Design Engineering

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

Modeling and Optimization Method of Molten Aluminum Distribution Scheduling Problem with Constrained Multi-Objective

Nan Dong, Jianhua Li*, Ning Tang
School of Mechanical & Electronical Engineering, Lanzhou University of Technology, Lanzhou, Gansu Province, 730000, China
*Corresponding Author: Jianhua Li

Abstract:

Established a mathematical model, and put forward a new optimization method in order to solve the problem of molten aluminum distribution scheduling with constrained multi-objective in the production of electrolytic aluminum. Firstly, An antibody expression pattern based on intermediate coding sequence was designed. And used the fitness evaluation method with reward and punishment function to deal with the optimization objectives of the shortest path length of the crane, the largest number of low-impurity ladle bags, and the constraints of quality, crane path span, and full load rate; Finally, the iterative calculation is carried out by using the immune clonal algorithm. In this paper, an example of molten aluminum distribution scheduling from an electrolytic aluminum plant in China is given to verify the effectiveness of the method.

***Keywords**: Molten aluminum distribution scheduling, Constrained multi-objective optimization, Immune clonal algorithm.*

I. INTRODUCTION

Aluminum scheduling is a key process in the technological process of electrolytic aluminum production [1-3]. It is a process in which electrolytic aluminum enterprises formulate a ladle operation plan according to the chemical composition requirements of their products and the production mode of aluminum liquid fusion casting. The specific technological process has been described in literature [4-5], so it will not be repeated in this paper. The calculation process of the aluminum scheduling problem is complex, and it needs to shorten the path length of crown clock operation as far as possible and maximize the number of aluminum packages with a low tramp iron content under the premise that aluminum liquid meets the requirement of chemical composition, the crown clock span doesn't exceed the upper limit, and the load factor reaches a certain index. Therefore, the aluminum scheduling problem is a complex constrained

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

multi-objective combinatorial optimization problem. The complex difference of each electrolytic cell makes it very difficult to calculate the manual allocation of aluminum. The quality accidents caused by excessive allocation of aluminum are very common, and the resource waste caused by poor allocation of aluminum is inestimable. In recent years, some domestic enterprises began to try to solve the aluminum distribution scheduling problem and made certain achievements [6-9], which played a certain auxiliary role in the calculation of manual aluminum distribution. Meanwhile, the problem of aluminum distribution scheduling has also attracted the attention of academic circles. In literature [10-11], by introducing genetic algorithm, the affinity evaluation function based on the aluminum output scene of single ladle and double electrolytic cells was proposed, and the optimization algorithm of aluminum distribution ladle was realized. Literature [12] adopted a hybrid genetic algorithm to establish a mathematical model of aluminum distribution scheduling problem, and propose an optimization algorithm under the scenario of aluminum output from a single ladle and three electrolytic cells. Literature [13] presented a mathematical proof of sufficient and necessary conditions for aluminum allocation for the extreme tank scenario, and proposed a scheduling model and optimization algorithm for multiple aluminum output from ultra-high impurity electrolytic cell.

The above methods play a positive role in guiding the production of aluminum allocation scheduling problem. However, as mentioned above, the aluminum distribution scheduling problem in practice is a combinatorial optimization problem under the constraints of multiple objectives. The aluminum distribution scheduling problem models established in the above methods are all single-objective optimization models under simple constraints, so it is difficult to for them to solve the requirements of multi-objective optimization under complex constraints in field application scenarios.

In this paper, to solve the aluminum distribution scheduling difficulty of electrolytic aluminum under constrained multi-objective conditions, an aluminum distribution scheduling model was established, and a new optimization method of aluminum distribution scheduling was proposed. Firstly, an antibody expression pattern based on intermediate coding sequence was designed. Then the affinity evaluation method with reward and punishment function was introduced to deal with the multi-optimization objectives including the shortest path length of the crane and the maximum number of low-impurity ladles, as well as the multi-constrained conditions including mass, span of the crane and load factor restrictions. Finally, the iterative calculation was carried out by using the immune clone algorithm. In this paper, an example of aluminum distribution scheduling in an electrolytic aluminum plant in China was given to verify the effectiveness of the method.

