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COST AND EXERGY ANALYSIS FOR OPTIMIZATION OF CHARGING MATERIALS FOR STEELMAKING IN EAF AND LF AS A SYSTEM*

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Expenditures on the charging materials used in an EAF + LF system at a steel plant in Turkey are optimized with allowance for different thermo-economic indices and different combinations of electric-arc furnace (EAF) and ladle furnace (LF). The EAF and LF are regarded as a single system, and the mass balance for the raw materials is determined based on literature data and company catalogues. Cost functions based on energy and exergy indices are constructed to perform the optimization. Constraints on the functions are introduced, the exact constraints depending on the chemical composition of the raw materials and other materials charged into the system, the system's productivity, the maximum amount of energy that can be used, and other parameters. The computer program WINQSB – which is well-suited for the solution of such problems – is used here because the changes in the parameters of the system are linear.

Keywords: *electric-arc furnace, ladle furnace, exergy optimization, steel production, liquid steel, Turkey.*

Notation: C_e – base cost of energy (U.S. dollars); C_{ELT} – cost of electric power (0.057 U.S dollars/kWh); C_{ex} – base cost of exergy (U.S. dollars); *CR* – combustion ratio (kg/kg); *E* – reaction energy (kJ/kg); EAF – electric-arc furnace; e_x – reaction exergy (kJ/kg); $E_{x\text{-}R}$ – reaction exergy (kJ); LF – ladle furnace; *M*, *m* – mass (kg); MKE – the Turkish company The Mechanical and Chemical Industry Corporation; *MR* – mass ratio (kg/kg); *n* – number of moles (kmole).

Indices in the formulas: AL – aluminum; Al_2O_3 – aluminum oxide; AR – argon; CAR – carbon; COK – coke; *CW* – coolant water; *DEOX* – material for reduction; *DKP* – scrap (a type of scrap used by the company); *e* – energy; *ex* – exergy; *ELD* – electrodes; *ELD(EAF)* – electrode for the EAF; *ELD(LF)* – electrode for the LF; *ELT* – electrical; *FBO* – ferroboron; FCR-*HC* – high-carbon ferrochromium; FCR-*LC* – low-carbon ferrochromium; *FLS* – fluorite; *FLX* – fluxes; FMN – ferromanganese; FMO – ferromolybdenum; FSI – ferrosilicon; HMS – heavy melting scrap; LIM – lime; MGO – magnesium oxide; MMN – metallic manganese; *NG* – natural gas; NI – nickel; OXY – oxygen; PIG – conversion pig iron; *PW* – metallic production wastes; SFMN – ferrosilicomanganese; *SS* – shredder unit; SULP – sulfur.

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TABLE 1. Prices for the Materials Entering and Leaving the EAF

Materials *entering* the EAF	Weight, tons	Weight per ton of liquid steel		Price per ton, U.S. dollars	Price per ton of liquid steel, U.S. dollars	Total cost, U.S. dollars
		tons	kg			
Scrap (production wastes)	17.500	0.318	318.182	111.000	35.318	1942.500
Scrap (heavy melting scrap)	10.000	0.182	181.818	111.000	20.182	1110.000
Scrap (from the shredder unit)	12.500	0.227	227.273	111.000	25.227	1387.500
Scrap (DKP)	10.000	0.182	181.818	111.000	20.182	1110.000
Conversion pig iron	7.500	0.136	136.364	120.000	16.364	900.000
Coke	1.000	0.018	18.182	99.000	1.800	99.000
Lime	1.500	0.027	27.273	240.000	6.545	360.000
Limestone	1.000	0.018	18.182	30.400	0.553	30.400
AlDEOX	0.200	0.004	3.636	896.000	3.258	179.200
Ferrosilicomanganese	0.350	0.006	6.364	470.000	2.991	164.500
Aluminum	0.050	0.001	0.909	1400.000	1.273	70.000
Electrodes	0.150	0.003	2.727	1890.000	5.155	283.500
Natural gas	0.131	0.002	2.386	240.000	0.573	31.495
Oxygen (pure)	3.510	0.064	63.821	76.000	4.850	266.770
Coolant water	600.000	10.909	10909.091	0.300	3.273	180.000
Total	665.391	12.098	12098.025	5905.700	147.543	8114.864
Materials *leaving* the EAF	Weight, tons	Weight per ton of liquid steel		Price per ton, U.S. dollars	Price per ton of liquid steel, U.S. dollars	Total cost, U.S. dollars
		tons	kg			
Liquid steel	55.000	1.000	1000.000	157.000	157.000	8635.000
Steel in the slag	0.300	0.005	5.455	0.000	0.000	0.000
Dust	3.116	0.057	56.654	2.170	0.123	6.762
Slag	2.741	0.050	49.842	0.000	0.000	0.000
Flue gases	4.234	0.077	76.983	0.000	0.000	0.000
Coolant water	600.000	10.909	10909.091	0.600	6.545	360.000
Total	665.391	12.098	12098.025	159.770	163.668	9001.762
Note. The company signed contracts for the purchase of raw materials and auxiliary materials. The prices are those in effect during April 2003.						

