Optimization Model of Trail Billet Cutting Setting under Dual Constraints of Subjective and Objective

Juan Sun, Zhao Ping, and Xaolan Wei

Abstract—**This paper studies the optimal cutting problem of continuous casting trail billet. Firstly, considering the scientificity and feasibility of continuous casting cutting, the target cutting length of the tail billet is determined according to the length range of the billet required by the user. Secondly, considering whether the target cutting length appears in the cutting and the number of occurrences, 0-1 variables and integer variables are introduced respectively, and an integer programming model with the smallest invalid cutting length is established. Thirdly, for the invalid cutting part, consider the billet length requirements of the next process to determine the cutting loss of the trail billet. Finally, aiming at different cutting schemes with the same cutting loss, a bulls-eye distance model centered on the user target value is established to test whether the model established in this paper is the optimal model by approaching the user target value, so as to set up the optimal trail billet cutting scheme under the subjective and objective constraints of considering the user requirements and the minimum cutting loss at the same time. The model substituted into the actual data is solved and tested by Lingo software. The results show that for the three cutting schemes with the same and minimum cutting loss, the cutting scheme obtained by the model established in this paper is the closest to the user's target value, reaching the dual goal of minimizing the cutting loss and more close to the user's target value.**

Index Terms—**trail billet cutting, optimization, integer programming, bulls-eye distance**

I. Introduction

CONTINUOUS casting and cutting [1],[2] is a process in which the molten steel is solidified and then cut into various steel products. When continuous casting is stopped, it is inevitable to produce trail billet. If the length and quality of trail billet (excluding scrap section) are within the cutting conditions, the cutting mode of trail billet is also an important link to determine whether continuous casting cutting is optimized.

The improvement of the production yield of continuous casting is the goal of the entire metallurgical manufacturing industry, and many scholars have done research on the optimization of improving the recovery rate of the slab. Pang et al. [3] aimed to improve the yield of billet during continuous casting and cutting, and determined the sequence of closing the casting flow when the molten steel is stopped by using the algorithm of the stopping time of the casting stream and the algorithm of judging whether the weight of the molten steel in the ladle is a multiple of the fixed length. This research plays a certain role in ensuring more qualified fixed length and fewer trail billet. Dai et al. [4] analyzed the relationship between cutting loss, actual available molten steel amount, tundish residue and total molten steel amount in tundish, and used the process control computer to calculate the optimal closing time of each flow，ensuring that the five-flow bloom can be cut by the algorithm that produces the largest number of fixed lengths, the smaller number of trail billets and the smaller length of trail billets. To a certain extent, the yield of molten steel has been improved, and certain economic benefits have been achieved. Liu [5] designed a trail billet optimized cutting system based on PLC and HMI to solve the waste of a large number of non fixed length billets during continuous casting, so that the length of the cut trail billet is an integral multiple of the fixed length or single length. According to the data after being put into use, the metal recovery rate of Tianjin Steel Pipe Group Co., Ltd. Special Steel Company has been improved to a certain extent. Zhao [6] conducted research on diverting and stopping pouring to avoid large waste for steel grades that can not be cut and optimized by the system, which saves production costs and improves the yield to a certain extent.Chen [7], in order to solve the problem of high rejection rate of casting slab caused by peeling treatment due to unqualified surface quality of tail billet during continuous casting of extra-thick slab in a certain factory, in the existing operation of final casting, capping, and pulling speed. On this basis, the fluid dynamics calculation software Fluent was used to simulate the influence of the new speed reduction process on the flow field of the tundish, which reduced the occurrence rate of tail blanks in the factory's extra-thick slab caster from 30% to 18.9%. Starting from the fixed-weight cutting technology, Sun et al. [8] established a Support Vector Machine (SVM) regression prediction mathematical model for billet weight with three impulses of "weight + length + pulling speed". The model takes "pulling speed, weight and length" as the related variables to form hierarchical control, which enhances the adaptability and real-time control of the model and achieves the goal of

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improving the yield of bar process, it has achieved great economic benefits and good social benefits. References [9]-[15] also did research on the optimal cutting of billet in order to improve the production yield.

