Nonlinear Optimization of Hot Metal Profit in Blast Furnace Based on a Decrease in Coke Consumption Rate
Case Study: Esfahan Steel Company

Mehdi Nasr-Azadani[1], Sayyed Mohammad reza Davoodi [2,*], Shahram Moeeni [3]

[1] *PhD student in Industrial management, Department of management, Islamic Azad University, Isfahan Branch, Isfahan, Iran.*
[2] *Assistant Professor, Department of management, Islamic Azad University, Dehaghan Branch, Dehaghan, Iran.*
[3] *Assistant Professor, Department of Economics, University of Isfahan, Isfahan, Iran.*

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ABSTRACT

Due to the low quality of domestic coking coal, and increased restrictions on international trade of importing coking coal, Iranian steel industry has been encountered serious challenges of supplying coke as the major source of blast furnaces energy while, the vast sources of domestic natural gas and pulverized coal have made it possible to replace coke with these sources of energy in the blast furnaces. High differences in the price of coke with natural gas and pulverized coal, the influence of replacing complexity on the cost of ferrous raw materials, coke, and energy consumption, blast furnace productivity, technical constraints, and carbon dioxide emissions level are the main reasons for conducting this research. In this study, a nonlinear optimization model is developed to determine the profit yield of hot metal in the blast furnace. Compared to the available studies, optimal decision making on the supply and replacement of raw materials and energy, together with new constraints, are analyzed. This proposed model was implemented in MATLAB and validated through the data obtained from Esfahan Steel Company. The results indicate that this model can decrease coke consumption by 26% and is highly effective company benefits.

1-Introduction

Great volumes of energy are consumed in the steel industry, thus, high volumes of CO2 emissions. This phenomenon is on a high growth that is from 200 million tons in 1950 to 1808 million tons in 2018. This upward growth has led to an increase in demand for raw materials and the release of about 7% of global greenhouse gases therein [1, 2]. Blast furnace (BF) is the most essential section of a steel company. Costs of production in steel companies, including the ferrous raw materials, energy, labor, and maintenance are contributive to the competitiveness of such plants. The ferrous burden materials of the blast furnaces are provided from different blends of sinter, pellet, and lump from mines with different iron contents and metallurgical coke as the primary source of energy supply and reduction gases [3]. The coke consumption rate and the cost of energy in a BF depend on the type and blending of ferrous burden materials of the BF.

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* Corresponding author:
E-mail address: smrdavoodi@ut.ac.ir

It is possible to replace some portion of coke with other carbon-bearing fuels like oil, natural gas, and pulverized coal to reduce energy cost in BF.The consumption rate of materials such as dolomite, lime, and fluxes is influenced by ferrous burden material charges. In some plants, the blend of raw materials in blast furnace is calculated empirically by technical experts in processes of coke making plant, sinter plant, and BF with respect to price analysis and the volume of possible supply in the market; being time-consuming process and it is based on the trial and error method [4].

In Esfahan Steel company (ESCO) as the subject steel plant, about 70% of coking coal is supplied from domestic mines, while 30% is imported. A decrease in local lump ore sources, an increase in price of foreign coking coal together with a reduction of domestic coking coal quality, environmental strict regulations on decreasing greenhouse gas emissions, competitiveness in business, and the affluent sources of natural gas, oil, and domestic pulverized coal have forced the steel industry to develop sources of supplying ferrous burden materials, and replace consuming coke with natural gas, oil, and pulverized coke. Considering vast varieties of mines and suppliers, ferrous burden materials, coke, pulverized coal, oil, natural gas and the current confinements as to having access to each one of these resources, environmental limitations, steel producers encounter different options in supplying ferrous burden materials, coke, and other carbon-bearing fuels; accordingly, the question: While complying with constraints, which set of options can lead to the most profit and production competitiveness.

In the available studies, there exists no complete study on determining the optimal blending of ferrous burden materials and optimal replacement of coke with other hydrocarbon fuels in BF [4]. The conducted studies have generally been focused on two main issues: reducing energy consumption and protecting the environment through decreasing CO_2 emission.

Considering the particular economic conditions in Iran, and according to the detailed review, there exists no study on modeling, the choosing type, and optimal blending of ferrous burden materials, coke, and other hydrocarbon fuels in the blast furnace to maximize the profit of hot metal production.

Some of the most recent and essential studies are mentioned briefly.

The blast furnace performance is modeled by applying mass and energy conservation equations. Based on this modeling, the blast furnace is considered as a control volume with specific inputs and outputs and blast furnace conditions in sustainable and time-independent [5]. He et al. adopted the law of conservation of mass, the first law of thermodynamics for energy, and material flow analysis consisting of three layers: raw materials, iron, and energy. Considering the volume of energy, carbon, and iron needed to produce one ton of crude steel, comparing their model outputs with practical measurements indicated model accuracy. According to the results, it is found that the volume of energy consumption and carbon emission to produce one ton of crude steel in China is higher than the global indicators [6]. Rasul et al. provided a model based on energy and mass balance equations and applied an empirical equation to estimate the blast furnace loss. Based on the model outputs, an increase in blast air temperature, a decrease in coke ash, and decrease volume of silicon of hot metal can reduce coke consumption and increase the blast furnace productivity. The model outputs are compared with the practical results of a blast furnace in India, and their accuracy is examined [7]. Ertem et al. evaluated the energy balance of the blast furnace input and output based on a Japanese model, where the energy required for the reduction process is estimated from the total difference in input energy from the total output energy [3]. Larson et al. assessed the effect of an optimized model of energy consumption on a steel-producing complex, where first, each coke-making unit, blast furnace, converter caster, and power plant is modeled and next, by applying a linear programming model, the objective function for minimizing the energy is defined, and then the energy intensity for eight different blending modes of charging materials in the blast furnace and converter are assessed and simulated. The optimization effect of energy consumption on decreasing carbon dioxide emission is assessed as well [8]. Kuramochi sought to find a way to reduce carbon dioxide emission in Japan steel industry by considering: process capabilities, business limitations, and flexibility in changing the production quantity, adopting different policies regarding Japan’s total production capacity and presented a quantitative model to evaluate and predict the process of carbon dioxide emission by 2030. He concluded that, in addition to decreasing carbon dioxide emission, scrap consumption could also lead to an increase in production cost [9]. In another study, Xu et al. examined carbon dioxide emission in the iron and steel industry of China. They provided an innovative calculation method and estimated that carbon dioxide production in China's steel industry is 1336 million tons per year and assessed the operations effective in decreasing carbon dioxide emission could affect the production cost [10]. Liu et al., analyzed optimization of energy flow by considering the blast furnace yield as the objective function and applied process relations and thermodynamic equations to analyze the effect of blast air enrichment, lower sinter consumption, increased pulverized coal on the blast furnace yield, indicating that an increase in the blast furnace yield is effective in decreasing production cost [11]. Moya et al. adopted a non-linear model and studied the corrective actions and claimed by applying the best available techniques can reduce energy consumption, and carbon dioxide emission in the EU steel industry are reduced; they also estimated the volume of investment to do these improvements and their effect [12]. Helle et al. applied the objective function to minimize the production cost of one-ton crude steel under process and raw material limitation, after removing carbon dioxide are fand the feasibility of recycling of the blast furnace top gas was economically established through applying a non-linear model and computer simulation. Their results reveal that removing carbon dioxide from the blast furnace top gas does not require oil charging anymore, consequently decrease the emission of greenhouse gases [13]. Zhang et al. considered the production cost as the objective function, which through a non-linear mathematical model is devised, to minimize the cost of blast furnace production. In the study, chemical analysis and the price of raw material and coke were considered as model inputs, while the volume of coal and coke consumption to produce one ton of hot metal is assumed to be fixed, and the optimized blending of ferrous burden materials are regarded as model outputs and compared to the empirical results extracted from a steel producer in China [4]. Wang et al. introduced an optimization method by cooperating with the Swedish steel producer SSAB for blast furnace processes and converter as an integrated system and proposed a bi-objective model to minimize the cost of steel production and the volume of carbon dioxide gas released from the charge of scrap in the blast furnace converter complex. It is concluded that with an increase in scrap in charge, the carbon dioxide rate decreases, while the cost of production increases. In their study, the constraint on the volume of scrap is 25% by considering the priority of converter, a portion of scrap charged to the converter, and some other portion charged in the blast furnace [12].