The productivity of the electric-arc furnace (EAF) has been increasing since the 1970s thanks to the use of modern ultra-high-power furnaces that can achieve high melting rates. Roughly 438 million tons of steel is made in electric furnaces worldwide each year (31% of all steel production). In Turkey, nearly 70% (about 20 million tons) of the country's steel is made in EAFs [1].

The main advantage of EAF + LF systems (LF – ladle furnace) is that they use steel scrap to produce liquid steel. This is another reason that steel production in EAFs has increased in Turkey and the rest of the world. One of the most important reasons for the high utilization factor of an EAF is that the capital investment per ton of untreated steel made in an EAF is significantly smaller than for steel made by other technologies, such as those employed by integrated plants [2].

TABLE 2. Prices for the Materials Entering and Leaving the LF

Materials *entering* the LF	Weight, tons	Weight per ton of liquid steel		Price per ton, U.S. dollars	Price per ton of liquid steel, U.S. dollars	Total cost, U.S. dollars
		tons	kg			
Liquid steel from the EAF	55.000	1.000	1000.000	157.000	157.000	8635.000
Ferromanganese	0.800	0.015	14.545	470.000	6.836	376.000
Ferrosilicon	0.120	0.002	2.182	419.000	0.914	50.280
Aluminum	0.050	0.001	0.909	1400.000	1.273	70.000
Ferroboron	0.010	0.000	0.182	1290.000	0.235	12.900
Carbon	0.150	0.003	2.727	96.000	0.262	14.400
Lime	0.350	0.006	6.364	240.000	1.527	84.000
Fluorite	0.030	0.001	0.545	92.000	0.050	2.760
Magnesium oxide	0.100	0.002	1.818	160.000	0.291	16.000
Al_2O_3	0.100	0.002	1.818	0.400	0.001	0.040
Electrodes	0.030	0.001	0.545	1890.000	1.031	56.700
Argon	6.600	0.120	120.000	375.000	45.000	2475.000
Oxygen (pure)	0.677	0.012	12.300	76.000	0.935	51.414
Total	64.017	1.164	1163.936	6665.400	215.354	11844.494
Materials *leaving* the LF	Weight, tons	Weight per ton of liquid steel		Price per ton, U.S. dollars	Price per ton of liquid steel, U.S. dollars	Total cost, U.S. dollars
		tons	kg			
Liquid steel	55.000	1.000	1000.000	157.000	157.000	8635.000
Dust	1.216	0.022	22.109	2.000	0.044	2.432
Slag	0.869	0.016	15.793	0.000	0.000	0.000
Flue gases	0.332	0.006	6.035	0.000	0.000	0.000
Argon	6.600	0.120	120.000	375.000	45.000	2475.000
Total	64.017	1.164	1163.936	534.000	202.044	11112.432
Note. The company signed contracts for the purchase of raw materials and auxiliary materials. The prices are those in effect during April 2003.						

The optimization methods that have been used for EAFs were described in [3, 4]. The first of these papers described a new strategy for controlling the introduction of oxidizing components and using oxygen more efficiently. The paper [4] described methods that are used to determine the optimum consumption of electric power for making steel in an EAF [5].

The goal of the present investigation is to optimize and modernize this technology and introduce technological innovations. The modernization of existing furnaces is examined within the framework of an exergo-economic approach.

Production of steel in an EAF and LF. The process of making steel in an EAF has been described in a number of publications [2, 3, 6–8]. Subsequent out-of-furnace treatment of the steel in an LF ensures the necessary degree of alloying and allows precise control of the temperature regime. The use of an EAF + LF system also makes it possible to reduce the sulfur content of the steel, make broader use of continuous casting, and establish closer control over the quality of the finished product.

