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Planning BOF repair system in conditions of quasi-periodic operation of units

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Abstract. Using the example of the steelmaking production of JSC EVRAZ United West Siberian Metallurgical Plant, the paper considers the task of synchronous calendar planning in the interval of several planned periods of operation of basic oxygen furnace (BOF), BOF shops, production as a whole, as well as ongoing repairs of BOF for steelmaking production (two BOF shops with two and three BOFs). Scheduled stops of the BOF for repair depend on the actual achieved duration of the lining campaign and production schedules of the units and are performed when the current duration of the BOF campaign reaches a given standard value. Thus, the current duration of the BOF campaign is described by a discrete, nonlinear quasi-periodic function that does not have a fixed period, but has some regularity. Technological limitations were formalized, determining the minimum and maximum values of the number of melts per day that each of the workshops can produce with one or two BOFs operating simultaneously. The authors formulated the conditions to avoid performing two "cold" repairs in one shop in one planned period and ensuring daily processing by BOF shops of all cast iron coming from the blast furnace shop. In the proposed mathematical formulation of the problem, it is required to find such schedules of BOF repairs and such calendar plans of their work that satisfy the formulated constraints and optimize the non-linear criterion. The proposed criterion is aimed at ensuring the constant readiness of the shops for implementation of the production program and design productivity. The task is formulated for the conditions of trouble-free operation and stable provision of the shops with liquid cast iron as the main component of the metal charge of BOF smelting.

Keywords: steelmaking, BOF, campaign duration, BOF shop, quasi-periodicity, calendar plan, design productivity

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Планирование системы ремонтов конвертеров в условиях квазипериодического функционирования агрегатов

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Аннотация. На примере сталеплавильного производства АО «ЕВРАЗ Объединенный Западно-Сибирский металлургический комбинат» рассматривается задача синхронного календарного планирования в интервале нескольких плановых периодов работы конвертеров, конвертерных цехов, производства в целом, а также текущих ремонтов конвертеров сталеплавильного производства (два конвертерных цеха с двумя и тремя конвертерами). Плановые остановки конвертера на ремонт зависят от реальной достигнутой продолжительности кампании по футеровке и производственных календарных планов работы агрегатов. Ремонты выполняются при достижении текущей длительности кампании конвертера заданного нормативного значения. Таким образом, текущая длительность кампании конвертера описывается дискретной, нелинейной квазипериодической функцией, не имеющей фиксированного периода, но обладающей некоторой регулярностью. Формализованы технологические ограничения, определяющие минимальные и максимальные значения количества

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плавок в сутки, которое может провести каждый из цехов при одном или двух одновременно работающих конвертерах. Сформулированы условия, позволяющие избежать выполнения в одном цехе двух «холодных» ремонтов в одном плановом периоде и обеспечивающие ежесуточную переработку конвертерными цехами всего поступающего из доменного цеха чугуна. В предлагаемой математической постановке задачи требуется найти такие графики ремонтов конвертеров и такие календарные планы их работы, которые удовлетворяют сформулированным ограничениям и оптимизируют нелинейный критерий. Предложенный критерий направлен на обеспечение постоянной подготовленности цехов для выполнения производственной программы и проектной производительности. Задача сформулирована для условий безаварийной работы и стабильного обеспечения цехов жидким чугуном как основной составляющей металлозавалки конвертерной плавки.

Ключевые слова: сталеплавильное производство, конвертер, длительность кампании, конвертерный цех, квазипериодичность, календарный план, проектная производительность

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Introduction

The basic oxygen furnace (BOF) process is widely regarded as the most effective method for improving economic efficiency and enhancing the quality of metallurgical products [1 – 3].

In Russia, BOF production mirrors the key challenges faced globally, including optimizing the composition of processed charges and reducing losses and resource consumption in the process [4 – 6]. Modern economic conditions demand improvements in production planning, technological advancements, the development of new refractory materials, and innovative BOF lining repair methods. These efforts aim to significantly extend unit campaign durations and reduce refractory consumption [6 – 9]. As a result, planning production metrics, along with the maintenance and repair of equipment and auxiliary systems, remains a critical focus for achieving the highest possible technical and economic performance in BOF shops [10 – 12].