Among the reviewed studies, as to the effect of blending of ferrous burden materials of the blast furnace on production cost, the findings by Zhang et al. [4] are closer to the subject of this study, while there exist the following drawbacks:

- Their primary focus is on decreasing the cost of raw materials, while the main economic factor in the blast furnace production is profit. A decrease in the cost of raw materials does not necessarily mean an increased profit. In this context, little attention is paid to the role of variables: productivity, defined by daily production per unit volume of the BF and production costs like oxygen cost, blast air, electrical energy, the volume of slag, and the top gas.
- They did not consider the replacement of a portion of the coke as the primary source of producing energy and reduction gas with fuels such as pulverized coal, oil, and natural gas.
- The coke consumption rate in a BF is assumed to be unchanged, while in practice, coke is a function of the blending of ferrous burden materials and other production variables, and consequently, this assumption is a great unrealistic approximation applied there.
- The possibility of applying scrap and direct reduction iron (DRI) as environmental friendly ferrous raw materials, which contributed to a decrease in energy consumption, is not addressed.

The novelty of this study is to overcome the above-mentioned drawbacks through a newly developed research model, where the objective function is changed from the cost of raw materials to production profit. Meanwhile, together with the energy and mass balance in the blast furnace, the hot metal chemical composition, the ferrous burden materials, the volume of flux, consumed coke, oxygen, the needed blast air, temperature, chemical composition of the top gas and the volume of the produced slag composition are examined.

- For the first time in this study, the simultaneous consumption of carbon-bearing materials like pulverized coal, natural gas and coke are modeled, and the effect of consuming pulverized coal on decreasing coke consumption, reducing carbon dioxide gas and increasing production profit is estimated through this newly developed model and compared with empirical conditions.
- Unlike their study, here the range of chemical composition of produced hot metal and parameters like, the temperature of the blast furnace raceway zone and the temperature of the top gas as constraints, which indicated that the amount of enrichment of blast air with oxygen is also measurable, are of major concern.

2. Modeling

A non-linear optimization model, extracted from thermodynamic equations, process relations, and mass and energy balances, is applied in this study. This model can be applied as a decision support system for purchasing and supplying coke-energy, ferrous burden materials, and examining the effect of consuming different raw materials on the carbon dioxide emission and evaluating the production profit. The subject blast furnace containing inputs like lump, sinter, pellet, scrap, DRI, manganese ore, coke, pulverized coal, lime, fluxes, blast air, and oxygen and the outputs including hot metal, slag, and top gas is schemed in Fig.1. Hot metal is the main product of blast furnace, containing about 94% iron and 4 to 5 % carbon. This material is the main feed of BOF for crude steel production. Slag and the BF top gas make the byproducts. Top gas has a heat value of about one-tenth of natural gas, which is applied to generate electricity in power plants. Slag is sold to cement factories and can be consumed as raw material for the production of acoustic and thermal insulation.

Typical chemical composition of hot metal in ESCO Blast furnace number 3 are: total Fe= 93.87%, Si =0.51%, P=0.196%, S=0.056%, Ti=0.1%, and

Typical chemical composition of slag in ESCO Blast furnace Number 3 are: SIO2= 35.65%, CaO=35.02%, Al2O3= 10.86%, MgO=8.05%, MnO=1.19%, FeO=0.48%, S=1.32%, TiO2=1.65%, V2O5=0.06%

Typical chemical composition of top gas in ESCO Blast furnace Number 3 are: CO=16.4%, CO2= 25.8%, H2=5.3%, N2=52.1%

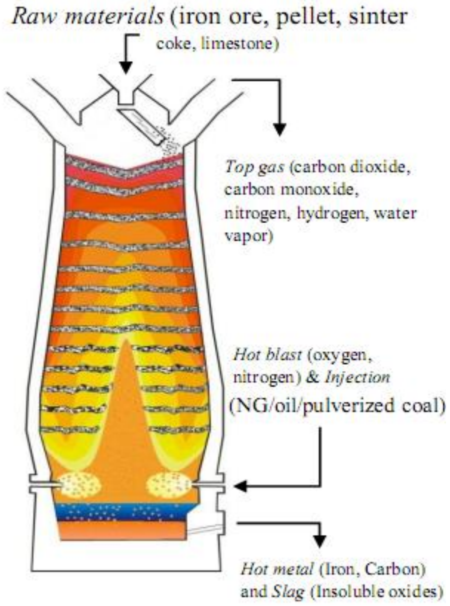

Fig.1. Inputs and outputs of a blast furnace [15]

2.1. Subscripts and Symbols

The applied subscripts and symbols of this model are defined as follows:

i: is the raw materials in the blast furnace.

j: is the chemical composition of raw materials. and carbon-bearing materials in the blast furnace.

k: is the element in a composition of raw materials and carbon-bearing materials in the blast furnace.

Table 1. Subscripts and Symbols

Subscript	i	j		k	Subscript	i	j	k
1	Sinter	Fe		Fe	12	Other 3	MgO	Mg
2	Pellet	SiO_2		Si	13	Other 4	Al_2O_3	Al
3	Lump	Cao		Ca	14	Other 5	K_2O	K
4	DRI	P		P	15	Oyher 6	Na_2O	Na
5	Scrap	As		As	16	Oxygen	$Fe_{0.947}O$	
6	Manganese ore	Cu		Cu	17	Natural Gas	C	
7	Lime-stone	Pb		Pb	18	Pulverized coal	H_2O	
8	Dolomite	Zn		Zn	19	Oil	ash	
9	Quartzite	S		S	20	Coke	H_2	
10	Other 1	Ti		Ti	21		N_2	
11	Other 2	Mn		Mn	22		O	

2.2. Parameters and main equations:

a_{ij} : is the weight percent of element j in the raw material i

$W_{j,total}$: is the weight of the material or element j in kg in burden, coal, coke, and … per ton of hot metal

$W_{k,total}$: is the weight of element k in kg in total burden, coal, coke, and other fuels per ton of hot metal