As is known, in the course of making steel of a certain composition, a large number of chemical reactions may take place between the materials charged into the furnace and between the elements and compounds that are used to treat the liq-

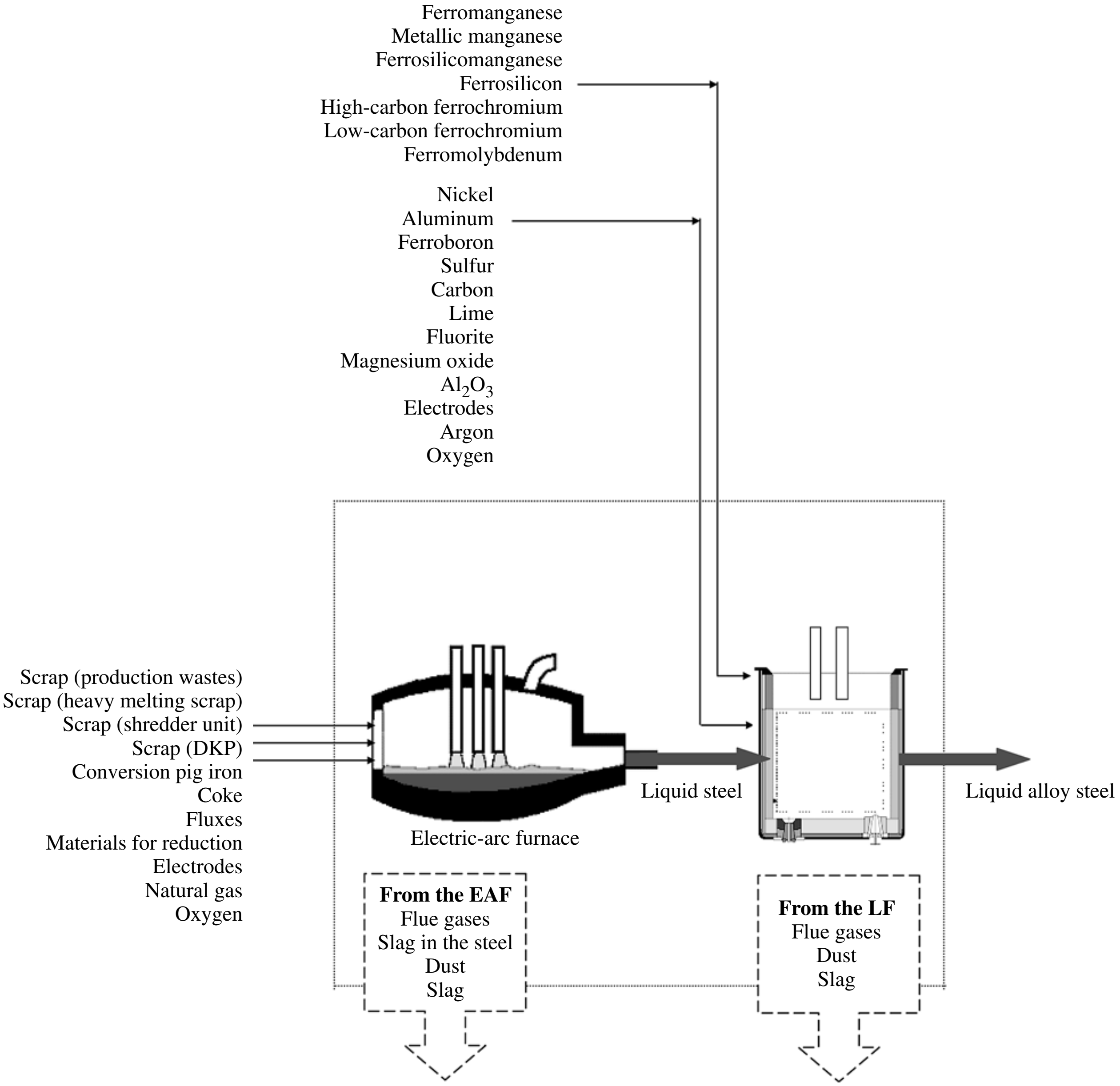

Fig. 1. Materials entering and leaving the EAF and LF [2, 10].

uid steel in the LF. Thus, the first step needed is to perform a mass analysis of the steel. To this end, the mass of each element in the charge, the semifinished product that enters the LF, and the material initially obtained from the LF were determined for a volume of production of 55 tons [7, 9].

Analysis of expenditures on the materials entering the system and the resulting products. The volumes of expenditure on the materials are shown in Tables 1 and 2. The initial data were obtained by the finite-element method, as well as from market data and information from sales contracts signed by the steel company.