II. ANALYSIS AND MODELING OF ALUMINUM DISTRIBUTION SCHEDULING PROBLEM UNDER THE CONSTRAINED MULTIPLE TARGETS

Mathematical modeling is carried out for aluminum distribution scheduling problem under the constrained multiple targets. Firstly, the following definitions are made:

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

Definition 1 The set of pending aluminum electrolysis cells with the number of n is $N=\{N_1,N_2,...,N_n\}$, where N_n represents the cell number of the nth electrolysis cell. The spacing distance between any two electrolysis cells is the reduction of their cell numbers, and the planned aluminum output of any electrolysis cell is expressed as W_{N_n}.

Definition 2 Impurity content set of each electrolytic cell is $P=\{P_{n1},P_{n2},...,P_{nm},P_{n(m+1)}\}$, where P_{nm} is the content of the mth type of impurity element of the neth electrolytic cell, and $P_{n(m+1)}$ is the sum of the content of the former m types of impurity elements.

Definition 3 The constraint set of the impurity element content of each ladle is $S=\{S_1,S_2,...,S_m,S_{m+1}\}$, where S_m represents the restriction for the impurity content of the mth element, and the determination requirement for low impurity ladle is expressed as $S_m^{'}$.

Definition 4 Aluminum output combination of electrolytic cell is i, that is, ladle i is expressed as set $C_i=\{1,2,...,n\},|C_i|=q$, and $D_i=w(C_i)=\{w_1,w_2,...,w_n\},C_i\to D_i$, where w_n denotes the aluminum liquid mass w when the nth electrolytic cell is actually loaded with ladle C_i, C_{iq} is used to denote the qth item in ladle C_i, and the security capacity of the ladle is denoted as W_C.

Definition 5 The jth aluminum distribution scheme is $I_j=\{C_1,C_2,...,C_i\},|I_j|=i$.

2.1 Optimization Objective Construction of Aluminum Allocation Scheduling Problem

2.1.1 The Total Driving Path of the Crown Clock is the Shortest

Shortening the driving path of the crown clock as far as possible is the key consideration in aluminum allocation scheduling. Excessively long driving path of the crown clock will lead to increased energy consumption of aluminum and premature cooling of aluminum liquid. Formulas (1) and (2) are defined for this optimization objective, as follows:

$$L_T=MIN\sum_{p=1}^{i}L_p \tag{1}$$

$$L_p=\sum_{k=q}^{2}\left|C_{ik}-C_{i(k-1)}\right| \tag{2}$$

Where L_T denotes the length of the shortest driving path of the crown clock, and L_k denotes the length of the driving path of the crown clock when the aluminum output is conducted to the aluminum output combination k of the electrolytic cell.

2.1.2 The Number of Low Impurity Ladles is the Largest

Electrolytic aluminum enterprises give priority to the production of high-quality liquid aluminum. Therefore, when conducting aluminum distribution scheduling, they will match more low-impurity ladles as far as possible under the condition that the driving path of the crown clock meets the requirements. Formulas (3) and (4) are defined for this optimization

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

objective, as follows:

$$E = MAX\sum_{k=1}^{i} evaluate(C_k) \tag{3}$$

$$evaluate(C_k) = \begin{cases} 1 & (\sum_{k=1}^{q}(P_{C_{ik}m}D_{ik}) \geq S_m^{'}) \\ 0 & (\sum_{k=1}^{q}(P_{C_{ik}m}D_{ik}) < S_m^{'}) \end{cases} \tag{4}$$

Where E represents the number of low-impurity ladles in the aluminum distribution scheme.