Planning BOF repairs in steelmaking production presents unique challenges, as it requires multifactorial solutions when developing a calendar plan for BOF operations. In the case of other metallurgical units, the BOF repair schedule is a key input for their overall calendar planning [13 – 15]. This distinction stems from the fact that BOFs are taken offline for repairs once the number of melts conducted on a given lining reaches the defined standard campaign duration [16; 17]. The timing of this milestone depends on the unit's operational calendar and often results in repairs being carried out at irregular intervals under production conditions [18 – 20].

Key concepts and notations

Let $O = \{O_I, O_{II}\}$ represent the structure of the steelmaking production, which includes two BOF shops: $O_I = \{o_1, o_2, o_3\}$ and $O_{II} = \{o_4, o_5\}$. The first shop operates three BOFs of the same type, while the second shop operates two. The planning interval for BOF repairs depends on the standard campaign durations of the BOFs, their charge capacities, and the monthly volumes of cast iron supplied for processing. Let $(T_1, T_2, ..., T_j, ..., T_P)$ denote the sequence of months in the BOF repair planning interval; $T_j = \left(\Delta t_{s_j} | s_j = \overline{1, S_j}\right)$; and S_j represent the number of days in the j-th month. The volumes of cast iron processed per melt cycle by the BOFs in the first and second shops are denoted as $g(O_I)$ and $g(O_{II})$ respectively. The cast iron consumption coefficients for producing one ton of steel in the corresponding shops are ρ_I, ρ_{II} and the standard campaign durations of the BOFs are K_I and K_{II}. Let $\left\{\left(s_j^{r_{i_c}^n}, s_{j'}^{r_{i_c}^e}\right) | c = \overline{1, 2, ...}\right\}$, $i = \overline{1, 5}$ represent the planned intervals for BOF repairs, where $s_j^{r_{i_c}^n}$ and $s_{j'}^{r_{i_c}^e}$ are the days when the c-th repair of the i-th BOF begins and ends, respectively. If $j = j'$, the repair starts and finishes within the same planning period j. If $j \neq j'$, the repair begins in period j and ends in period j', with the repair lasting $\left(S_j - s_j^{r_{i_c}^n}\right)$ days in period j and $s_{j'}^{r_{i_c}^e}$ days in period j'.

It is important to note that the reduction in scrap metal supply under current market conditions has made scrap metal prices comparable to the cost of cast iron production. As a result, the cast iron consumption coefficients ρ_I and ρ_{II} are no longer considered constants and are now given as interval-based estimates:

$$\rho_I \in \left(\rho_I^{\min}, \rho_I^{\max}\right);$$
$$\rho_{II} \in \left(\rho_I^{\min}, \rho_I^{\max}\right). \quad (1)$$

Advancements in BOF production technology – such as the introduction of secondary steelmaking, real-time monitoring of BOF lining conditions, and periodic "hot" repairs between scheduled overhauls involving lining replacement – have significantly extended BOF campaign durations, which now often exceed 6000 melts. At the same time, the total number of "cold" BOF repairs has decreased. Additionally, different suppliers of specialized materials for "hot" repairs offer varying guarantees on BOF campaign durations, leading to the widespread use of the term "guaranteed BOF durability." In modern practice, campaign duration is typically determined by the refractory supplier under a specific contractual agreement:

$$K_I = \left(K_1^{\min},\ K_1^{\max}\right);$$
$$K_{II} = \left(K_{1I}^{\min},\ K_{1I}^{\max}\right). \qquad (2)$$

The understanding of "cold" repairs has also evolved. Previously, this term referred exclusively to the time required to replace the BOF lining. Today, such repairs are generally combined with maintenance of auxiliary equipment and other metallurgical units. As a result, BOF stop for repairs may exceed the duration of the current planned production period.

Unless otherwise specified, the evaluations of the parameters introduced will be treated as point estimates rather than interval estimates.

Let us denote the number of melts produced daily by BOF i in shops O_I and O_{II} as $m_{ij}\left(\Delta t_{s_j}\right)$, $m_{Ij}\left(\Delta t_{s_j}\right)$, $m_{IIj}\left(\Delta t_{s_j}\right)$. It is evident that:

$$\sum_{i=1}^{3} m_{ij}\left(\Delta t_{s_j}\right) = m_{Ij}\left(\Delta t_{s_j}\right);$$
$$\sum_{i=4}^{5} m_{ij}\left(\Delta t_{s_j}\right) = m_{IIj}\left(\Delta t_{s_j}\right). \qquad (3)$$

The calendar plan for the operation of the i-th BOF in the j-th month is defined as the sequence

$$m_{ij}\left(\Delta t_{s_j}\right) \mid s = \overrightarrow{1, S}_j. \qquad (4)$$