Determination of economic and energy costs based on exergy. The total costs for operation of the EAF and LF (see Fig. 1) can be determined with allowance for all the materials that are employed and the exergy of the chemical energy:

$$C_{ex} = C_{ex\text{-}PW} \cdot m_{PW} + C_{ex\text{-}HMS} \cdot m_{HMS} + C_{ex\text{-}SS} \cdot m_{SS} + C_{ex\text{-}DKP} \cdot m_{DKP} + C_{ex\text{-}PIG} \cdot m_{PIG} + C_{ex\text{-}COK} \cdot m_{COK} +$$

TABLE 3. Chemical Analysis of the Materials Used in the EAF and LF [2, 10]

Materials	Content of elements, %								Total (%)	Other			
	Fe	C	Si	Mn	P	S	Cr	Al					
Production wastes (scrap)	97.31	0.55	0.35	0.5	0.025	0.035	0.9		99.67	Ni	Mo	Cu	
										0.10	0.03	0.20	
Heavy melting scrap	97.57	0.35	0.4	0.6	0.04	0.04	0.25		99.25	Ni	Mo	Cu	
										0.25	0.25	0.25	
Scrap from the shredder	98.56	0.2	0.02	0.8	0.02	0.03	0.05		99.68	Ni	Mo	Cu	
										0.05	0.02	0.25	
DKP scrap	99.05	0.35	0	0.35	0.025	0.025	0.05		99.85	Ni		Cu	
										0.05		0.10	
Conversion pig iron	94.27	3.5	1	1	0.15	0.08			100				
Coke	0	88.5	0			0.5			89	SiO_2	Al_2O_3	H_2O	
										4	3	2	
Fluxes								1.72	1.72	$CaCO_3$	CaO	Other	
										35.05	50.81	12.42	
Substances for reduction	9	1.48	16	62	0.1	0.02		11	99.8	Zn			
										0.2			
Electrodes	0.15	99.3	0.15					0.05	99.65	Ca	SiO_2	Al_2O_3	
										0.15	0.05	0.05	
Natural gas (vol.%)										CH_4	C_2H_6	C_3H_8	N_2
										98.67	0.40	0.13	0.80
Oxygen										O_2			
										100			
Ferromanganese	11.15	7	1.5	80	0.3	0.05			100				
Metallic manganese				100					100				
Ferrosilicomanganese	10	1.5	18.33	70	0.15	0.02			100				
Ferrosilicon	16.25	0.2	80	1	0.05	0.5		2	100				
High-carbon ferrochromium	21.395	7	1.5		0.075	0.03	70		100				
Low-carbon ferrochromium	27.24	0.5	1.5		0.01	0.75	70		100				
Ferromolybdenum	27.55	0.25	1.5		0.1			0.1	29.5				
Nickel		0.1							0.1				
Aluminum				1				96	97	Zn	Cu		
										1.5	1.5		
Ferroboron	74.8	0.2	2					3	80	Bo			
										20			
Sulfur						100			100				
Carbon		98.45			0.05	0.5			99				
Lime										CaO	Al_2O_3		
										97	3		
Fluorite										CaF_2	$CaCO_3$	SiO_2	Al_2O_3–Fe_2O_3–H_2O
										76	6	6	12
Magnesium oxide										MgO			
										100			
Al_2O_3													
Electrodes	0.15	99.3	0.15					0.05	99.65	Ca	SiO_2	Al_2O_3	Other
										0.15	0.05	0.05	0.1

TABLE 4. Reaction Products Formed for Each 100 kg of Components Entering the EAF and LF [2, 10]

Element/ component	Content in the liquid steel, kg	Slag in the liquid steel, kg	Amount of the component in the dust, slag, and flue gases of the EAF and LF, kg													
			Fe_2O_3	FeO	C	CO	SiO_2	MnO	P_2O_5	CaS	Cr_2O_3	CaO	Al_2O_3	B_2O_3	ZnO	CO_2	Total
Fe	95.9	0.51	1.39	2.2													100
C	8.5	0.02			1.48	90											100
Si	30.31	0.04					69.65										100
Mn	46.36	0.12						53.52									100
P	30.64	0.16							69.2								100
S	41.96	0.3								57.74							100
Cr	69.79	0.05									30.16						100
Ni	99.46	0.54															100
Mo	99.46	0.54															100
Cu	99.47	0.53															100
$CaCO_3$												56				44	100
Al													100				100
Zn															100		100
B														100			100
Ca												100					100