$X_{\text{i wet}}$: is the weight percent of wet raw material in the total ferrous burden

d_{hearth}: is the hearth diameters of the blast furnace in meter

n_{tuyere}: is the number of tuyers of blast furnace

V_{bf} : is the sufficient volume of the blast furnace in a cubic meter

C_{fix}: is the annual fixed costs of the blast furnace in Rials

$Pr_{i\,(i=1,2,3,\ldots..15)}$: is the price per kilogram for the raw material in Rials

Pr_{O2}: is the price of each normal cubic meter of oxygen in Rials

Pr_{NG}: is each normal cubic meter of natural gas in Rials

Pr_k: is the price of each kilogram of dry coke in Rials

Pr_{oil}: The price of each kilogram of oil in Rials

Pr_{PC} : is the price of each kilogram of pulverized coal in Rials

Pr_{slag} : is the price of each kilogram of slag in Rials

Pr_{hm} : is the price of each kilogram of hot metal in Rials

r_{si} : is the amount of Silicon in kilograms per one ton of hot metal

T_{wrz}: is the wustite reduction zone temperature in Kelvin

T_{tg} : is the temperature of blast furnace top gas in Kelvin

T_{blast}: is the blast air temperature in Kelvin

HV_{tg} : is the thermal value of one normal cubic meter of the blast furnace top gas in Kilojoules

LHV_{NG} : is the lower limit of the thermal value of each normal cubic meter of natural gas in Kilojoules

Ash_K : is the percent of ash in coke

Ash_C : is the percent of ash in coal

X_{KAj} : is the weight percent of element j in coke

X_{CAj} : is the weight percent of element j in pulverized coal

CRS: is the coke strength after reaction

H_{tx} : is the enthalpy of element x in temperature T in Kilojoules

H_{tx}^{f} : is the enthalpy of formation of material x from its elements in temperature T in Kilojoules

η: is the BF productivity, in a ton of hot metal per cubic meter of the blast furnace volume per day

ϕ: is the amount of pure iron per one ton of hot metal is 945 kilograms

λ: is the recovery rate coefficient of molten iron is 0.963

θ_j: is the refining residual coefficient

2.3. Variables

X_i $(i=1,2,\dots 15)$: is the dry weight percent of raw material i on the total weight of the ferrous burden

r_{O2}: is the oxygen rate of blast air, in normal cubic meters per ton of hot metal

r_{ba} : is the blast rate, in normal cubic meters per ton of hot metal

$r_{V\,NG}$: is the consumption rate of natural gas, in normal cubic meters per ton of hot metal

r_C : is the consumption rate of pulverized coal in kilogram per ton of hot metal

r_{oil} : is the consumption rate of oil in kilogram per ton of hot metal

r_k : is the consumption rate of dry coke in kilogram per ton of hot metal

Table 2. Main equations of the model [7, 16]

Symbol	**Equation**	**Description**
W_{burden}	$X_i = X_{wet} \times \frac{1 - a_{i18}}{100}$, $W_{burden} = \frac{10000 \times \phi}{\lambda \times \sum_{i=1}^{15} a_{i1} \times x_i}$	BF burden Calculation
W_{mi}	$W_{mi} = \frac{W_{burden} \times X_i}{100}$	Weight of material i in bf burden
W_j	$W_j = \frac{\phi \times \sum_{i=1}^{i=15} X_i \times a_{ij}}{\lambda \times \sum_{i=1}^{i=15} X_i \times a_{ij}}$	Weight of element j in bf burden
$HM_{Com\ j}$	$W_{j\ total} = W_j + \frac{W_{coke} dry \times Ash_K \times X_{KAj}}{10000} + \frac{W_{PC} \times Ash_C \times X_{CAj}}{10000}$ $HM_{Com\ j} = \frac{W_{j\ total} \times \theta_j}{10}$	Weight of element j in hot metal
$Fe_{m-burden}$	$Fe_{m-burden} = \frac{X_4 \times [a_{41} - a_{4\ 16} \times 52.88 / 68.88]}{100} + \frac{X_5 \times [a_{51} - a_{5\ 16} \times 52.88 / 68.88]}{100}$	Weight of metallic Fe in BF burden
$Fe_{t-burden}$	$Fe_{t-burden} = \frac{\sum_{i=1}^{i=15} X_i \times a_{i1}}{\sum_{i=1}^{i=15} X_i}$	Total Fe percentage in bf burden
W_{slag}	$W_{slag} = \Sigma(W_j) \times (1 - \Theta j)$, j =2,3,10,11,12,13	Weight of slag
Basicity	Basicity = $\frac{10000 \times \phi \times \sum_{i=1}^{15} X_i \times a_{i3} + \lambda \times \sum_{i=1}^{15} X_i \times a_{i1} \times U}{10000 \times \phi \times \sum_{i=1}^{15} X_i \times a_{i2} + \lambda \times \sum_{i=1}^{15} X_i \times a_{i1} \times V}$ U $= W_{Coke-dry} \times Ash_K \times X_{kA3} + W_{pc} \times Ash_C \times X_{CA3}$ V $= W_{Coke-dry} \times Ash_K \times X_{kA2} + W_{pc} \times Ash_C \times X_{CA2} - 214000 \times HM_{Comp.2}$	The slag alkalinity.
H_{Si}	$H_{Si} = (-H^f_{1200\,SiO_2}) + (H_{1723\,Si_l} - H_{1200\,Si_s}) + H^M_{Si}$	Enthalpy of SiO_2 reduction, Heating, fusion and solving

H_{Fe}	$H_{Fe}=(-H^{f}_{1200FeO})+(H_{1723Fe_l}-H_{1200Fe_S})$	Enthalpy of Wustite reduction, Heating, fusion and solving
H_{Mn}	$H_{Mn}=(-H^{f}_{1200MnO})+(H_{1723Mn\,l}-H_{1200Mn\,s})+H^{M}_{Mn}$	Enthalpy of Mno reduction, Heating, fusion and solving
H_C	$H_C=(H_{1723C}-H_{1200C})+H^{M}_{C}$	Enthalpy of carbon in iron.
H^{Slag}	$H^{Slag}=n_i^{Slag}\left\{(H_i^{fus})+\left(H_{1823}-H_{1300}\right)_i\right\}$	Slag enthalpy
h_{loss}	$h_{loss}=\dfrac{5.4\times10^3\times Hearth\,dia.+0.85\times10^3\times No\,of\,Tuyers}{\dfrac{Pig\,iron\,production\,per\,hour}{55.85}\times\dfrac{Pig\,iron\,Fe\%}{100}}$	BF heat loss
$\mathrm{H_i}$	$H_I=-H^{f}_{298,\mathrm{injectant}}+x\left[H^0_{1200}-H^0_{298}\right]_C+y\left[H^0_{1200}-H^0_{298}\right]_{H_2}$ $+\dfrac{z}{2}\left[H^0_{1200}-H^0_{298}\right]_{O_2}$	Heat demand for injectant $C_x(H_2)_yO_z$
n_O^B	$n_O^B=1.28n_C^A+0.42n_{H_2}^I-\left\{1.06+2(Si/Fe)^m+(Mn/Fe)^m\right\},$	Requiured oxygen in blast air
n_C^A	$n_C^A=\dfrac{H_D^{wrz}+H_{Blast}\left\{1.06+2(Si/Fe)^m+(Mn/Fe)^m\right\}-0.42n_{H_2}^I(249.473+H_{Blast})}{192.658+1.28H_{Blast}}$	Active carbon moles
n_{CO}^{tg}	$n_{CO}^{tg}=n_C^A.X_{CO}^{tg}$	CO moles in bf top gas
$n_{CO_2}^{tg}$	$n_{CO_2}^{g}=n_C^A.X_{CO_2}^{g}$	CO_2 moles in bf top gas
$n_{H_2}^{g}$	$n_{H_2}^{tg}=n_{H_2}^I.X_{H_2}^{tg}$	H_2 moles in bf top gas
$n_{H_2O}^{tg}$	$n_{H_2O}^{tg}=n_{H_2}^I.X_{H_2O}^{tg}$	H_2O moles in bf top gas