Summarizing the existing literature, it can be seen that most of the existing literature starts from the perspective of fixed length, with the goal of cutting the largest number of fixed-length and the minimum number of trail billet and the length of trail billet, which reflects the improvement of production recovery rate. From the perspective of fixed weight, a small number of literatures put forward the optimization scheme of trail billet cutting by comprehensively considering the parameters of the casting machine itself, user demand parameters, and production process demand parameters. However, no matter from the perspective of fixed length or fixed weight, the starting point of the existing literature is to control the generation of tail blanks, which has played a significant role in improving the production recovery rate, but the generation of trail billet in the continuous casting production process is inevitable, while little research has been done on cutting optimization of tail blanks that have been produced and whose lengths are known. Therefore, on the basis of the existing literature, the author comprehensively considers the user's needs and the basic requirements of the continuous casting process, and designs an optimization model of tail billet cutting under the dual constraints of subjective and objective, which plays an important role in the entire optimization system of iron and steel production.

II. Problem Description

The control parameters that generally need to be considered in the cutting of tail billets are: the range of user requirements, the parameters of the continuous casting machine, the conditions for transport and the requirements of the next process. The terms involved in the optimized cutting model and their meanings:

(i) Target cutting length: the cutting length that meets the user's requirements.
(ii) Effective cutting length: the sum of cutting lengths that meet the needs of users.
(iii) Invalid cutting length: The cutting length that does not meet the user's needs.
(iv) Cutting Loss (Scrap Billet Length): The cutting length that neither meets the customer's needs nor the secondary off-line cutting.

The problems to be solved and the limiting parameters are as follows:

(i) Problems to be solved: Assuming that the user's target value is 9.5 m and the target range is 9.0~10.0 m, the optimal cutting plan is given for the following tail billets lengths: 109.0, 80.9, 62.7, 52.5, 14.5 (unit: m).
(ii) Tail billet will be generated when continuous casting is stopped, and the cutting of tail billets is also an important part of continuous casting and cutting.
(iii) General requirements for continuous casting cutting: the cutting scheme shall give priority to the cutting loss, then consider the user's requirements, and then consider the cutting length as close as possible to the user's target value.
(iv) The basic requirements of continuous casting and cutting: the length of the cut billet must be between 4.8~12.6 m, otherwise it cannot be transported away, hindering production; the acceptable length of the billet in the next process is 8.0~11.6 m, if it is not within this range, the billet can be transported away for two off-line cutting, but the cut part is scrapped, resulting in loss.
(v) Normal requirements for continuous casting cutting: normal cutting is to cut according to the length required by the user. User requirements include target value and target range. The cutting length of billet shall meet the target value as far as possible, and the length within the target range is also acceptable. Loss occurs when the billet length is not within the target range.

III. Establishment of Model

A. Building an Integer Programming Model with Invalid Cut Minimum

The target range of the user's demand is 9.0~10.0m, in order to meet the user requirements and consider the actual calculation, the billet length meeting the user requirements is cut, and a decimal value is reserved within the target range of user requirements, that is, the target cutting lengths $x_i (i = 1,2,...,11)$ are defined as 9.0, 9.1, 9.2, 9.9,10 (unit: m).

It is considered that the cutting of each section of trail billets is independent, that is, the model of cutting scheme is the same. Each section of trail billet is cut into two parts: effective cutting and invalid cutting by continuous casting machine. For the invalid cutting part, if the billet length range of secondary offline cutting is 8.0~11.6 m, this section of billet can be transported away for offline cutting to meet the needs of users, and the remaining part will be scrapped, that is, cutting loss. When the cutting loss of independent trail billet reaches the minimum, the total cutting loss of all trail billet will be the minimum[16]-[22].

Step 1: Introduce 0-1 variables.

Whether the target cutting length appears in the effective cutting, the variable 0-1 $t_{ij} (i = 1,2,...,11; j = 1,2,...,5)$ is introduced, if the *j*-th target cutting length of the *i*-th segment rtail billet appears, then $t_{ij} = 1$, otherwise $t_{ij} = 0$.

Step 2: Introduce integer variables.

The number of occurrences of the *j*-th target cutting length of the *i*-th tail billet is expressed as $k_{ij} (i = 1,2,...,11; j = 1,2,...,5)$, where k_{ij} belongs to a positive integer, that is, $k_{ij} \in N_+$.

Step 3: Calculate the effective cutting length.

$$Y_j = \sum_{i=1}^{11} x_{ij} k_{ij} t_{ij} \tag{1}$$

Among them, $Y_j (j = 1,2,...,5)$ represents the effective cutting length of the j-th tail billet.