$$+ C_{ex\text{-}FLX}\cdot m_{FLX} + C_{ex\text{-}DEOX}\cdot m_{DEOX} + C_{ex\text{-}ELD(EAF)}\cdot m_{ELD(EAF)} + C_{ex\text{-}NG}\cdot m_{NG} + C_{ex\text{-}OXY}\cdot m_{OXY} + C_{ex\text{-}CW}\cdot m_{CW} +$$
$$+ C_{ex\text{-}FMN}\cdot m_{FMN} + C_{ex\text{-}MMN}\cdot m_{MMN} + C_{ex\text{-}SFMN}\cdot m_{SFMN} + C_{ex\text{-}FSI}\cdot m_{FSI} + C_{ex\text{-}FCR\text{-}HC}\cdot m_{FCR\text{-}HC} + C_{ex\text{-}FCR\text{-}LC}\cdot m_{FCR\text{-}LC} +$$
$$+ C_{ex\text{-}FMO}\cdot m_{FMO} + C_{ex\text{-}NI}\cdot m_{NI} + C_{ex\text{-}AL}\cdot m_{AL} + C_{ex\text{-}FBO}\cdot m_{FBO} + C_{ex\text{-}SULP}\cdot m_{SULP} + C_{ex\text{-}CAR}\cdot m_{CAR} + C_{ex\text{-}LIM}\cdot m_{LIM} +$$
$$+ C_{ex\text{-}FLS}\cdot m_{FLS} + C_{ex\text{-}MGO}\cdot m_{MGO} + C_{ex\text{-}\mathrm{Al2O3}}\cdot m_{\mathrm{Al2O3}} + C_{ex\text{-}ELD(LF)}\cdot m_{ELD(LF)} + C_{ex\text{-}ELT}\cdot(E_{ELT}^{EAF} + E_{ELT}^{LF}) +$$
$$+ C_{ex\text{-}AR}\cdot m_{AR} - (E_{x\text{-}R1} + E_{x\text{-}R2} + E_{x\text{-}R3} + E_{x\text{-}R4} + E_{x\text{-}R5} + E_{x\text{-}R6} + E_{x\text{-}R7} + E_{x\text{-}R8} + E_{x\text{-}R9} + E_{x\text{-}R10} + E_{x\text{-}R11} +$$
$$+ E_{x\text{-}R12} + E_{x\text{-}R13})\cdot(1/3600)\cdot C_{ex\text{-}ELT}, \quad (1)$$

where 1/3600 is a coefficient used to convert kJ into kWh. The values of C_{ex} and m were obtained from the data in Tables 1 and 2 for the materials of the EAF and LF system. The quantities $E_{x\text{-}R1}$–$E_{x\text{-}R13}$ represent the exergy resulting from the exothermic and endothermic chemical reactions that occur in the system. The values of these quantities depend on the materials charged into the EAF and LF. The data in Tables 3–5 were used to calculate $E_{x\text{-}R1}$–$E_{x\text{-}R13}$. Calculation of the indices $E_{x\text{-}R1}$–$E_{x\text{-}R13}$ is discussed in greater detail in [10]. A detailed explanation of the determination of $E_{x\text{-}R1}$ is given below before the final equations are presented.

For the reaction Fe_2O_3: $2[Fe] + 3[O] \rightarrow [Fe_2O_3]$

$$E_{x\text{-}R1} = [97.31/100 m_{PW} + 97.57/100\cdot m_{HMS} + 98.56/100\cdot m_{SS} + 99.05/100\cdot m_{DKP} + 94.27/100\cdot m_{PIG} +$$
$$+ 9/100\cdot m_{DEOX} + 0.15/100\cdot m_{ELD(EAF)} + 11.15/100\cdot m_{FMN} + 10/100\cdot m_{SFMN} + 16.25/100\cdot m_{FSI} + 21.395/100\cdot m_{FCR\text{-}HC} +$$
$$+ 27.24/100\cdot m_{FCR\text{-}LC} + 27.55/100\cdot m_{FMO} + 74.8/\ 100\cdot m_{FBO} + 0.15/100\cdot m_{ELD(LF)}]CR_{\mathrm{Fe}}\cdot MR_{\mathrm{Fe_2O_3}}\cdot e_{x\text{-}\mathrm{Fe_2O_3}},$$

where CR_{Fe} (the combustion ratio for Fe) = 1.39 kg of the Fe-reacting substance/100 kg of the Fe-system; $MR_{\mathrm{Fe_2O_3}}$ (the mass ratio for Fe_2O_3) = 10 kg Fe/7 kg Fe_2O_3; $e_{x\text{-}\mathrm{Fe_2O_3}}$ (the exergy of the Fe_2O_3 reaction) = 8536 kJ/kg.

