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OPTIMISATION OF METAL CHARGE MATERIAL FOR ELECTRIC ARC FURNACE

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The analysis of the changes in the crude steel production volumes implies gradual increase of production since the mid 20th century. This tendency has been slightly hampered by the economic depression. At the same time, the market requirements enforce improvement of the quality of the products manufactured on simultaneous minimisation of the production costs. One of the tools applied to solve these problems is mathematical optimisation. The author of this paper has presented an example of application of the multi-criteria optimisation method to improvement of efficiency of steel smelting in an electric arc furnace (EAF) through appropriate choice of the charge scrap. A measurable effect of applying such a methodology of choosing the metal charge is the ability to reduce the unit cost of steel smelting.

Key words: EAF, multi-criteria optimisation, charge scrap, crude steel

Optimizacija metalnog uloška elektrolučne peći. Analiza promjena proizvodne mase sirovog čelika ukazuje na značajno povećanje proizvodnje od sredine 20. stoljeća. Ta tendencija neznatno je usporena uslijed ekonomske depresije. Istodobno, zahtjevi tržišta prisilili su poboljšanje kvalitete proizvoda simultanom minimizacijom proizvodnih troškova. Jedan od alata koji se primjenjuje za rješavanje tih problema je matematičko optimiziranje. Autor ovog rada prikazao je primjer primjene metode multi-kriterijskog optimiziranja na poboljšanje efikasnosti taljenja u elektrolučnoj peći (ELP) odgovarajućim izborom otpatka u ulošku. Mjerljiv utjecaj primjene takve metodologije izbora metalnog uloška je mogućnost smanjenja jediničnih troškova taljenja čelika.

Ključne riječi: ELP, multi-kriterijsko optimiziranje, uložni otpadak, sirovi čelik

INTRODUCTION

Steel has remained the most crucial of all structural materials. However, the steel production processes have changed over the years. Currently, due to the tendency of eliminating high energy consuming technologies, in both the international and domestic steel industry, liquid steel is manufactured in two basic aggregates: oxygen-blown converters and electric arc furnaces [1]. The development of technique and technology in the scope of steel production in an arc furnace is aimed at improving the efficiency of the installations used, increasing the quality of steel and reducing the production costs.

The basic iron-bearing medium for EAF is steel scrap. Strong competition requires efficient utilisation of raw materials, especially secondary raw materials like steel scrap. Bearing in mind the contemporary tendencies to implement and develop technologies contributing to protection of natural resources and environment, including those reducing the carbon dioxide emission, an EAF as a scrap-based steel smelting aggregate is a particularly attractive solution. Steel smelting in an electric furnace enables steel recycling, which can be stressed as its great environmental advantage [2]. In light of the market economy requirements and strong competition in the global market, the fact of undertaking various subjects in the field of economic optimisation of steel production seems completely justified. The presented paper constitutes an analysis of the example of application of two criteria optimisation solution where one of the criteria is the cost of the charge scrap and the second one is the yield of crude steel smelting in EAF.

OPTIMISATION AND CHOICE OF A CRITERION

The contemporary economy is characterised by an increase in the number of manufacturers of identical products competing with one another. The same phenomenon can be noticed in the steel industry and it occurs in all stages of the final product manufacture. In practice, there is usually a problem a solution of optimisation task covering two functions: achievement of a maximum effect (e.g. yield of crude steel) on simultaneous minimisation of expenditures. Such problems are considered to function under the class of multi-criteria optimisation models the most common of which are two-criteria problems. The examinations in question were performed at an electric steel-smelting shop assuming a quotient programming model [3,4] being one

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T. Lis, Department of Metallurgy, Silesian Technical University, Katowice, Poland