The joint operation of BOFs in the shops is governed by technological constraints that define the range of daily melts in each shop, depending on whether one or two BOFs are operating simultaneously:

$$\underline{m_I^1} \le m_{ij}\left(\Delta t_{s_j}\right) \le \overrightarrow{m_I^1},\ i = \overline{1,3},\ j = \overrightarrow{1,P}; \qquad (5)$$

$$\underline{m_{II}^1} \le m_{ij}\left(\Delta t_{s_j}\right) \le \overrightarrow{m_{II}^1},\ i = \overline{4,5},\ j = \overrightarrow{1,P}; \qquad (6)$$

$$2\underline{m_I^1} \le \left(m_{ij}(\Delta t_s) + m_{i'j}(\Delta t_s)\right) \le \overline{2m_I^1};$$
$$i \ne i',\ i,\ i' = \overline{1,3},\ j = \overrightarrow{1,P}; \qquad (7)$$

$$2\underline{m_{II}^1} \le \left(m_{4j}(\Delta t_s) + m_{5j}(\Delta t_s)\right) \le \overline{2m_{II}^1},\ j = \overrightarrow{1,P}, \qquad (8)$$

where $\underline{m_I^1}$, $\overrightarrow{m_I^1}$, $\underline{m_{II}^1}$, $\overrightarrow{m_{II}^1}$, $2\underline{m_I^1}$, $\overrightarrow{2m_I^1}$, $2\underline{m_{II}^1}$, $\overrightarrow{2m_{II}^1}$ are the minimum and maximum numbers of melts produced in the first and second shops, respectively, when operating a single BOF, as well as the minimum and maximum numbers of melts produced when two BOFs are in operation.

Operating three BOFs in the first shop is technologically challenging to implement.

We define the function $k_{ij}(s_j)$, which represents the number of melts produced by the i-th BOF by the end of day s_j in the j-th period. The number of melts is limited by the campaign durations of the BOFs

$$k_{ij}\left(s_j\right) \le \begin{cases} K_I,\ i = \overline{1,3}; \\ K_{II},\ i = \overline{4,5}. \end{cases} \qquad (9)$$

The set of possible start times $s_j^{r_{i_c}^n}$ for BOF repairs is determined by the following relationships

$$\left\{ s_j^{r_{i_c}^n} \mid k_{ij}\left(s_j\right) \ge K_I \right\},\ i = \overline{1,3};$$
$$\left\{ s_j^{r_{i_c}^n} \mid k_{ij}\left(s_j\right) \ge K_{II} \right\},\ i = \overline{4,5}. \qquad (10)$$

The completion time $s_j^{r_{i_c}^e}$ for repairs is determined by their specified duration r_{i_c}, $c = \overline{1,2,...}$

In steelmaking production, the design and repair management system ensures that no two "cold" repairs are carried out in the same shop during a single planned period. Additionally, the first shop is designed to maintain the continuous operation of two BOFs, while the third is either under repair or held in reserve. As a result, during each planned period T_j one of the following four operating modes is implemented in each shop:

1. No repairs are performed on either of the two operational BOFs

$$\left(s_j^{r_{i_c}^n}, s_j^{r_{i_c}^e}\right) \not\subset T_j. \qquad (11)$$

2. One of the operational BOFs is undergoing repairs

$$\left(s_j^{r_{i_c}^n}, s_j^{r_{i_c}^e}\right) \subset T_j. \qquad (12)$$

3. Repairs on one of the operational BOFs, started in a previous period, are completed

$$T_{j-1}\left(s_{j-1}^{r_{i_c}^n}, s_j^{r_{i_c}^e}\right) \cap T_j = \overline{1, s_j^{r_{i_c}^e}}. \qquad (13)$$

4. Repairs on one of the operational BOFs are initiated and will be completed in a subsequent period

$$T_{j+1}\left(s_j^{r_{i_c}^n},\ s_{j+1}^{r_{i_c}^e}\right) \cap T_j = \overline{s_{j+1}^{r_{i_c}^n}, S_j}. \qquad (14)$$