TABLE 5. Values of the Chemical Energy of the Elements and Components Used in the EAF + LF System [10]

Component	$\bar{h}_0^0$	n, g/mole	Chemical energy	
			kJ/kg	kJ/1 kg of incoming element
Fe_2O_3	196,300	160	–5139	–7341.7
CaO	151,600	56	–11335	–15869
MnO	92000	71	–5425	–7003.7
Al_2O_3	400,000	102	–16461	–31092
Cr_2O_3	270,000	152	–7437	–10870
ZnO	83200	81.4	–4280	–5326.6
SiO_2	217,600	60	–15184.85	–32539
FeO	63200	72	–3675	–4725.3
P_2O_5	356,600	142	–10515	–24082
CO	26400	28	–3948	–9211.4
CO_2	94050	44	–8950	–32816
H_2O	32600	18	–11437	–
MgO	143,700	40.3	–14930	–24760
CaS	110,000	72	2551	4591.55
B_2O_3	306,100	70	–18309	–58256
CaF_2	292,000	78	–15674	–30565
$CaCO_3$	288,400	100	1789.94	1299.58

Then the values of $E_{x\text{-}R1}$ and the other parameters can be found as follows:

$$E_{x\text{-}R1} = (0.9731 m_{iA} + \ldots + 0.0015 m_{ELD(LF)})\cdot 169.5,$$
$$E_{x\text{-}R2} = (0.005 m_{iA} + \ldots + 0.01 m_{AL})\cdot 4560,$$
$$E_{x\text{-}R3} = (0.017 m_{CYA} + \ldots + 0.0005 m_{ELD(LF)})\cdot 5317,$$
$$\ldots$$
$$E_{x\text{-}R12} = -(0.35 m_{CYA} + 0.06 m_{FLS})\cdot 2.5\cdot 1300,$$
$$E_{x\text{-}R13} = -(0.00035 m_{iA} + \ldots + 0.005 m_{KAR})\cdot 5436.$$

The exergy of the chemical reactions which have taken place in the system is calculated by means of the equation

$$e_x = (h_c - T_0 s_c) - (h_g - T_0 s_g). \tag{2}$$

The exergy of certain typical chemical reactions in the system is shown below:

$$e_{x\text{-}Fe_2O_3} = (\bar{h}^0 - T_0 s^0)_{Fe_2O_3} - 2(\bar{h}^0 - T_0 s^0)_{Fe} - 3(\bar{h}^0 - T_0 s^0)_{O} = 8536 \text{ J/kg-}Fe_2O_3,$$
$$e_{x\text{-}MnO} = (\bar{h}^0 - T_0 s^0)_{MnO} - (\bar{h}^0 - T_0 s^0)_{Mn} - (\bar{h}^0 - T_0 s^0)_{O} = 6600 \text{ J/kg-MnO},$$

$$
\begin{aligned}
&e_{x\text{-Al}_2\text{O}_3} = (\bar{h}^0 - T_0 s^0)_{\text{Al}_2\text{O}_3} - 2(\bar{h}^0 - T_0 s^0)_{\text{Al}} - 3(\bar{h}^0 - T_0 s^0)_{\text{O}} = 29284 \text{ J/kg-Al}_2\text{O}_3,\\
&e_{x\text{-SiO}_2} = (\bar{h}^0 - T_0 s^0)_{\text{SiO}_2} - (\bar{h}^0 - T_0 s^0)_{\text{Si}} - 2(\bar{h}^0 - T_0 s^0)_{\text{O}} = 30596 \text{ J/kg-SiO}_2,\\
&e_{x\text{-ZnO}} = (\bar{h}^0 - T_0 s^0)_{\text{ZnO}} - (\bar{h}^0 - T_0 s^0)_{\text{Zn}} - (\bar{h}^0 - T_0 s^0)_{\text{O}} = 4868 \text{ J/kg-Zn},\\
&e_{x\text{-FeO}} = (\bar{h}^0 - T_0 s^0)_{\text{FeO}} - (\bar{h}^0 - T_0 s^0)_{\text{Fe}} - (\bar{h}^0 - T_0 s^0)_{\text{O}} = 4346 \text{ J/kg-FeO},\\
&e_{x\text{-P}_2\text{O}_5} = (\bar{h}^0 - T_0 s^0)_{\text{P}_2\text{O}_5} - 2(\bar{h}^0 - T_0 s^0)_{\text{P}} - 5(\bar{h}^0 - T_0 s^0)_{\text{O}} = 21740 \text{ J/kg-P}_2\text{O}_5,\\
&e_{x\text{-CO}} = (\bar{h}^0 - T_0 s^0)_{\text{CO}} - (\bar{h}^0 - T_0 s^0)_{\text{C}} - (\bar{h}^0 - T_0 s^0)_{\text{O}} = 11436 \text{ J/kg-CO},\\
&e_{x\text{-CO}_2} = (\bar{h}^0 - T_0 s^0)_{\text{CO}_2} - (\bar{h}^0 - T_0 s^0)_{\text{Ca}} - (\bar{h}^0 - T_0 s^0)_{\text{S}} = 32878 \text{ J/kg-S},\\
&e_{x\text{-CaO}} = (\bar{h}^0 - T_0 s^0)_{\text{CaO}} - (\bar{h}^0 - T_0 s^0)_{\text{Ca}} - (\bar{h}^0 - T_0 s^0)_{\text{O}} = 15089 \text{ J/kg-CaO},\\
&e_{x\text{-Cr}_2\text{O}_3} = (\bar{h}^0 - T_0 s^0)_{\text{Cr}_2\text{O}_3} - 2(\bar{h}^0 - T_0 s^0)_{\text{Cr}} - 3(\bar{h}^0 - T_0 s^0)_{\text{O}} = 10084 \text{ J/kg-Cr}_2\text{O}_3,\\
&e_{x\text{-CaCO}_3} = (\bar{h}^0 - T_0 s^0)_{\text{CaCO}_3} - (\bar{h}^0 - T_0 s^0)_{\text{CaO}} - (\bar{h}^0 - T_0 s^0)_{\text{CO}_2} = -1300 \text{ J/kg-CaCO}_3,\\
&e_{x\text{-CaS}} = (\bar{h}^0 - T_0 s^0)_{\text{CaS}} - (\bar{h}^0 - T_0 s^0)_{\text{Ca}} - (\bar{h}^0 - T_0 s^0)_{\text{S}} = -5231 \text{ J/kg-S}.
\end{aligned}
\tag{2a}
$$

