Data-Driven Design: A New Paradigm and Application Exploration for Aluminium Reduction Cell Design

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Abstract

With the transformation and upgrading of the aluminum smelter industry, traditional design methods can no longer meet the complexity and efficiency requirements of modern engineering projects. This paper proposes a data-driven design paradigm for aluminum reduction cells, integrating 3D Building Information Modelling (BIM) technology, intelligent optimization platforms, and machine-learning algorithms to achieve full digital management of the design process. This paradigm significantly improves design accuracy and efficiency, providing precise material quantity estimation and multi-physics simulation support during the planning phase. It offers strong support for investment decisions and engineering optimization. Furthermore, this paper explores the potential application of big data computing power in the development and planning of high amperage cells, providing new insights for future intelligent design and large-scale optimization. Through practical project verification, this method has shortened the design cycle by 40 %, reduced design changes by 25 %, and demonstrated significant advantages in cost reduction, providing a new solution for the intelligent transformation of the aluminum smelter industry.

Keywords: Data-driven design, Aluminum reduction cell design, 3D BIM technology, Intelligent optimization platform; Machine-learning.

1. Introduction

1.1 Industry Background

As an energy-intensive industry, the aluminum smelter industry is facing severe energy efficiency challenges. In recent years, although the energy consumption level of the global aluminum smelter industry has declined, there is still much room for energy saving. According to the statistics of the International Aluminum Association, there are obvious differences in the energy consumption level of the aluminum smelter industry in different countries and regions. The average energy consumption of some countries with advanced aluminum smelter technology has dropped to 12.8 kWh/kg Al level, but the average energy consumption of aluminum smelters in many countries is still above 13.5 kWh/kg Al, indicating that there is still potential to further reduce energy consumption through technological innovation and management optimization. Therefore, improving the energy efficiency level of the aluminum smelter industry has become an urgent need for the transformation and upgrading of the industry.

1.2 Limitations of Traditional Design Methods

The traditional cell design mainly uses the design-bid-build (DBB) mode, which faces many limitations in complex projects. First of all, the high rate of design change is a prominent problem. Due to the incomplete consideration of project requirements and site conditions in the early design stage, design changes frequently occur during the construction phase, which increases the project cost and construction period. According to statistics, the rate of change of the cell design project under the traditional design mode is as high as 30 %. Secondly, the long design cycle is also an important factor restricting the development of the industry. It usually takes 6–8 months from project initiation to design completion, which is difficult to meet the requirements of rapid progress of modern engineering projects.

1.3 Technology Opportunities

With the rapid development of information technology, data-driven and BIM technologies are gradually rising in the field of industrial design. BIM technology realizes information integration and sharing in the design, construction and operation and maintenance stages by establishing a three-dimensional digital model [1]. In the field of metallurgy, BIM technology has been applied to the design optimization of iron and steel plants and has achieved remarkable results. At the same time, the technology of intelligent optimization platform is also increasingly mature. Machine learning algorithms have been preliminarily applied in the optimization of electrolytic cell parameters. Through the establishment of mathematical models, the current efficiency, electrode distance and other key parameters of the electrolytic cell are optimized, and the design accuracy is improved.

1.4 Research Objectives

Although BIM technology has been widely applied in the field of construction [1], its integration in cell design still faces two major challenges:

1) the lack of specialized parametric modeling tools;
2) The magnetic field criterion is not suitable for the characteristics of high-current cells [2].

This study aims to propose a ‘data-BIM-algorithm’ trinity design paradigm to address the shortcomings of inaccurate material estimation and inability to conduct simulation analysis in traditional designs. Through the integration of data-driven technology, BIM technology and intelligent optimization algorithms, the full-process digital management of aluminum-reduction-cell design is realized, the design accuracy and efficiency are improved, and a new solution is provided for the intelligent transformation of aluminum reduction industry.

2. Method

2.1 Technical Framework Diagram

The intelligent design system of aluminum reduction cell on cloud developed by this project is mainly based on open-source software Python. Its technical framework includes data layer, modeling layer and analysis layer as shown in Figure 1. The data layer is responsible for receiving and preprocessing data. Through the scheme planning software module implemented with Python, the designer can quickly determine the scheme of the cell by only determining the key parameters and pass it to the core module Pot3D. The modeling layer is divided into two levels. The first level is the core module Pot3D, which is responsible for data comparison, revision and conversion, and outputs the data format and script code that can be recognized by the 3D modeling software; The second level is the traditional commercial 3D modeling software, such as ANSYS SCDM® Solidworks, etc., which automatically generates the 3D scheme model by running the script output by Pot3D. In the analysis layer, simulation software such as ANSYS Workbench® and COMSOL® are used for pre-analysis and calculation to evaluate the feasibility of the scheme.
After evaluation, the use of the "Cloud-Based Aluminum Electrolytic Cell Intelligent Design System"-Pot3D has significant advantages compared to traditional design methods. See Table 1 for details.

Figure 9 shows the measured vertical magnetic field distribution of the electrolytic cell during actual production, which effectively reflects the characteristics of the improved scheme.

4. Discussion

4.1 Project Innovations

Tool innovation: the first special BIM system for the cell, which realizes the whole chain automation from parameter input to multi-physical-field simulation;

Theoretical innovation: propose C_0, C_x multi parameter criteria to solve the blind spot of magnetic field design of high current cells. Especially the C_x introduction has solved the problem of inadequate vertical magnetic field criteria for modern high amperage cells.

Algorithm innovation: NSGA-II optimization framework driven by case base, balancing electromagnetic/economic/engineering objectives.

4.2 Scope and Limitations of the System

At present, the system can only be used for technology suppliers with a large case base, and the scheme relies heavily on the accuracy of simulation operation, which takes a long time. Single optimization takes 6 hours (Intel Xeon 16 cores) and further parallelization is required; The coverage rate of the case library for cell types above 630 kA is only 4 %.

4.3 Improvement Direction

The future research can further enhance the machine-learning algorithm to automatically optimize the reduction cell shell, lining and busbar scheme.

5. Conclusions

In this paper, a new data-driven design paradigm of aluminum reduction cell is proposed. Through the integration of 3D BIM technology, intelligent optimization platform and machine learning algorithms, the whole process digital management of the design is realized. This method significantly improves the design accuracy and efficiency, and shows the advantages in shortening the design cycle, reducing design changes and reducing costs through the actual project verification. This study breaks through the pure theoretical analysis of previous work [5] and achieves the engineering implementation of criteria for the first time. The research results of this project provide new solutions for the intelligent transformation of the aluminum smelter industry and offer new ideas for future research.

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7. References

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