2.2 Constraints of Aluminum Distribution Scheduling Problem

2.2.1 The Impurity Content of Any Aluminum Ladle and Aluminum Liquid reaches the Minimum Requirement

Under the continuous casting process, the quality of each package of aluminum liquid prepared by electrolytic aluminum enterprises should meet the specified impurity content requirements. Formula (5) is defined for this constraint condition, as follows:

$$P_{I_j} = \sum_{k=1}^{q}(P_{C_{ik}m}D_{ik}) \leq S_m\sum_{k=1}^{q} D_{ik} \tag{5}$$

2.2.2 The Driving Path of Any Aluminum Sheathed Aluminum Liquid Crown Clock Shall not exceed the Index Requirements

During the aluminum tapping production, due to the consideration of safety, energy consumption, efficiency and other factors, the electrolytic aluminum enterprises often stipulate the upper limit of the single driving distance of the crown clock. Formula (6) was defined for this constraint condition, as follows:

$$L_{I_j} = \left| N_{C_{iq}} - N_{C_{i(q-1)}} \right| \leq L_{MAX} \tag{6}$$

Where L_{MAX} represents the maximum span of a single moving path of the crown clock.

2.2.3 The Load Factor of Any Aluminum Package meets the Index Requirements

Too little aluminum liquid in the ladle will cause the waste of the enterprise's transportation resources. Therefore, the electrolytic aluminum enterprises often stipulate the proportion of the minimum liquid aluminum in the safe capacity of the ladle. Formula (7) was defined for this constraint condition, as follows:

$$R_{I_j} = \sum_{k=1}^{q} D_{ik} \Big/ W_C \geq R_{MIN} \tag{7}$$

Where R_{MIN} represents the minimum load factor requirement of a single ladle.

III. OPTIMIZATION METHOD OF ALUMINUM DISTRIBUTION SCHEDULING

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

PROBLEM UNDER THE CONSTRAINTS OF MULTIPLE OBJECTIVES

In this paper, an antibody expression mode based on intermediate coding sequence was designed to simplify the data structure and reduce the algorithm complexity, and then an affinity evaluation with reward and punishment function was introduced to solve the constrained multi-objective optimization problem, and the immune clone algorithm was used to solve the model.

3.1 Antibody Expression based on Intermediate Coding Sequence

The antibody was expressed by the ladle sequence, that is, the aluminum tapping combination of the electrolytic cell. The data structure of single antibody is very complex, the algorithm complexity is high, and it is difficult to obtain the solution. Therefore, an antibody expression method based on intermediate coding sequence was designed to simplify the data structure and reduce the algorithm complexity.

Set the set of n aluminum tapping electrolytic cells as $N=\{N_1,N_2,...,N_n\}$, and the planned aluminum output quantity of any electrolytic cell was W_{N_n}. If aluminum was allowed to be split from the electrolytic cell, according to the impurity content P_{nm} of the electrolytic cell, the high-impurity electrolytic cell could be split to obtain $N^{'}=\{N^{'}_{11},N^{'}_{21},N^{'}_{22},...,N^{'}_{n1},...,N^{'}_{nj}\}$, where $N^{'}_{nj}$ represents the jth part after splitting electrolytic cell N_n, and the corresponding planned aluminum tapping amount was $W_{N^{'}_{nj}}$, and then $W_{N_n}=\sum_{k=1}^{j}W_{N^{'}_{nk}}$. The intermediate coding sequence $I=\{1,2,3,...,n\}$ was obtained according to the arrangement order of electrolytic cell. If aluminum is not allowed to be split, the intermediate coding sequence I was obtained according to N.

When conducting affinity evaluation, the group packet operation needed to be conducted to the intermediate coding sequence, that is, the intermediate coding sequence was converted into a ladle sequence. The specific operation steps are as follows:

Step 1: Obtain the maximum safety capacity W_C of ladle C_i and record the loaded weight of ladle C_i as $W_{C_i}=0$.

Step 2: Take out serial number n according to the coding sequence, and obtain the electrolytic cell number and the aluminum output weight W_n according to the mapping relationship.