The exergy-based objective function is calculated based on the expenditures for all the materials and the exergies of the chemical reactions represented by Eqs. (2*a*). Then, depending on the mass used in the system, the exergy-based objective function can be written by means of the following equation:

$$
\begin{aligned}
C_{ex} = {} & (0.1007718)m_{PW} + (0.101466)m_{HMS} + (0.104835)m_{SS} + (0.1046802)m_{DKP} + (0.093624)m_{PIG} + \\
& + (-0.237088)m_{COK} + (0.253121)m_{FLX} + (0.302449)m_{DEOX} + (-0.385005)m_{ELD(EAF)} + 0.24m_{NG} + 0.076m_{OXY} + \\
& + 0.0003m_{CW} + (0.372668)m_{FMN} + (0.727801)m_{MMN} + (0.279963)m_{SFMN} + (-0.17901)m_{FSI} + (0.911897)m_{FCR\text{-}HC} + \\
& + (0.93731)m_{FCR\text{-}LC} + (0.457507)m_{FMO} + (8.899619)m_{NI} + (0.557062)m_{AL} + (1.24504)m_{FBO} + (0.12108)m_{SULP} + \\
& + (-0.27819)m_{CAR} + (0.03)m_{LIM} + (0.095087)m_{FLS} + (0.16)m_{MGO} + (0.4)_{m\text{Al}_2\text{O}_3} + (-0.385005)m_{ELD(LF)} + \\
& + (0.057)E_{ELT}^{EAF} + (0.057)E_{ELT}^{LF} + 0.375m_{AR}.
\end{aligned}
\tag{3}
$$

Modeling by the method of linear programming. We used linear programming to solve Eq. (3). Linear programming is an optimization method that can be used when the objective function and the constraints can be expressed in the form of linear combinations of variables [11, 12]. The objective function F is the sum of the products of C_n (a constant) and X_n (the variables), as can be seen from the formula

$$F = C_1X_1 + C_2X_2 + \ldots + C_nX_n. \tag{4}$$

The next step is determining the constraints. The general formula for the constraints is:

$$A_{i1}X_1 + A_{i2}X_2 + \ldots + A_{in}X_n \le, =, \ge B_i, \quad i = 1, 2, \ldots, n, \tag{5}$$

where A_{in} and B_i are assigned constants and X_n represents the variables. The values of A can be positive, negative, or equal to zero, while the values of B are always positive in the study being discussed in this article.

To construct the cost function for the EAF and LF system (see Fig. 1), we take into account the costs of the energy and materials that will enter and exit the system. This function is represented by Eqs. (1, 2). Tables 1 and 2 present information on the expenditures made on the materials used in the EAF and LF. The data in Tables 3–5 is used for chemical analysis of the materials and the reaction products and for values of chemical energy, respectively [5].