Let k_{ij}^{n} represent the number of melts produced by the *i*-th BOF at the beginning of the *j*-th planning period. Based on expression (4), the number of melts k_{ij}^{e}, produced by the *i*-th BOF by the end of the *j*-th planning period, for each operating mode, is described by the following functions

$$k_{ij}^{e} = k_{ij}^{n} + \sum_{l=1}^{S_j} m_i\left(\Delta t_{s_j}\right); \tag{15}$$

$$k_{ij}^{e} = k_{ij}^{n} + \sum_{l=1}^{s_j^{r_{ic}^{n}}} m_i\left(\Delta t_{s_j}\right) + \sum_{l=s_j^{r_{ic}^{e}}+1}^{S_j} m_i\left(\Delta t_{s_j}\right); \tag{16}$$

$$k_{ij}^{e} = k_{ij}^{n} + \sum_{l=s_j^{r_{ic}^{e}}+1}^{S_j} m_i\left(\Delta t_{s_j}\right); \tag{17}$$

$$k_{ij}^{e} = k_{ij}^{n} + \sum_{l=1}^{s_j^{r_{ic}^{n}}} m_i\left(\Delta t_{s_j}\right). \tag{18}$$

The function $k_{ij}(s_j)$, which represents the number of melts produced by the *i*-th BOF by the end of day s_j exhibits quasi-periodic behavior (irregular periodicity). It has a "sawtooth" shape, with a maximum value of K_I for BOFs in the first shop and K_{II} for BOFs in the second shop. The length of the "sawtooth base" depends on the number of melts produced daily by the BOF until the function reaches its maximum value, at which point it resets to zero. The spacing between the "teeth" of the saw corresponds to the BOF repair duration, during which the function also equals zero.

The oscillations of $k_{ij}(s_j)$ follow a regular pattern but lack a fixed period.

Using the sequences

$$\left(g_j^{\text{in}}\left(\Delta t_{s_j}\right) | s_j = \overline{1, S_j}\right),$$

$$\left(g_{Ij}^{\text{in}}\left(\Delta t_{s_j}\right) | s_j = \overline{1, S_j}\right),$$

$$\left(g_{IIj}^{\text{in}}\left(\Delta t_{s_j}\right) | s_j = \overline{1, S_j}\right)$$

we can describe the daily inflow of liquid iron from blast furnace production to the steelmaking facilities as a whole, as well as to the first and second shops during the *j*-th period. It is evident that $g_{Ij}^{\text{in}}\left(\Delta t_{s_j}\right) + g_{IIj}^{\text{in}}\left(\Delta t_{s_j}\right) = g^{\text{in}}\left(\Delta t_{s_j}\right),\ s_j = \overline{1, S_j}$. Let

$$\sum_{s_0=1}^{S_j} g_j^{\text{in}}\left(\Delta t_{s_j}\right) = G_{T_j}^{\text{in}},$$

where $G_{T_j}^{\text{in}}$ is the monthly volume of cast iron requiring processing. Similarly, we define the values $G_{IT_j}^{\text{in}}$ and $G_{IIT_j}^{\text{in}}$, $G_{IT_j}^{\text{in}} + G_{IIT_j}^{\text{in}} = G_{T_j}^{\text{in}}$. To calculate the number of melts required to process the incoming cast iron on day s_j described by the sequence $\left(g_{Ij}^{\text{in}}\left(\Delta t_{s_j}\right) | s_j = \overline{1, S_j}\right)$, we use the following recursive procedure:

$$\begin{aligned} m_{Ij}^{\text{in}}(\Delta t_1) &= \left[\frac{g_{Ij}^{\text{in}}(\Delta t_1)}{g(O_I)}\right]; \\ m_{Ij}^{\text{in}}(\Delta t_2) &= \left[\frac{g_{Ij}^{\text{in}}(\Delta t_2) + g_{Ij}^{\text{in}}(\Delta t_1)}{g(O_I)} - \frac{m_{Ij}^{\text{in}}(\Delta t_1)\, g(O_I)\rho_I}{g(O_I)}\right] \end{aligned} \tag{19}$$

continuing until $s_j = S_j$.

This results in a sequence $\left(m_{Ij}^{\text{in}}\left(\Delta t_{s_j}\right) | s_j = \overline{1, S_j}\right)$, that describes the daily number of melts the first shop must produce. A similar sequence can be calculated $\left(m_{IIj}^{\text{in}}\left(\Delta t_{s_j}\right) | s_j = \overline{1, S_j}\right)$ for the second shop. Let us represent the monthly volumes of cast iron requiring processing in the $M_{IT_j} = \sum_{s_j=1}^{S_j} m_I^{\text{in}}\left(\Delta t_{s_j}\right)$ and $M_{IIT_j} = \sum_{s_j=1}^{S_j} m_{II}^{\text{in}}\left(\Delta t_{s_j}\right)$ first and second shops, respectively, expressed as the number of melts. It is evident that $M_{IT_j} g(O_I) + M_{IIT_j} g(O_{II}) = G_{T_j}^{\text{in}}$.