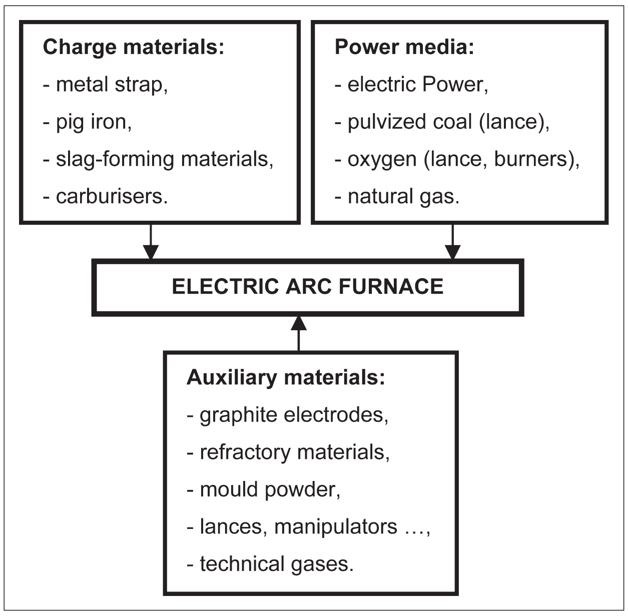

Figure 1 Block diagram presenting components of the variable steelmaking cost in EAF [6]

of the methods of finding compromising solutions under the tasks of multi-criteria optimisation with two contradictory functions.

Two constituents comprise an overall product cost: constant cost and variable cost. Only the variable cost can be altered during current production. The relevant calculations imply that the share of variable cost in the overall cost of steel smelting in EAFs is 75 – 85 %, therefore, from the perspective of the steel production optimisation process for an electric furnace, one of the most significant criteria is the minimisation of the production cost variable constituent.

Based on the cause and effect analysis (diagram by Ishikawa) conducted [5], a block diagram was prepared for the variable cost components for crude steel smelted in the EAF – Figure 1.

The Pareto-Lorenz analysis conducted showed that two cost components, namely the metal charge costs and the electric power costs, out of all crude steel production variable cost components (metal charge, electric power, graphite electrodes, sag-forming additives, mould powders, auxiliary materials, refractory materials, technological oxygen, natural gas, technical gases), accounted for more than 85 % including the scrap material cost of ca. 70 % [5,6]. Therefore, one of the optimisation criteria chosen was the metal charge cost. It was determined that the crude steel cost was also significantly influenced by the efficiency of the steel smelting process conducted in the EAF. Consequently, the second criterion assumed was the yield of mass from scrap materials, being a parameter particularly significant for the furnace capacity.

EXAMINATIONS

The examinations were conducted at a steel-smelting shop equipped with an UHP electric arc furnace with eccentric bottom tapping (EBT) manufactured by Mannesmann Demag. The variables assumed for the steel manufacture in the EAF were the masses of the individual sorts of charge materials. A problem of quotient programming with a hyperbolic objective function was established to find a compromise solution in which one of the functions was to be the cost minimisation and the other – maximisation of the metal yield from scrap.

The quotient programming task model is composed of limiting conditions in a linear form, boundary conditions as well as objective functions in a fractional form [7].

The objective function was established as follows:

$$F(X) = \frac{\sum_{j=1}^{n} c_j \cdot X_j}{\sum_{j=1}^{n} d_j \cdot X_j} \rightarrow \min \qquad (1)$$

where:

c_j – unit cost of scrap material (for $j = 1,2 \ldots n$ scrap sorts),

d_j – yield of scrap mass (for $j = 1,2 \ldots n$ scrap sorts),

X_j – share of steel scrap in the charge burden (for $j = 1,2 \ldots n$ scrap sorts; $X_1 + X_2 + \ldots . X_n = 1$).

An additional limitation was the non-negativeness of decisive variables. In the example being analysed, the following optimum values must be obtained:

$$F_1(X) = \sum_{j=1}^{n} d_j \cdot X_j \rightarrow \max \qquad (2)$$

$$F_2(X) = \sum_{j=1}^{n} c_j \cdot X_j \rightarrow \min \qquad (3)$$

The solution to such a problem is an attempt to find a certain compromise, since it is impossible to come to a solution enabling that criterion F_1 (yield of crude steel from the charge scrap) reaches its maximum, and criterion F_2 (cost of charge scrap) reaches its minimum.