Constraints function for the production of certain types of steel. To solve the optimization problem, we use a computer program to determine the maximum and minimum volumes. The optimization problem includes 33 variables. Table 6

TABLE 6. Maximum and Minimum Volumes of the Materials Entering the EAF + LF System to Make Different Types of Steels (the variables were determined for solving an optimization problem)

Types of steel			Steel 25CrMo4–1.7218		Steel 38Cr2–1.7003	
Variables	Symbol	Material entering the system	Min.	Max.	Min.	Max.
X1	PW	Production wastes, kg	0	60000	0	60000
X2	HM	Heavy melting scrap, kg	0	60000	0	60000
X3	SS	Scrap from the shredder, kg	0	60000	0	60000
X4	DK	DKP scrap, kg	0	60000	0	60000
X5	PI	Conversion pig iron, kg	0	60000	0	60000
X6	CO	Coke, kg	900	1000	900	1000
X7	FL	Fluxes, kg	0	1	0	1
X8	DE	Materials for reduction, kg	0	1	0	1
X9	ELTe	Electrodes (EAF), kg	140	150	140	150
X10	NG	Natural gas, kg	121	131	121	131
X11	OX	Oxygen, kg	4000	4187	4000	4187
X12	CW	Coolant water, kg	590,000	600,000	590,000	600,000
X13	FM	Ferromanganese, kg	0	M	0	M
X14	MM	Metallic manganese, kg	0	M	0	M
X15	SF	Ferrosilicate, kg	0	M	0	M
X16	FS	Ferrosilicon, kg	110	120	110	120
X17	FCH	High-carbon ferrochromium, kg	0	M	0	M
X18	FCL	Low-carbon ferrochromium, kg	160	M	0	M
X19	FM	Ferromolybdenum, kg	0	1	0	1
X20	Ni	Nickel, kg	0	1	0	1
X21	Al	Aluminum, kg	95	100	95	100
X22	FB	Ferroboron, kg	9	10	9	10
X23	SU	Sulfur, kg	0	1	0	1
X24	CA	Carbon, kg	140	150	140	150
X25	LI	Lime, kg	1750	1850	1750	1850
X26	FL	Fluorite, kg	28	30	28	30
X27	MO	Magnesium oxide, kg	95	100	95	100
X28	Al2	Al_2O_3, kg	95	100	95	100
X29	ELTl	Electrodes (LF), kg	28	30	28	30
X30	ELC_EAF	Electric power (EAF), kWh	22000	22500	22000	22500
X31	ELC_LF	Electric power (LF), kWh	7250	7500	7250	7500
X32	Ar	Argon, kg	6500	6600	6500	6600
X33	LS	Liquid steel, kg	50000	60000	50000	60000

shows data on the maximum and minimum volumes of the materials. The objective functions and the constraints on the types of steels that are made were examined in detail by the author in [10].

Results. The physical and chemical properties of the scrap and the auxiliary materials affect the chemical properties of the liquid steel and the energy and time needed to make it, either in an electric-arc furnace or a ladle furnace.

The optimum values for the materials entering the system and the electric power needed for the EAF and LF were calculated by means of the optimization program WINQSB. Shown below are the optimum values obtained for two types of steel which the company has designated as 25CrMo4–1.7218 and 38Cr2–1.7003:

Raw materials entering the system	Steel 25CrMo4–1.7218	Steel 38Cr2–1.7003
Production wastes, kg	55000	909.74
Heavy melting scrap, kg	0	20664.75
Scrap from the shredder, kg	0	0
DKP scrap, kg	0	0
Conversion pig iron, kg	0	33425.51
Coke, kg	1000	1000
Fluxes, kg	0	0
Materials for reduction, kg	0	0
Electrodes (EAF), kg	150	150
Natural gas, kg	121	121
Oxygen, kg	4000	4000
Coolant water, kg	590,000	590,000
Ferromanganese, kg	0	0
Metallic manganese, kg	0	0
Ferrosilicomanganese, kg	412.35	131.09
Ferrosilicon, kg	120	120
Ferrochromium, kg:		
with a high carbon content	99.31	0
with a low carbon content	160	0
Ferromolybdenum, kg	0	0
Nickel, kg	0	0
Aluminum, kg	95	95
Ferroboron, kg	9	9
Sulfur, kg	0	0
Carbon, kg	150	150
Lime, kg	1750	1750
Fluorite, kg	28	28
MgO, kg	95	95
Al_2O_3, kg	95	95
Electrodes (LF), kg	30	30
Electric power (EAF), kWh	22000	22000
Electric power (LF), kWh	7250	7250
Argon, kg	6500	6500
Liquid steel, kg	52460.53	51618.09

Conclusions. Being one of the most important sectors of industry in many nations, metallurgy is a highly energy-intensive enterprise. Thus, the primary goal should be to make use of new technologies that will save energy. Using such technologies will require changes to the process parameters of the system discussed here.

The demand for and use of alloy steel is rising in the developed and developing countries, which is raising the cost of energy and the raw materials and auxiliary materials used to operate electric-arc furnaces. All these factors will ultimately have the effect of shortening the production cycle and increasing productivity, thanks to optimization of the processes and methods that are used to make alloy steel.

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