Step 3: Judge whether $W_{C_i}+=W_n$ was greater than W_C; If it was not, n would be recorded into ladle C_i; If it was, judge whether aluminum is allowed to be split. If not, ladle C_i would be considered to be full, and the actual charge weight set D_i was recorded, and then jumped to Step 2 and conducted the package combination of the next ladle from $n+1$; If it was allowed,

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

calculate whether $W_n-(W_C-W_{C_i})$ was greater than the minimum aluminum tapping amount W_m at a single time; if it was not, n would loaded into C_i with a weight of W_n-W_m, the set of actual loading quantity would be recorded as D_i, and then jump to Step2 and start the group package of the next ladle, and the remaining weight of n would be loaded into the next ladle; If it was, the charge weight would be recorded as W_C-W_{C_i}, the set of actual charge weight would be recorded. Then jump to Step2 and start the group package of the next ladle, and the remaining weight of n would be loaded into the next ladle.

Step 4: Determine whether the electrolytic cells in the sequence have all been packaged. If so, output the ladle sequence; if it was not completed, then skip Step2 until all electrolytic cell packets in the sequence were completed.

The operation chart of intermediate coding sequence and package grouping is shown in Fig 1:

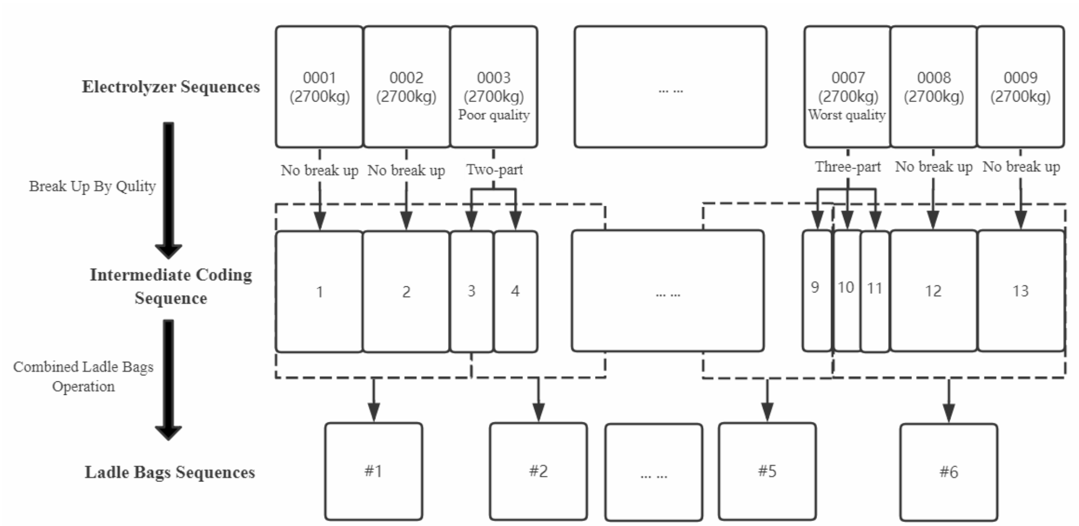

Fig 1: Operation chart of intermediate coding sequence and packet grouping

The mutation operator was used to analyze and evaluate the time complexity of $Big\text{-}O$ algorithm with the intermediate encoding sequence as antibody expression and the packet sequence as antibody expression. For the mode taking intermediate encoding sequence as antibody expression, the variation operation was completed by exchanging the stored values of any two points in the sequence. When the size of antibody population was n, the time complexity could be expressed as $O(n)$. For the mode taking ladle sequence as antibody expression, due to the limitation of ladle capacity, the electrolytic cell number of any two ladles couldn't be directly exchanged, it needed to be converted into the electrolytic cell sequence after splitting, and the ladle sequence was reconstituted again after exchanging any two electrolytic cell numbers inthe exchange sequence. When the size of antibody population is n, the time complexity could be expressed as $O(n\log n)$. It could be seen that the time complexity of the algorithm which conducting antibody expression based on intermediate coding was much lower than that conducting antibody expression based on ladle sequence. The comparison of the time complexity of $Big\text{-}O$ algorithm of the two antibody expression modes was shown in Fig 2:

