., cell temperature, anode effect coefficient), carbon efficiency conflict points in aluminium electrolysis production are precisely identified. Combined with TOC, a dynamic constraint boundary adaptive model is developed to achieve real-time multi-objective synergy optimization of “carbon – energy - efficiency”. This study overcomes the core difficulties of slow dynamic response and poor multi-objective coordination in aluminium electrolysis low-carbon optimization, offering a systematic solution that integrates theoretical innovation with practical implementation. This solution is of significant practical importance for advancing the green upgrade of the aluminium industry.

Keywords: QFD-TOC model, Low-carbon aluminium electrolysis process, Dynamic optimization, Carbon efficiency synergy.

1. Introduction

The aluminium electrolysis industry, being a high-energy consumption and high-carbon emission sector, is undergoing a critical period of green low-carbon transformation. Currently, the industry faces core challenges such as rough process optimization, lagging carbon efficiency management, and difficulty in multi-objective dynamic synergy. There is an urgent need to develop a systematic method for low-carbon process optimization. This paper innovatively proposes a QFD-TOC dual-drive dynamic optimization model that deeply integrates Quality Function Deployment (QFD) with the Theory of Constraints (TOC) [1]. The goal is to establish a low-carbon process optimization system that links “policy demand - process constraints - real-time regulation.” By using QFD to hierarchically analyse dual-carbon policies, enterprise cost-reduction needs, and technical characteristics (such as cell temperature and anode effect coefficient), carbon efficiency conflict points in aluminium electrolysis production are precisely identified. Combining TOC, a dynamic constraint boundary adaptive model is established to achieve real-time multi-objective synergy optimization for “carbon – energy - efficiency.” This study successfully addresses the core issues of slow dynamic response and poor multi-objective synergy in low-carbon optimization in aluminium electrolysis. It provides a systematic solution that combines theoretical innovation with practical application, offering significant real-world value for advancing the green transformation of the aluminium industry.

2. Background and Current Situation

As a vital basic material industry in China, aluminium electrolysis has seen rapid development in recent years. According to the latest statistics, the carbon emissions from China's aluminium electrolysis industry are approximately 420 million tonnes per year, accounting for 77 % of the carbon emissions in the non-ferrous metals industry and 5 % of the country's total carbon emissions. The electricity consumption is 502.2 TWh, accounting for 6.7 % of the national total. The aluminium electrolysis accounts for 78 % of the total carbon emissions in aluminium industry, making it the main battlefield for pollution reduction and carbon emissions reduction. In July 2024, the National Development and Reform Commission (NDRC) and other departments jointly issued the *Special Action Plan for Energy Conservation and Carbon Reduction in the Aluminium Electrolysis Industry* [2, 3], which clearly states that by the end of 2025, the production capacity of the aluminium electrolysis industry that meets or exceeds the energy efficiency benchmark level should reach 30 %. Capacities below the energy efficiency baseline should undergo technological transformation or be eliminated, while the utilization rate of renewable energy in the industry should reach more than 25 %, and the output of recycled aluminium should reach 11.5 million tonnes. By implementing energy conservation and carbon reduction modifications, the aluminium electrolysis industry is expected to save about 2.5 million tonnes of standard coal and reduce CO_2 emissions by approximately 6.5 million tonnes from 2024 to 2025 [4, 5].

However, the low-carbon transformation of the aluminium electrolysis industry still faces numerous bottlenecks. Firstly, process optimization is often rudimentary, with existing process parameter adjustments mainly based on empirical judgment, lacking systematic analysis and optimization. Secondly, carbon efficiency management is lagging, as the industry has yet to establish scientific, systematic methods for carbon efficiency evaluation and management. Lastly, achieving multi-objective dynamic synergy is challenging, as aluminium electrolysis production involves multiple objectives such as carbon emissions, energy consumption, and production efficiency, with complex conflicts between these goals, making dynamic synergy optimization difficult. Additionally, the aluminium industry is not only a high-energy-consuming sector, but also approximately 87 % of China's electrolytic aluminium is powered by thermal power. The structural contradiction in energy use is the biggest challenge in achieving the aluminium industry's "dual carbon" goals. The global average carbon emission per tonne of aluminium from electricity consumption is 10.4 tonnes, while in China it is 12.8 tonnes. The aluminium electrolysis accounts for 78 % of the carbon emissions in aluminium industrial chain.

3. Challenges and Areas for Improvement

The core challenges faced by the aluminium electrolysis industry in its low-carbon transformation include the following:

(1) Traditional aluminium electrolysis process parameter adjustments are often based on empirical judgment, lacking systematic analysis and optimization. There are complex interactions and conflicts between process parameters such as bath temperature, current density, and molecular ratio. These adjustments require multi-objective balancing, but existing methods struggle to achieve comprehensive, dynamic parameter optimization.

(2) In aluminium electrolysis production, carbon emissions mainly come from electricity consumption, basic reaction for making aluminium and PFCs (e.g., CF_4, C_2F_6) generated by anode effects. CF_4 has global warming potential (GWP) of 7 380, and CF_6 has a GWP of 12 400 (according to IPCC 6th Assessment Report [6]), much higher than CO_2's GWP of 1. However, the industry has yet to establish a scientific, systematic method for carbon efficiency evaluation and management, making it difficult to accurately measure and effectively control carbon emissions.

dynamic coordination. By constructing a QFD House of Quality, we accurately identified carbon-efficiency conflict nodes in aluminium production and proposed targeted optimization strategies. Through the application of TOC, we developed a dynamic constraint boundary adaptive model, enabling real-time multi-objective coordination across carbon, energy, and efficiency dimensions. The QFD-TOC model is not merely a single-point technical improvement; it establishes a complete optimization loop from macro-level policy requirements (translated via QFD) to micro-level process bottlenecks (broken through with TOC), and ultimately to dynamic, real-time process regulating. This effectively tackles core issues in traditional aluminium electrolysis process optimization, such as inefficiency, carbon management delays, and the challenge of dynamically balancing carbon, energy, and efficiency goals.

Results show that the QFD-TOC model can significantly reduce carbon emissions and energy consumption in aluminium electrolysis while improving production and energy efficiency. The model demonstrated notable optimization effects at key conflict points, such as current density vs. anode effect and bath temperature vs. energy consumption. Moreover, it can adapt to dynamic conditions like fluctuations in green electricity supply, enabling adaptive adjustment of process parameters. By precisely identifying and optimizing energy-efficiency-related technical characteristics through QFD, and managing energy consumption bottlenecks (such as ineffective power use caused by anode effects) through TOC, the model can achieve an average energy consumption reduction of about 3 % per unit product (simulation data, roughly 350–400 kWh/t Al), along with a 1.5–2 % increase in current efficiency. The QFD-TOC model provides a scientific, systematic, and highly actionable methodological framework and technical implementation path for the low-carbon transition of the aluminium electrolysis industry, and potentially other high-energy-consuming process industries.

8. References

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