The current campaign durations of the BOFs are significantly higher than the monthly production volume of their respective shops:

$$M_{IT_j} \ll K_I;\ M_{IIT_j} \ll K_{II}. \tag{20}$$

Now, let us define a condition to prevent two "cold" repairs from being carried out in the same shop during a single planning period. We will start with the second shop, which operates two BOFs. Due to the quasi-periodic nature of the functions $k_{4j}(s_j)$ and $k_{5j}(s_j)$, and because the campaign durations K_{II} of the BOFs are identical, the maximum possible difference between the values $k_{4j}(s_j)$ and $k_{5j}(s_j)$ of these functions is $K_{II}/2$:

$$\left|k_{4j}\left(s_j\right) - k_{5j}\left(s_j\right)\right| \le K_{II}/2. \tag{21}$$

Therefore, the best way to stagger the repairs of the fourth and fifth BOFs is to maintain the approximate equality

$$\left|k_{4j}\left(s_j\right) - k_{5j}\left(s_j\right)\right| \approx K_{II}/2. \tag{22}$$

Equation (20) also indicates that if one BOF is taken offline for repair, the remaining BOF has enough capacity to handle the entire production plan for the current planning period.

For the first shop, which operates three BOFs, the design provides for the continuous operation of two BOFs, while the third is either under repair or held in reserve. The reserved BOF is brought online whenever one of the operating BOFs is taken offline for repair. Under this scheme, with two BOFs operating continuously, the condition for staggering their repairs, similar to that of the second shop, can be written as

$$\left|k_{ij}\left(s_j\right)-k_{i'j}\left(s_j\right)\right| \approx K_I/2;\ i,\ i' \in \{1, 2, 3\}, \qquad (23)$$

where i, $i' \in \{1, 2, 3\}$ are the BOFs operating in the first shop on day s_j.

Task formulation for planning BOF repairs and operations across planned periods ($T_1, T_2, ..., T_j, ..., T_P$)

The objective is to determine sequences

$$\left(m_{ij}\left(\Delta t_{s_j}\right) | s_j = \overline{1, S_j}\right),\ i=\overline{1,5},\ j=\overline{1,P} \qquad (24)$$

and BOF repair schedules

$$\left(s_j^{r_{ic}^n}, s_j^{r_{ic}^e}\right) \subset \bigcup_{j=1}^{P} T_j,\ i=\overline{1,5},\ c=\overline{1,2,...}, \qquad (25)$$

that satisfy equations (5) – (8), the constraint

$$g(O_I)\sum_{i=1}^{3} m_{ij}\left(\Delta t_{s_j}\right) + g(O_{II})\sum_{i=4}^{5} m_{ij}\left(\Delta t_{s_j}\right) = g_j^{\text{in}}\left(\Delta t_{s_j}\right), \qquad (26)$$

and conditions (11) – (14) for performing repairs under specific operational modes, while minimizing criterion

$$Q=\sum_{j=1}^{P}\left\{\left(\left|k_{ij}^e - k_{i'j}^e\right| - 0{,}5K_1\right) + \right.$$
$$\left. + \left(\left|k_{4j}^e - k_{5j}^e\right| - 0{,}5K_{II}\right)\right\} \to \min, \qquad (27)$$

where i, $i' \in \{1, 2, 3\}$ denote the indices of the BOFs operating in the first shop on day S_j, and the values k_{ij}^e are determined in accordance with rules (15) – (18).

The criterion is designed to ensure conditions that enable the shops to achieve their design production capacities during each planning period.

Conclusions

Using the steelmaking production at JSC EVRAZ United West Siberian Metallurgical Plant as an example, the problem of synchronous calendar planning is examined. This planning covers multiple periods, including the operation of BOFs, BOF shops, and the production process as a whole, as well as ongoing BOF repairs. Scheduled BOF stops for repairs depend on the actual duration of the lining campaign achieved and the production schedules of the units. Repairs are carried out when the current campaign duration of a BOF reaches the specified standard value.

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V. V. Zimin – technological description of the task, justification of the research direction, analysis of the results.

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