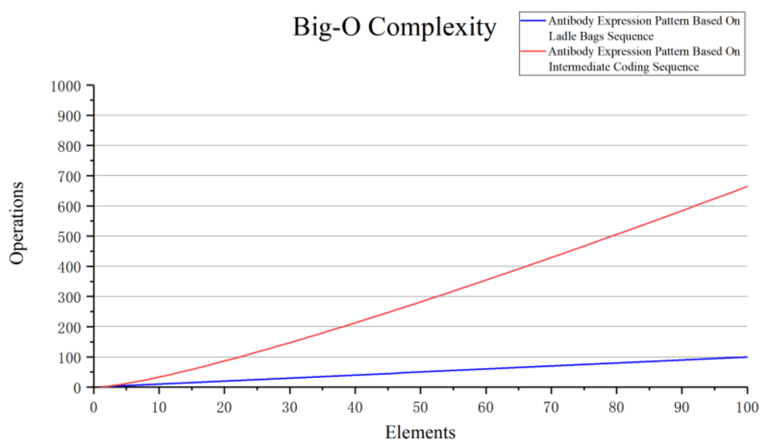

Fig 2: Comparison diagram of time complexity of $Big\text{-}O$ algorithm

3.2 Affinity Evaluation with Reward and Punishment Functions

For constrained multi-objective aluminum distribution scheduling problem, in this paper, the reward and punishment function was introduced into the affinity evaluation function to transform constrained multi-objective problems into non-constraint single objective problems. At the same time, the introduction of reward function could realize the directional search of the solution space, guide the evolution process, and make the final result present the desired characteristics.

The formulas of the affinity evaluation function (8), (9), (10) and (11) were defined as follows:

$$fitness(I_j) = \eta(I_j) \times (\varphi(I_j) + f(I_j)) \tag{8}$$

$$f(I_j) = {L_s}/{L_k} \tag{9}$$

$$\varphi(I_i) = \partial \times \sum_{k=1}^{i} evaluate(C_k) \quad \varphi(I_i) = D \times \sum_{i=1}^{q} evaluate(C_i) \tag{10}$$

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

$$\eta(I_j)=\begin{cases}1 & (P_{I_j}\le S_m\sum_{k=1}^{q}D_{ik}\wedge L_{I_j}\le L_{MAX}^{'}\wedge R_{I_j}\ge R_{MIN})\\ 0 & (P_{I_j}> S_m\sum_{k=1}^{q}D_{ik}\vee L_{I_j}> L_{MAX}^{'}\vee R_{I_j}< R_{MIN})\end{cases}\qquad \eta(C_i)=\begin{cases}1 & ()\\ 0 & ()\end{cases}\qquad (11)$$

$$\varphi(I_i)=D\times\sum_{i=1}^{q}evaluate(C_i)$$

Where $f(I_j)$ is the objective function, and L_s objective represents the driving path of the indicator crown clock, that is, the driving path of the crown clock passing through all electrolytic cells sequentially; $\phi(I_j)$ is the reward function, where ∂ is the reward coefficient, which conducts the affinity reward to the antibody containing the desired characteristics, so that its good characteristics can be more easily retained in the iterative evolution process; $\eta(I_j)$ is the penalty function, the constraint conditions mentioned in 1.2 were all strong constraints for the aluminum distribution scheduling problem. Therefore, if the constraint conditions were not met, antibody affinity would be set to zero and the antibodies with gene characteristics that did not meet the constraint conditions would directly eliminated to ensure that the calculation results met the constraint conditions. If so, the original affinity remains would be unchanged.