While creating a mathematical model the task of which is to optimise the metal charge material for EAF, one must identify the classification of the charge scrap being applied. It is very diverse and depends on the grades of steel manufactured and the sorts of charge scrap available commer-cially in the market [8,9]. The following properties should be entailed for the sake of the scrap material classification:

- content of alloying elements possible to be reclaimed in the steel smelting process;
- content of harmful elements (including sulphur, phosphorus, copper, zinc) and undesirable elements (e.g. chromium, nickel, molybdenum, tin);
- geometry of scrap (mass density and scrap size) – the knowledge of the scrap material geometry enables optimum filling of the EAF charge baskets.

In terms of the scrap material origin, one can speak of home scrap and outside scrap (scrap from fully depreciated machines, tools). Within the last twenty five years, the share of post-depreciation scrap in use has risen considerably due to the development of the continuous casting technology and the increase in manufacture of steel-containing products replaced by users with new ones (e.g. cars, household appliances) [9,10]. However, due to the large share of outside scrap in the overall mass of charge materials, its quality drops, which applies particularly to the increase of the content of undesirable elements and copper.

The classification of scrap assumed in the case being analysed was the one applied in the electric steel smelting shop entailing the individual sorts (Table 1) without the home scrap due to the impossibility of determining its price.

Table 1 **Metal charge scrap classification (scrap sorts)**

Scrap (independent variable)		Bulk density / Mg·m^{-3}	Dimensions max. / mm
Name	Signify		
Light scrap	X_1	<0,6	1 000 x 500 x 500
Medium-weight scrap	X_2	0,6 – 0,7	1 200 x 500 x 500
Heavy scrap	X_3	> 0,7	1 200 x 500 x 500
Scrap in package	X_4	to 1,0	1 000 x 500 x 500
Pressed steel chips	X_5	0,6 – 0,8	50 - 150
Special scrap (Cu < 0,15 %)	X_6	> 0,7	1 200 x 500 x 500

Since the purpose of the mathematical model being developed was to find a compromising solution between minimi-sation of the charge scrap cost and maximisation of the metal yield from this scrap, in the first instance, both the metal yield from the individual sorts of scrap material (crude steel mass) and the scrap material prices needed to be estimated. In order to estimate the mass of crude steel, data from 3 638 melts were used after the initial selection by the 3S method [11] (assuming that the variables are subject to normal distribution), and on such a basis, a specific dependence in the form of a multiple regression equation was established to enable programming of the crude steel yield depending on the composition of the metal scrap. Table 2 contains a collation of the metal yield ratios obtained for the individual sorts of scrap material as well as the price relations between these sorts.

Table 2 **Empirical metal yield ratios for the individual sorts of scrap and their price relations**

Variable X_j	Yield of scrap mass / d_j	Unit cost of scrap material / c_j
X_1	0,8135	1,000 *c*
X_2	0,8646	1,385 *c*
X_3	0,9143	1,575 *c*
X_4	0,8561	1,310 *c*
X_5	0,8327	1,225 *c*
X_6	0,9253	1,586 *c*

The problem of quotient programming with an objective function (1) entailed the limiting conditions related to the scrap material geometry (optimum filling of charge baskets and time required to melt the heavy scrap) as well as the technological conditions applicable in the steel smelting shop (assuming that the charge was loaded into the EAF with two charge baskets):

- on the bottom of both charge baskets, there should be light scrap in the quantity not exceeding 15 % of the scrap mass, the mass of pressed steel chips should not exceed 5 % of the charge scrap mass, and the volume of light scrap and pressed steel chips should not exceed 38 % of the capacity of both charge baskets, this is about 32 % of the charge scrap mass:

$$X_1 \geq 0{,}15$$
$$X_5 \leq 0{,}05$$
$$X_1 + X_5 \leq 0{,}32$$

- the mass of heavy scrap including the special scrap should not exceed 40% of the overall charge scrap mass, and its minimum share should not be smaller than 20 %:

$$0{,}20 \leq X_3 + X_6 \leq 0{,}40$$

- the mass of packed scrap should not exceed 5 % of the charge scrap mass:

$$X_4 \leq 0{,}05$$

- for the steel of the Cu content < 0,4%, the special scrap (X_6) share in the overall charge scrap mass should be smaller than 7 %,
- for the steel of the Cu content < 0,35%, the special scrap (X_6) share in the overall charge scrap mass should be smaller than 10 %.