2.3. The objective function

The annual hot metal production profit is optimized through changing the blending of burden materials and replacing of coke with other sources of energy. The mathematical expression is presented through Eq. : 1, and it is written as follows:

$$Z= Max\ [350\times\eta\times V_{bf}\ \times\Big(Pr_{hm}+Pr_{slag}\times W_{slag}+Pr_{NG}\times r_{tg}\times\frac{HV_{tg}}{LHV_{NG}}-\frac{100\times\phi\times\sum_{i=1}^{i=15}X_i\times Pr_i}{\lambda\times\sum_{i=1}^{i=15}a_{i\,1}\times X_i}-Pr_k\times r_{\mathrm{k}}-Pr_{O2}\times r_{O2}-Pr_{ba}\times r_{ba}-Pr_{NG}\times r_{V\,NG}-Pr_C\times r_c-Pr_{oil}\times r_{oil}\Big)-C_{fix} \qquad (1)$$

The annual production in the blast furnace is assumed as 350 working days, η is the blast furnace productivity and defines the daily production volume per unit of the blast furnace, which depends on all variables and is described through the function *f1* below:

$$\eta = f_1(x_1,x_2,,x_3,x_4,x_5,x_6,x_7,,x_8,x_9,x_{10},x_{11},x_{12},x_{13},x_{14},x_{15},x_{16},x_{17},x_{18},x_1 \qquad (2)$$

The coke and blast rates considered as the blast furnace inputs are the functions of other inputs like the pulverized coal consumption, natural gas, oil, sinter, lump, DRI, scrap volumes, the blast air temperature, and oxygen described through *f2* and *f3*:

$r_k=f_2(x_1,x_2,,x_3,x_4,x_5,x_6,x_7,,x_8,x_9,x_{10},x_{11},x_{12},x_{13},x_{14},x_{15},x_{16},x_{17},x_{18},x_{19},r_{ba},r_{V\,NG},r_c,r_{oil})$ (3)

$r_{ba}=f_3(x_1,x_2,,x_3,x_4,x_5,x_6,x_7,,x_8,x_9,x_{10},x_{11},x_{12},x_{13},x_{14},x_{15},x_{16},x_{17},x_{18},x_{19},r_k,r_{V\,NG},r_c,r_{oil},)$ (4)

The blast furnace top gas and carbon dioxide emissions volume depend on the blending of the blast furnace burden and hydrocarbon fuels, described as *f4* and *f5*, respectively.

$r_{tg}=f_4(x_1,x_2,,x_3,x_4,x_5,x_6,x_7,,x_8,x_9,x_{10},x_{11},x_{12},x_{13},x_{14},x_{15},x_{16},x_{18},x_{19},r_k,r_{ba},r_{V\,NG},r_c,r_{oil},)$ (5)

$r_{CO_2-BF}=f_5(x_1,x_2,,x_3,x_4,x_5,x_6,x_7,,x_8,x_9,x_{10},x_{11},x_{12},x_{13},x_{14},x_{15},x_{16},x_{18},x_{19},r_k,r_{ba},r_{V\,NG},r_c,r_{oil},)$ (6)

The objective here is to provide a model for the calculation of the maximum profit of the BF production according to the process equations, the mass, and energy balance equations, and thermodynamic laws in the process of the blast furnace. Moreover, based on this model, the amount of coke consumption, the rate of carbon dioxide emission, and the blast furnace productivity can be calculated.

2.4. Constraints

The balance of input and output energy in the BF, balance between the input and output materials of the BF, the maximum allowable scrap and DRI in the burden, the maximum possible of monthly supply of raw materials in the market, blast furnace process, technical limitations, and the relations between variables constitute the relevant constraints, the symbols and equations of which are presented as below:

S_i : is the monthly possible supplying amount of raw material i

C_i : is the possible monthly consumption of raw material i

B_1: is the low limit of slag alkalinity

B_2: is the upper limit of slag alkalinity

L_{Ej}: is the low limit of element j in hot metal in kilogram per ton hot metal

U_{Ej} : is the upper limit of element j in hot metal in kilogram per ton hot metal

L_{Fi} : is the low limit of the percent of the ferrous burden material i in the ferrous burden materials

U_{Fi}: is the upper limit of the percent of the ferrous burden material i in the ferrous burden materials

T_{flame}: is the minimum raceway temperature in Kelvin

The balanced equation of iron mass in the blast furnace is: $W_{Fe}^{Out}=W_{Fe}^{In}$ (7)

The balanced equation of oxygen mass in the BF is: $n_o^{tg} = n_o^{Blast} + n_o^{Burden}$ (8)

The balanced equation of carbon mass in the BF is: $n_c^I + n_c^{coke} = (\frac{C}{Fe})^m + (n_{co}^{tg} + n_{co2}^{tg})$ (9)

The balanced equation of energy in the BF is:

$H_S = H_D$ (10)

The constraint on the scrap and DRI charging rate in the BF is: $X_4 + X_5 \leq 25\%$ (11)

Monthly item supplying should be greater than its monthly consumption of each item is: $C_i \leq S_i$ (12)

The amount of element i in charge of raw materials is obtained as follows:

$$\frac{\phi \sum_{i=1}^{15} x_i a_{ij}}{\lambda \sum_{i=1}^{15} x_i a_{i,1}} + \frac{r_k Ash_K a_{16j} + r_c Ash_C a_{17j}}{10000} \leqslant U_{Ej} \quad ,\text{where} \quad j = 2,3,12,13,14, \quad (13)$$

$$\frac{\phi \sum_{i=1}^{15} x_i a_{ij}}{\lambda \sum_{i=1}^{15} x_i a_{i,1}} + \frac{r_k Ash_K a_{16j} + r_c Ash_C a_{17j}}{10000} \geq L_{Ej} \quad ,\text{where} \quad j = 2,3,12,13,14, \quad (14)$$

The amount of element i in hot metal with respect to loss during the production process should be in an allowed range.