Step 4: Calculate the invalid cutting length.

$$M_j = X_j - Y_j = X_j - \sum_{i=1}^{11} x_{ij} k_{ij} t_{ij} \tag{2}$$

Where $M_j (j = 1,2,...,5)$ is the invalid cutting length of the *j*-section trail billet; $X_j (j = 1,2,...,5)$ is the length of the *j*-section tailstock.

Step 5: Construct the smallest integer programming model with an invalid cut.

Considering that the invalid cutting part is at least 0 and at most does not exceed the lower limit of the user's demand range, an integer programming model with the minimum invalid cutting is established as follows:

$$\begin{aligned} &Min \quad M_j = X_j - \sum_{i=1}^{11} x_{ij} k_{ij} t_{ij} \\ &S.t \quad 0 \le X_j - \sum_{i=1}^{11} x_{ij} k_{ij} t_{ij} < 9 \\ &\qquad t_{ij} = 1 \, or \, 0 \\ &\qquad k_{ij} \in Z \end{aligned} \tag{3}$$

Step 6: Calculate the cutting loss of each tail billet and the total cutting loss.

For the cutting length that does not meet the user's needs, if it meets the cutting length of the next process, offline secondary cutting can be carried out to ensure the effective utilization of billet. Otherwise, it will be a scrap section, that is, cutting loss.

If the invalid cutting loss of the trail billet of section j is $0 \le M_j < 8$ (unit: m), the cutting loss of the trail billet of section j is $L_j = M_j$; If the invalid cutting loss of the trail billet of section j is $8 \le M_j < 9$ (unit: m), the invalid cutting of the trail billet of Section j meets the next process, and the cutting loss is $L_j = 0$.

The total cutting loss is: $L = \sum_{j=1}^{5} L_j$.

B. *Build a bulls-eye distance model centered on the user's target value*

For t cutting schemes with the same cutting loss, consider the effective cutting to approach the user target value as much as possible, and establish a bulls-eye distance model [22]-[27] centered on the user target value to test the optimality of Model 3.

$$r_{nj} = \sum_{i=1}^{11} \sqrt{k_{ij} t_{ij} \left(x_{ij} - \theta \right)^2} \, (n = 1, 2, ..., t) \tag{4}$$

Where θ represents the user target value; r_{nj} indicates the deviation degree between the *n*-th cutting scheme of the tailstock of section j and the user's target value. The smaller r_{nj} indicates the smaller the deviation degree between the effective cutting and the user's demand, the better the scheme is. On the contrary, the greater the deviation degree between the effective cutting and the user's demand, the worse the scheme is. Therefore, the cutting scheme corresponding to $\min\{r_{1j}, r_{2j}, ..., r_{tj}\}$ is the optimal cutting scheme for this section of trail billets.

IV. MODEL SOLVING

Substitute the tail billet data of 5 segments with lengths of 109.0, 80.9, 62.7, 52.5, and 14.5 (unit: m) into Model 3, and use Lingo software to solve the cutting plan of the tail blank as follows:

TABLE I
CUTTING SCHEME AND CUTTING LOSS OF TRRAIL BILLET WITH DIFFERENT LENGTHS

Trail billet (unit:m)	Model cutting scheme	Cutting loss (unit: m)
109	9*9+9.3*2+9.4*1	0
80.9	9.8*8	2.5
62.7	9.7*6	4.5
52.5	9.6*5	4.8
14.5	10*1	4.5
	Other scheme I	
109	10*10+9*1	0
80.9	10*6+9.2*2	2.5
62.7	10*4+9.1*2	4.5
52.5	10*1+9.6*1+9.5*2+9.1*1	4.8
14.5	#	4.5
	Other scheme 2	
109	9*11+10*1	0
80.9	10*6+9*1+9.4*1	2.5
62.7	10*4+9*1+9.2*1	4.5
52.5	10*2+9.7*1+9*2	4.8
14.5	#	4.5

Remarks: $a * n_1 + b * n_2 + c * n_3 + ...$: means to cut out a m long n_1 section, b m long n_2 section, c m long n_3 section, etc.;

#: Indicates no cutting scheme.