3.3 Model Resolving based on Immune Cloning Algorithm

Immune cloning algorithm has a lot of advantages, including strong global search ability, good diversity of antibody population, strong robustness, simple algorithm structure, and easy implementation [14-15]. In this paper, immune cloning algorithm was used to resolve the aluminum distribution scheduling model, and its process was described as follows:

Step 1: Initialization: As described in 2.1, the electrolytic cell sequence was sequentially sorted and split to generate the initial antibody I_1, and any two points in the coding sequence of antibody I_1 were cyclically exchanged according to the requirements of population size, and finally, the initial antibody population I was finally obtained.

Step 2: Calculate affinity: Calculate the affinity of each antibody according to affinity evaluation function $fitness(I_j)$. If the affinity of the antibody population was all 0, then the antibody population was generated again according to Step1.

Step 3: According to the clone size, cloning and amplification: Cloning and amplification were performed for each antibody in the initial population I to obtain a new antibody population $I^{'}$.

Step 4: Clonal variation: According to the set antibody variation probability, each antibody in the antibody population is judged. In case of variation, any two positions in the antibody coding sequence are exchanged, and the antibody population is finally obtained.

Step 5: clonal selection: roulette selection strategy is used to select the antagonistic population to reduce its population size to the set value of population size.

Step 6: judge whether the iteration times meet the requirements, if not, jump to setp2; if so,

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

the model calculation is finished, and the antibody with the highest affinity in the current evolution algebra is output.

Step 7: convert the output antibody from the intermediate coding sequence to the package lifting sequence as the result of the calculation.3. Analysis of examples

In this paper, the actual production data of a certain work area of a certain electrolytic aluminum factory in China was used for example analysis. The planned aluminum output and chemical test data of each electrolytic cell in the work area, as well as the constraint conditions are shown in TABLE I and TABLE II:

TABLE I. Planned aluminum output and chemical test data

Cell number	Planned aluminum output/Kg	Fe %	Si %	Al %
0001	2850	0.138	0.051	99.78
0002	2910	0.110	0.05	99.81
0003	2910	0.093	0.037	99.84
0004	2600	0.196	0.295	99.48
0005	2850	0.141	0.044	99.79
0006	2880	0.084	0.042	99.85
0007	2850	0.102	0.048	99.82
0008	2940	0.135	0.067	99.77
0009	2940	0.076	0.039	99.86
0010	2850	0.09	0.037	99.85
0011	2850	0.081	0.046	99.85
0012	2500	0.132	0.057	99.79
0013	2910	0.150	0.150	99.67
0014	2000	0.145	0.069	99.76
0015	2880	0.107	0.048	99.82
0016	2800	0.135	0.075	99.76

TABLE II. Constraint requirements of aluminum distribution scheduling

Impurity content %	Crown block span	Load factor %	Low-impurity ladle standard %	Ladle capacity Kg
$Fe \leq 0.2$ $Si \leq 0.2$ $Total \leq 0.5$	7	≥ 80	$Fe \leq 0.085$	6000

The aluminum distribution scheduling calculation was carried out according to the method

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

in this paper: the population size was set as 80, the number of iterations was 100, the reward coefficient was 2, the electrolytic cell was not allowed to split aluminum, and finally the aluminum distribution scheduling results were obtained, as shown in TABLE III. To further prove the effectiveness of the aluminum distribution scheduling method described in this paper, 20 times of calculation was conducted to the above example. Under the condition that CPU was Intel Core i7-8750H, the calculation time was 3.4 S on average, and in the results, each ladle met various constraint conditions in TABLE II. The average driving path of the crown clock was 27 per day, the number of ladles whose Fe content was less than 0.085% could reach 2, and calculation effect was excellent and stable, so it could meet the practical operating requirements of aluminum distribution scheduling.