$$\frac{\phi \sum_{i=1}^{15} x_i a_{ij}}{\lambda \sum_{i=1}^{15} x_i a_{i,1}} + \frac{r_k Ash_K a_{16j} + r_c Ash_C a_{17j}}{100} \leqslant \frac{U_{Ej}}{\theta_j} \quad ,\text{where} \quad j = 4,5,\ldots,11, \quad (15)$$

$$\frac{\phi \sum_{i=1}^{15} x_i a_{ij}}{\lambda \sum_{i=1}^{15} x_i a_{i,1}} + \frac{r_k Ash_K a_{16j} + r_c Ash_C a_{17j}}{100} \geq \frac{L_{Ej}}{\theta_j} \quad ,\text{where} \quad j = 4,5,\ldots,11, \quad (16)$$

Considering the technical limitations, the slag alkalinity in the BF should be within 1 and 1.10 ranges.

$$\frac{10000\phi \sum_{i=1}^{15} a_{i,3} x_i + \lambda \sum_{i=1}^{15} x_i a_{i,1} (r_k Ash_K a_{16,3+} r_c Ash_C a_{17,3})}{10000\phi \sum_{i=1}^{15} a_{i,2} x_i + \lambda \sum_{i=1}^{15} x_i a_{i,1} . (r_k Ash_K a_{16,2+} r_c Ash_C a_{17,2} - 214000 . r_{si})} \leqslant 1.10 \quad (17)$$

$$\frac{10000\phi \sum_{i=1}^{15} a_{i,3} x_i + \lambda \sum_{i=1}^{15} x_i a_{i,1} (r_k Ash_K a_{16,3+} r_c Ash_C a_{17,3})}{10000\phi \sum_{i=1}^{15} a_{i,2} x_i + \lambda \sum_{i=1}^{15} x_i a_{i,1} . (r_k Ash_K a_{16,2+} r_c Ash_C a_{17,2} - 214000 . r_{si})} \geq 1 \quad (18)$$

The percentage share of each ferrous material in the burden of the blast furnace is within the following minimum and maximum boundaries:

$x_i \geq L_{Fi} \quad \forall i \in I,$ (19)

$x_i \leq U_{Fi} \quad \forall i \in I,$ (20)

$x_i \geq 0 \quad \forall i \in I,$ (21)

The total percentages of ferrous burden material charge in the blast furnace are 100.

$\sum_{i=1}^{5} x_i + \sum_{i=10}^{15} x_i = 100$ (22)

The volume of natural gas consumption in the blast furnace is between 0 to 110 normal cubic meters per ton of hot metal. : $0 \leq r_{VNG} \leq 110$ (23)

The raceway temperature should be higher than or equal to 2050-centigrade degrees.

$T_{flame} \geq 2323$ K (24)

The temperature of the blast furnace top gas should be greater than or equal to 110 centigrade degrees.

$T_{tg} \geq 383$ K (25)

Enrichment rate of the blast air with oxygen is between zero and a maximum 10 %

$0 \leq r_{O2} \leq 10\%$ (26)

Capacity restriction of pulverized coal injection rate in the blast furnace is between zero to 150 kilograms per ton of hot metal.: $0 \leq r_C \leq 150$ (27)

Oil injection rate in the blast furnace is between zero and a maximum of 90 kilograms per ton of hot metal: $0 \leq r_{oil} \leq 90$ (28)

2.5. The solution to the optimization problem

Considering the objective function and the constraints, this model is non-linear, implemented in MATLAB software as follows [17]:

Min f (x)

$$\text{s.t.} \quad \begin{aligned} & C(x) \leq 0 \\ & Ceq(x) = 0 \\ & Ax \leq b \\ & A_{eq}\, x = b_{eq} \\ & lb \leq X \leq ub \end{aligned}$$

where, X = [X_i] is the vector of the optimal variables, f(x) is the objective function, lb, ub are the column vectors of the upper and lower constraints of the vector of variable X, b and b_{eq} are the column vectors, c(x), and ceq(x) are the non-linear functions of the optimal variables, and A and Aeq are the matrixes. As the objectives of this study are to maximize the objective function; therefore, the objective function must be multiplied by -1 to change to a minimum to meet MATLAB standard form. The key to solving the optimization problem is to choose the appropriate solving function and optimization algorithm. The 'fmincon' function in the optimization toolbox of MATLAB is adopted because the 'fmincon' function is a very efficient solving function for the nonlinear programming problems. Moreover, as the sequential quadratic programming algorithm (SQP) has the advantage of global and superliner convergence, it is one of the most efficient nonlinear programming algorithms for nonlinear programming problems. Thus, the calculation program is compiled on MATLAB. The initial guess vector of answer X_o as the initial point is applied. Hence, the optimal response is obtained by performing repetitive sequences and evaluating the objective function and constraints. The general form of the fmincon function in MATLAB is expressed as: [Xopt, fopt] =fmincon ('fun', X_0, A, b, Aeq, beq, lb, ub,'nonlcon') where, X_0, A, b, Aeq, beq, lb, ub,'nonlcon' are the inputs of fmincon function and nonlcon is the non-linear constraints. The optimal answer and the minimum volume of the objective function are presented in Xopt and fopt, respectively. To make the task easy, the input data is first fed to Excel and to read by MATLAB, and next, the obtained model results return to Excel. The input data include: chemical composition of all BF raw materials, the price of each kilogram of raw material, the chemical composition and technical parameters of coke energy carriers, the main technical specification of BF, the maximum volume of supplying and purchasing raw materials and energy in the market, the fixed costs of the production including the costs of management, manpower, electricity, water, repairs etc., the technical composition of hot metal, the boundaries of the elements in the hot metal, the price of selling slag per kilogram, the price of each unit of oxygen and the cost of each produced unit of blast air, the limits of alkalinity, the temperature of the blast furnace top gas, and the flame temperature. This model is written in m-files in MATLAB program where fmincon function is applied to optimize the model, and the outputs include the optimal production profit, the percentage, and the volume of optimal blending raw materials and energy carriers and the volume of carbon dioxide. The solution procedure of this proposed program is flow charted in Fig. (2).