The three cutting schemes with the same cutting loss are tested with Model 4 as follows: (Take the first section of tail blank as an example)

$$\begin{aligned} r_{11} &= \sqrt{\sum_{i=1}^{11} k_{i1} t_{i1} (x_{i1} - 9.5)^2} \\ &= \sqrt{2 \times (9.0 - 9.5)^2 + 3 \times (9.2 - 9.5)^2 + 5 \times (9.4 - 9.5)^2} \\ &= \sqrt{2.34} \end{aligned}$$

$$\begin{aligned} r_{21} &= \sqrt{\sum_{i=1}^{11} k_{i1} t_{i1} (x_{i1} - 9.5)^2} \\ &= \sqrt{10 \times (10 - 9.5)^2 + 1 \times (9.0 - 9.5)^2} \\ &= \sqrt{2.75} \end{aligned}$$

$$\begin{aligned} r_{31} &= \sqrt{\sum_{i=1}^{11} k_{i1} t_{i1} (x_{i1} - 9.5)^2} \\ &= \sqrt{1 \times (10 - 9.5)^2 + 11 \times (9.0 - 9.5)^2} \\ &= \sqrt{3} \end{aligned}$$

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The degree of deviation of each scheme from the user's target value is obtained as shown in Table II:

TABLE II
DEVIATION DEGREE BETWEEN DIFFERENT SCHEMES WITH THE SAME CUUTTING LOSS AND USER DEMAND VALUE

degree of deviation r_{nj}	Model cutting scheme	Cutting loss (unit: m)
r_{n1}	$r_{11}=\sqrt{2.34}$	0
r_{n2}	$r_{12}=\sqrt{0.72}$	2.5
r_{n3}	$r_{13}=\sqrt{0.24}$	4.5
r_{n4}	$r_{14}=\sqrt{0.05}$	4.8
r_{n5}	$r_{15}=\sqrt{0.25}$	4.5
	Other scheme I	
r_{n1}	$r_{11}=\sqrt{2.75}$	0
r_{n2}	$r_{22}=\sqrt{1.68}$	2.5
r_{n3}	$r_{23}=\sqrt{1.32}$	4.5
r_{n4}	$r_{24}=\sqrt{0.42}$	4.8
r_{n5}	#	4.5
	Other scheme 2	
r_{n1}	$r_{11}=\sqrt{3}$	0
r_{n2}	$r_{32}=\sqrt{1.76}$	2.5
r_{n3}	$r_{33}=\sqrt{1.34}$	4.5
r_{n4}	$r_{34}=\sqrt{1.04}$	4.8
r_{n5}	#	4.5

It can be seen from Table II:

$$\min\{r_{11},r_{21},r_{31}\}=\min\left\{\sqrt{2.34},\sqrt{2.75},\sqrt{3}\right\}=\sqrt{2.34}=r_{11}$$

$$\min\{r_{12},r_{22},r_{32}\}=\min\left\{\sqrt{0.72},\sqrt{1.68},\sqrt{1.76}\right\}=\sqrt{0.72}=r_{12}$$

$$\min\{r_{13},r_{23},r_{33}\}=\min\left\{\sqrt{0.24},\sqrt{1.32},\sqrt{1.34}\right\}=\sqrt{0.24}=r_{13}$$

$$\min\{r_{14},r_{24},r_{34}\}=\min\left\{\sqrt{0.05},\sqrt{0.42},\sqrt{1.04}\right\}=\sqrt{0.05}=r_{14}$$

$$\min\{r_{15},r_{25},r_{35}\}=\min\left\{\sqrt{0.25}\right\}=\sqrt{0.25}=r_{15}$$

In conclusion, for five kinds of trail billet with different lengths, under the condition of minimum and same cutting loss, the cutting schemes given in model 3 are all cutting schemes closer to the user's target value, which shows that the model established in this paper has good optimization effect, has strong practicability for the cutting of independent trail billet, and can improve the utilization rate of billet for the production of iron and steel plant.

V. Conclusion

In this paper, on the premise that the length of the trail billet has been defined in the continuous casting cutting control system, the optimal cutting model of the trail billet is formulated according to the user's needs and production process requirements, which can ensure the high utilization rate of the trail billet and reduce the waste of resources. It is an indispensable step in the continuous casting cutting optimization process. The model can not only solve the optimal cutting problem of independent trail billet, but also solve other similar cutting problems, and has good popularization value.

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