TABLE III. Aluminum distribution scheduling results

Serial number	Cell number	Weight Kg	Fe%	Si%	Al%	Load factor%
1	0001 0002	5760	0.124	0.050	99.795	96
2	0003 0004	5510	0.142	0.159	99.670	91.8
3	0005 0007	5700	0.122	0.046	99.805	95
4	0008 0012	5440	0.134	0.062	99.779	90
5	0009 0010	5790	0.083	0.038	99.855	96.5
6	0006 0011	5730	0.083	0.044	99.850	95.5
7	0013 0014	4910	0.148	0.117	99.707	81.8
8	0015 0016	5680	0.121	0.061	99.790	94.7

IV. CONCLUSION

In this paper, the aluminum scheduling problem of electrolytic aluminum under the constrained multiple targets was studied. Firstly, it was analyzed and modeled, and the expression mode of antibody based on intermediate coding sequence was designed, and the affinity evaluation method with reward and punishment function was introduced to deal with the constrained multi-objective conditions. Then the model was solved by immune clone algorithm, and the algorithm design and implementation steps were given. Finally, a practical example was used to verify the effectiveness of the proposed method.

The optimization method described in this paper can effectively solve the aluminum distribution scheduling problem under the constraints of multiple targets in actual production, but it still has some shortcomings. Firstly, the penalty function directly sets the antibody affinity which does not meet the constraint conditions to be zero, which limits the diversity of the antibody population to some extent. Secondly, it is hard to manually choose the reward coefficient in the reward function reasonably. To improve these deficiencies will be the focus of future research.

ACKNOWLEDGEMENT

National Key Research and Development Program of China (No.2018YFB1309005).

REFERENCES

[1] Wang Jie. (2006) Electrolytic aluminum production process and equipment. Metallurgical Industry Press.

[2] Wang Hongwei, Ma Keyou. (2013) Aluminum metallurgy production operation and control. Metallurgical Industry Press.

[3] Niu huixiao, Ding Ziyang, Yuan Wenxiao. (2013) Research and development trend of aluminum processing technology. Henan science and technology 13: 60-61

[4] Zhang Yali. (2009) Research and development of intelligent packing software for discharging aluminum from aluminum reduction cell. Beijing: North University of technology.

[5] Lu Yufei. (2004) Current situation and trend of electrolytic aluminum industry at home and abroad. Yunnan metallurgy 06: 58-63

[6] Sun Teng Chen. (2005) Aluminum distribution scheduling method and device for electrolytic aluminum. Chinese patent, cn200410047877.2, 2005-03-09

[7] Xia Yuanming. (2005) Analysis and software development of aluminum distribution algorithm for primary aluminum casting. Light metal 2005000 (7): 38-41

[8] Liu Jian, Liu Yulan, Li Feng. (2005) Automatic control system for quantitative aluminum production from electrolytic aluminum. Metallurgical industry application 6: 129-131

[9] Chen Yanhua. (2006) Development and application of optimized aluminum distribution system for primary aluminum casting. China nonferrous metals 10: 68-69

[10] Li Jianhua, Wei Xing. (2014) A new approach to blending and loading problem of molten aluminum.Journal of engineering and technological sciences 46(4): 1462-1469.

[11] Li Jianhua, Wei Xing. (2014) Analytical method on computational capabilities of multi-parameter natural algorithm. Seventh International Symposium on Computational Intelligence and Design, Hangzhou 12: 285-287.

[12] Li Jianhua, Wei Xing, Rui Zhiyuan, et al. (2014) Aluminum liquid stowage modeling and hybrid genetic algorithm optimization . Control and decision making 29 (5): 933-936

[13] Li Jianhua, Liu Lu, Bian Korea. (2018) An optimization method for aluminum solution with high impurity. Light metals 11: 27-31

[14] Shang R, Jiao L, Liu F, et al. (2012) A Novel Immune Clonal Algorithm for MO Problems. IEEE Transactions on Evolutionary Computation 16(1): 35-50.

Design Engineering

ISSN: 0011-9342
Issue: 11 | Pages: 803 - 814

[15] Shang R, Jiao L, Ren Y, et al. (2014) Immune clonal co-evolutionary algorithm for dynamic multi-objective optimization. Soft Computing 18(4): 743-756.