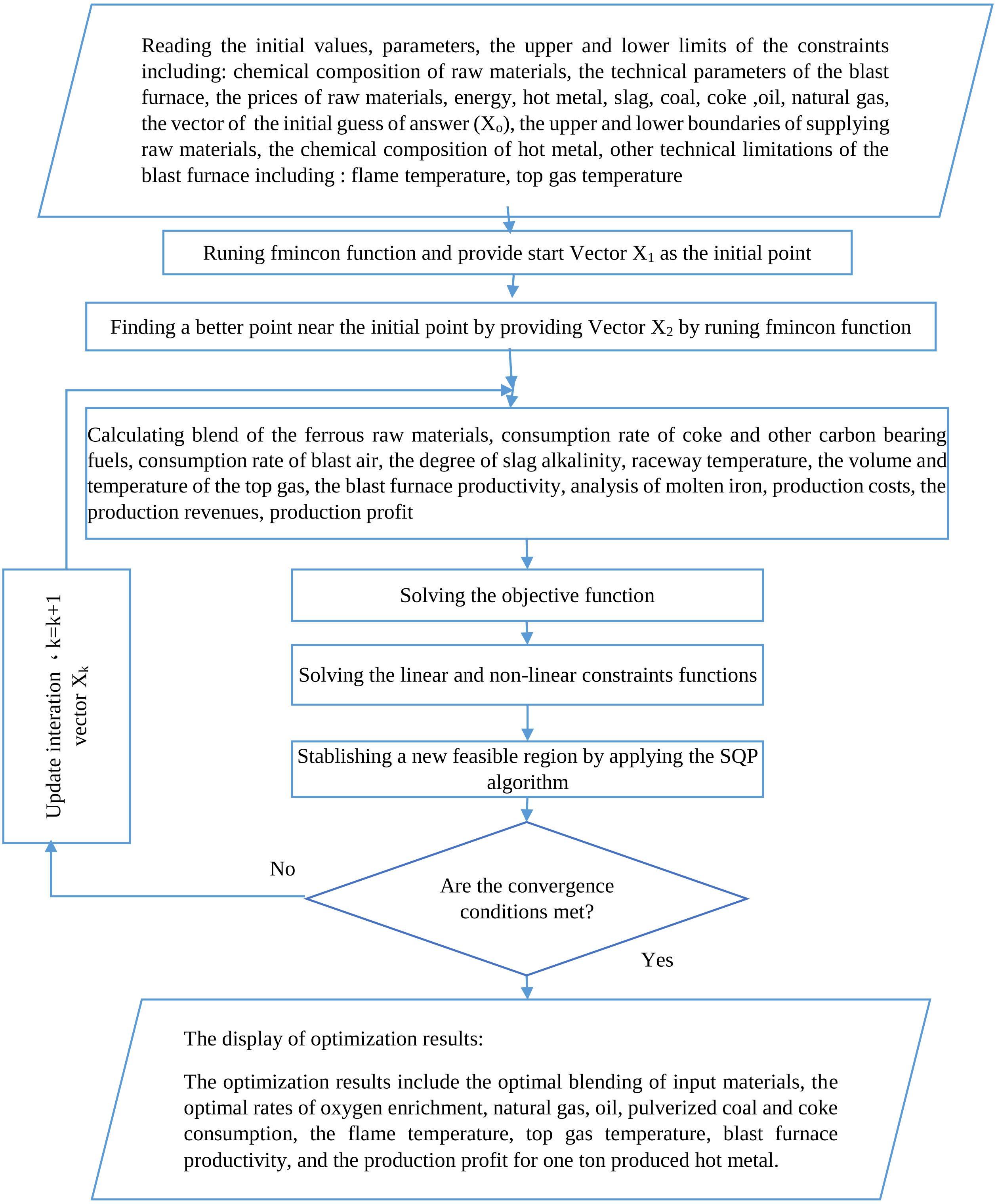

Fig. 2. Solution procedure of this proposed optimization model in MATLAB program

3. Results and discussion

Based on the above optimization model, the maximization of production profit as the objective function is executed for ESCO BF number 3. This proposed model can determine the optimal blending of ferrous burden materials and the optimal consumption rate of coke, pulverized coal, oil, and natural gas to maximize production profit together with saving in coke consumption. To calculate the optimal answer for the above-mentioned BF, first, the input data should be fed into the model including main technical specification of the BF, the chemical composition of burden raw materials, upper and lower limits of the constraints, prices of the ferrous burden materials, coke, and other hydrocarbon fuels. The possible monthly supply limit for the blast furnace are: 136.000 tons sinter, 37.600 tons pellet, and 55.200 tons lump and, the maximum pulverized coal injection rate is 150 kilograms per ton of hot metal. The maximum possible charge of natural gas is 110 normal cubic meters per ton of hot metal, and oil charge limitation is 90 kilograms per ton of hot metal production. The model for ESCO BF number 3 is run in MATLAB for the possible following three options:

Option1: When coke is the primary source of energy and reduction gas and no other carbon-bearing fuels, including natural gas, oil, and pulverized coal are consumed

Option 2: When it is possible to replace natural gas with a portion of coke

Option 3: When it is possible to replace natural gas, pulverized coal, and oil with a portion of coke

The results of implementing the optimization model for the above-mentioned options are presented in Table 3.

Table 3. Outcomes of the model for options 1, 2 and 3

Row	**Description**	**Option: 1**	**Option: 2**	**Option: 3**
1	Profit per ton HM (Rls.)	80	3540	5310
2	Total cost per ton HM (Rls.)	25430	22020	20220
3	Sinter Consumption per ton HM (Kg)	1275	1142	1177
4	Pellet Consumption per ton HM (Kg)	370	176	0
5	Lump Ore Consumption per ton HM (Kg)	0	323	477
6	DRI Consumption per ton HM (Kg)	0	0	0
7	Scrap Consumption per ton HM (Kg)	0	0	0
8	Mn Ore Consumption per ton HM (Kg)	0	0	0
9	Limeston Consumption per ton HM (Kg)	0	0	0
10	Dolomite Consumption per ton HM (Kg)	0	0	0
11	Quartzite Consumption per ton HM (Kg)	7	2	4
12	Oxygen enrichment per ton HM (Nm^3)	0	60.95	18.90
13	Natural gas Consumption per ton HM (Nm^3)	0	110	14
14	Pulverized coal Consumption per ton HM (Kg)	0	0	150
15	Oil Consumption per ton HM (Kg)	0	0	0
16	Coke Consumption per ton HM (Kg)	483	446	357
17	Ferrous burden per ton HM (Kg)	1646	1642.08	1654
18	Slag weight per ton HM (Kg)	361	340	351
19	Flame temperature (C^o)	2269	2050	2050
20	Top gas temperature (C^o)	284	312.86	348
21	Heat Value of top gas ($Kcal/Nm^3$)	624	881	759
22	The volume of bf top gas per ton HM (Nm^3)	1845	1702	1700
23	Blast air per ton HM (Nm^3)	1367	1167	1202
24	BF productivity (ton HM /day/m^3)	1.74	2.04	1.98
25	Iron-making total CO_2 Emission per ton HM (Kg)	2189	2019	1911

Note: 1 US $ exchange with 42.500 Iranian Rls. in 2018

By adopting option 3, the maximum profit is earned, and the volume of carbon dioxide emission is reduced. In this option, coke is replaced with natural gas and pulverized coal; therefore, the coke consumption decreases by 26% in comparison with option 1, which leads to the production profit of 5310 Rials per one kilogram of hot metal, which is greater than the profits of other options. Here it is observed that the carbon dioxide emission rate for each ton of hot metal production is less than the other two options too. As to option 2, only natural gas is injected as carbon-bearing fuel, where, compared to option 3, less production profit, lower reduction in coke consumption, and higher carbon dioxide emission is yield. A comparison run between options 2 and 3 indicates that under current Iranian hydrocarbon fuel prices, the injection of oil is not economically feasible, while the consuming pulverized coal together with coke is feasible.

3.1. Effects of pulverized coal injection

The sensitivity analysis of blast furnace number 3 of Esfahan Steel Company is run here. The result of the optimization model and the effect of increasing the pulverized coal injection rate on coke consumption is graphed in Fig. (3). Through the injection of pulverized coal in the blast furnace, a portion of carbon of coke is replaced with hydrogen, which is a reducing agent, entered into the blast furnace; thus, less carbon is provided by a coke for blast furnace reduction reactions.