Based on dependence (2) and (3), the objective function in the optimisation problem being analysed assumes the following form (data in Table 2):

$$F(X) = \frac{c(X_1 + 1{,}385 \cdot X_2 + 1{,}175 \cdot X_3 +}{0{,}8135 \cdot X_1 + 0{,}8646 \cdot X_2 + 0{,}9143 \cdot X_3 +} \quad \frac{+ 1{,}31 \cdot X_4 + 1{,}225 \cdot X_5 + 1{,}586 \cdot X_6}{+ 0{,}8541 \cdot X_4 + 0{,}8327 \cdot X_5 + 0{,}9253 \cdot X_6} \rightarrow \min \tag{4}$$

The metal charge was chosen for the following grades of steel:

- for the grades most commonly manufactured at the steelworks examined (normal quality structural steel – without special scrap) – set I,
- for the steel of copper content below 0,35 % – set II,
- for the charge scrap without packed scrap – set III.

The shares of the individual grades of steel obtained as well as the values of the objective function, the assumed yield of crude steel from metal charge and its prices have been provided in Table 3.

Table 3 **Optimum composition of metal charge for EAF**

	share in the charge scrap mass / %		
	Set I	**Set II**	**Set III**
X_1	0,32	0,32	0,32
X_2	0,43	0,38	0,48
X_3	0,20	0	0
X_4	0,05	0,05	0
X_5	0	0,05	0
X_6	0	0,20	0,2
$F(X)$	1,51141c	1,503318c	1,513271c
$F_1(X)$	0,857663	0,858268	0,860388
$F_2(X)$	1,29605c	1,29025c	1,302c

The calculations performed imply that under the conditions present at the steel smelting shop examined, entailing the limiting conditions, the minimum price of metal charge on maximum yield of crude steel from scrap can be attained if the charge material is composed of 32 % of light scrap, 38 % of medium-weight scrap, 5 % of pressed steel chips and packed scrap respectively and 20 % of special scrap. Such a composition of the metal charge can be used for smelting of both standard structural steel and the steel with copper content not exceeding 0,35 % of Cu. The share of packed scrap exerts an influence on the price reduction, whereas the share of special scrap may increase the yield of crude steel. If in set I, the heavy scrap is replaced with special scrap, then the yield of crude steel will come to 0,859863, and the price of 1 Mg of scrap will equal 1,29825 of the light scrap. Consequently, the share of special scrap in the charge material exerts a positive influence on the yield of crude steel from scrap material, and at the same time, it does not cause a significant increase in the price of the charge material (assuming the share of special scrap on the level of 20 %).

CONCLUSIONS

It is the market economy that requires the criterion of production optimisation to remain in the economic domain, and in most cases, it can be the variable cost of the product manufactured. Striving to solve such optimisation tasks, as e.g. attaining the maximum yield of crude steel from metal scrap on minimum steel scrap costs, it is reasonable to find a compromising solution by applying the quotient programming method with a hyperbolic objective function. An additional advantage resulting from application of mathematical, multi-criteria optimisation models is the possibility of using common spreadsheets featuring the basic tools of mathematical analysis.

The optimisation solution defined for the EAF charge material implies that under the conditions present at the electric steel smelting shop examined and assuming the aforementioned limiting conditions:

– the cost of 1 Mg of scrap in the EAF charge material should not exceed 1,3 of the price of 1 Mg of light scrap, and at the same time, it enables attaining the yield of crude steel on the level of 0,857 ÷ 0,86,
– the metal charge optimisation under the conditions of the steelworks examined should lead to reduction of the price of 1 Mg of metal charge by ca. 0,15 ÷ 0,52 of the price of 1 Mg of light scrap.

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Note: The responsible for English language is P. Nowak, Katowice, Poland.