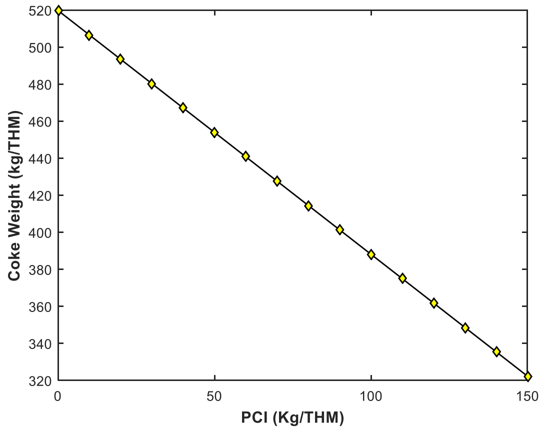

Fig. 3. Effect of increasing pulverized coal injection on coke consumption.

As observed, the coefficient of replacing coke with coal is 0.97, indicating 970 kilograms saving in coke consumption per/ton of coal charged in the blast furnace. Considering the coke price at 29.800 Rls. per / kg and 13.500 Rls. Per/kg of coal, the profit curve derived from this replacement is graphed in Fig. (4).

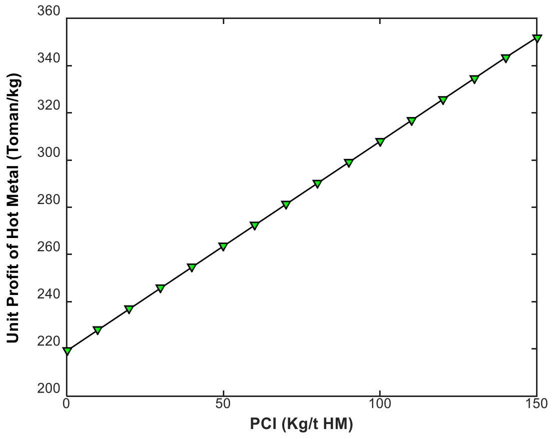

Fig. 4. Effect of increasing pulverized coal injection on the profit of hot metal.

The pulverized coal contains 0.05 hydrogen. During the reduction processes, hydrogen is replaced with CO, and CO reduction reactions are expressed as follows:

$FeO + CO = Fe + CO_2$ (29)

$CO + Fe_2O_3 = 2FeO + CO_2$ (30)

Considering the reactions, after the reduction of iron oxide with CO, carbon dioxide is produced, while the reduction of iron oxide with hydrogen-producing water:

$H_2 + Fe_2O_3 = 2FeO + H_2O$ (31)

$H_2O + FeO = H_2O + Fe$ (32)

Based on the constraint equation (27), to produce one ton of hot metal, the volume of injected pulverized coal in the blast furnace is between zero and 150 kilograms. As observed in Fig. (5), an increase in the replacement of pulverized coal with coke decreases the carbon dioxide emission.

The changes in the carbon dioxide emission rate in the Iron-making sector of the steel plant due to the replacement of pulverized coal with coke in the blast furnace are shown in Fig. (6).

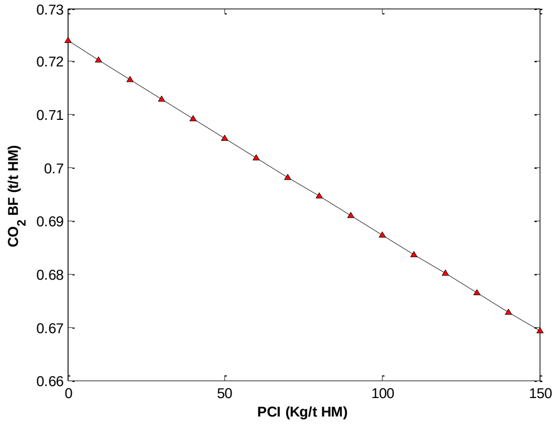

Fig. 5. Effect of increasing pulverized coal injection on the blast furnace CO_2 emission.

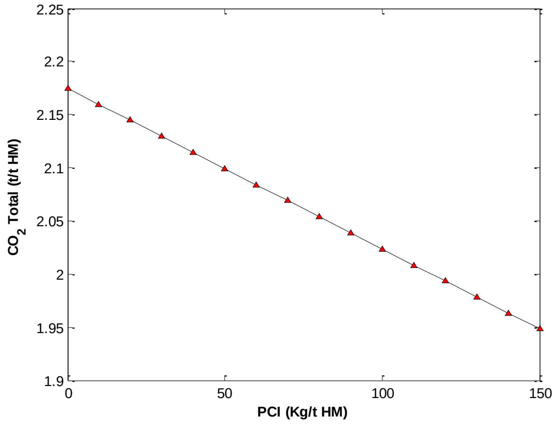

Fig. 6. Effect of increasing pulverized coal injection on Ironmaking CO_2 emission.

3.2. Effects of natural gas injection

The sensitivity analysis of blast furnace 3 of Esfahan Steel Company is analyzed. The effect of increased replacement of natural gas with coke in the blast furnace is graphed in Fig. (7), where, as expected, increased injection of natural gas in the blast furnace lowers coke consumption. Natural gas contains carbon and hydrogen, and both are reducing agents. The injection of natural gas in the blast furnace reduces coke consumption needed for reduction and thermal energy supply. Based on the results presented in figure 7, it can be concluded that the injection of each cubic meter of natural gas in the blast furnace saves up to 0.8 kg of coke.

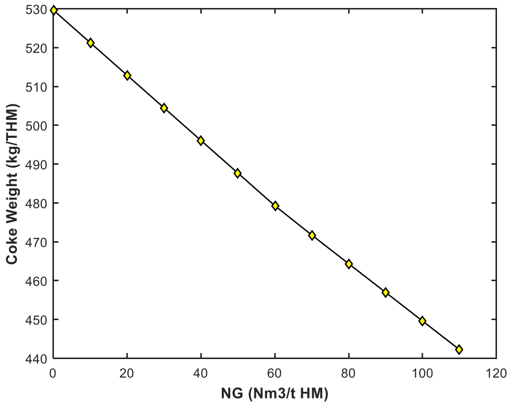

Fig. 7. Effect of increasing natural gas injection on coke consumption.

The effect of the replacement of natural gas by coke on profits obtained from the hot metal production in the blast furnace is graphed in Fig. (8). With respect to this analysis, because the unit price of coke in MATLAB software is 29.800 Rls./kg and each cubic meter of natural gas is 3.000 Rls., the profit from the natural gas injection in the blast furnace is expected.

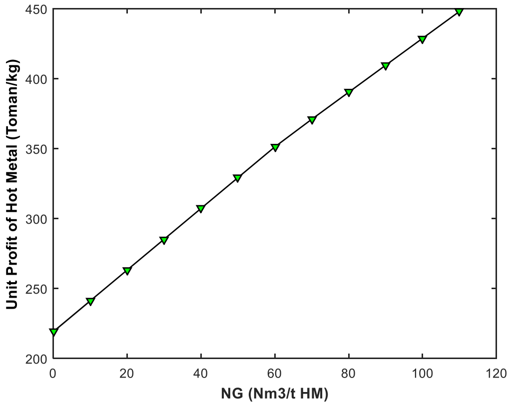

Fig. 8. Effect of increasing natural gas injection on the profit of hot metal.

The effect of increasing natural gas consumption on the carbon dioxide emission rate of the blast furnace is graphed in Fig. (9), where an increase in the volume of replacing natural gas with coke leads to a drop in carbon dioxide emission. Natural gas, similar to pulverized coal, is hydrocarbon fuel. After the injection of natural gas in the blast furnace, in addition to carbon, hydrogen as a reduction gas is entered into the blast furnace. The reduction reactions of iron oxides with CO are expressed as below:

$\mathrm{FeO + CO = Fe + CO2}$ (33) ;
$\mathrm{Fe2O3 + CO = 2FeO + CO2}$ (34)

The reducing reactions of iron oxides with hydrogen are expressed as below:

$Fe2O3 + H2 = 2FeO + H2O$ (35) ;

$FeO + H2 = H2O + Fe$ (36)

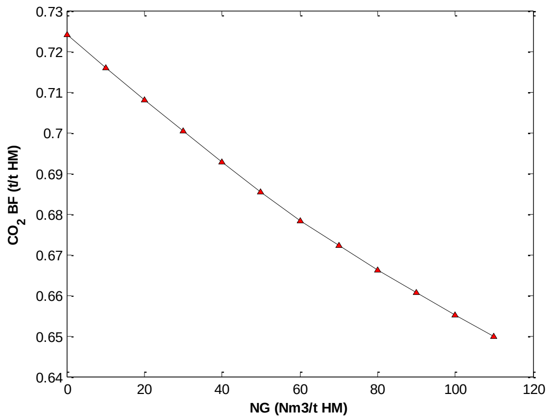

Fig. 9. Effect of increasing natural gas injection on the blast furnace CO_2 emission.

The total changes in carbon dioxide emission of the Iron-making plants due to the replacement of natural gas with coke are graphed in Fig. (10).. Replacing coke with natural gas can decrease the volume of CO_2 emission from blast furnace Fig. (9), and decrease the coke consumption, thus a decrease in CO_2 emission in coke making plant.

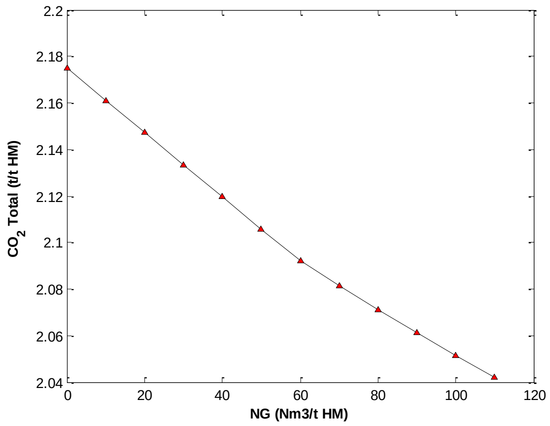

Fig. 10. Effect of increasing natural gas injection on iron making CO_2 emission.

4. Validation

This model is validated by applying actual production data from ESCO blast furnace number 3. Until the initiation date of this study in Esfahan Steel Company, it is equipped only with a natural gas injection unit; all practical comparison of the software model is run by consuming natural gas as the hydrocarbon fuel together with coke. By considering the existing working conditions of blast furnace number 3, sinter, lump ore, and about 34000 tons of pellets per month are considered as the ferrous burden materials. The comparison of model predictions and empirical results in Table 4 reveals the high accuracy of this model, indicating a good agreement between the results here and that of available data. The reason for the slight difference between this model's computational profit and the measures provided by financial and economic sectors of Esfahan Steel Company is due to the difference between the outputs here and the available experimental values of the consumption of coke, oxygen, natural gas, blast air, and ferrous burden materials. According to Table 4, this difference is greater for coke, oxygen, and blast air, while their expenditures highly contribute to the difference between model profit and actual profit.

The reasons for the differences between the outputs here and the practical results as to coke and blast air consumption are assessed in the following manners:

- The errors in coke weight measurement system and hot metal ladle weighing, the measurement of the chemical composition of raw materials and lime constitute the other erroneous effective factors of in estimating coke consumption in this model and its difference with practical conditions
- Errors in the analysis of natural gas injected in the blast furnace and the presence of hydrogen in natural gas can affect the volume of oxygen consumption, consequently affecting the temperature of the blast furnace. Because the analysis of natural gas composition is not regularly measured, its changes can lead to computational and measurement errors. In hot metal weight, blast air and oxygen can cause a difference in this model estimation and the actual results.
- The reducing gases pass through the free spaces among coke and ferrous burden materials . If the coke and ferrous burden materials are not distributed in a uniform manner, some gases exit from the blast furnace with no effective contact with the surface of ferrous burden materials. This phenomenon decreases productivity and makes coke consumption greater than the calculated values of the

quantitative model. Low top pressure in the blast furnace decreases the retention time of these gases in the blast furnace; therefore, reducing ferrous burden materials impossible; thus, the practical efficiency of the top CO gas is less than this model value, leading to an increase in coke consumption.

- Due to limitation in reducing of ferrous burden materials, a portion of hematite in the hematite reduction zone enter the wustite reduction zone, thus, making (O/Fe) in this zone slightly more than the estimation of this model compared to the actual situation leading to an increase in coke consumption and loss of oxygen balance in this zone
- The most important reason for the difference between the outcomes of this model and the measured, practical results for the blast air consumption is the difference obtained from the actual and calculated coke consumption in the blast furnace

Table 4. Comparison of model predictions and empirical results.

Row	**Description**	**Optimal value**	**Actual value**	**Deviation**
1	Profit per ton HM (Rls.)	3540	3363	5%
2	Total cost per ton HM (Rls.)	22020	23451	6.5 %
3	Sinter Consumption per ton HM (Kg)	1142.35	1124.87	1.5%
4	Pellet Consumption per ton HM (Kg)	176.2	179.52	2%
5	Lump Consumption per ton HM (Kg)	323.2	328.49	1.7%
6	DRI Consumption per ton HM (Kg)	0	0	0
7	Scrap Consumption per ton HM (Kg)	0	0	0
8	MnO_2 Consumption per ton HM (Kg)	0	0	0
9	Limestone Consumption per ton HM (Kg)	0	0	0
10	Dolomite Consumption per ton HM (Kg)	0	0	0
11	Quartzite Consumption per ton HM (Kg)	2.1	2.26	8%
12	Oxygen enrichment per ton HM (Nm^3)	60.95	67	10%
13	Natural gas Consumption per ton HM (Nm^3)	110	104.5	5%
14	Pulverized coal Consumption per ton HM (Kg)	0	0	0
15	Oil Consumption per ton HM (Kg)	0	0	0
16	Coke Consumption per ton HM (Kg)	446	487	9%
17	Ferrous burden per ton HM (Kg)	1642.08	1679.84	2.3%
18	Slag weight per ton HM (Kg)	340	345.44	1.6%
19	Flame temperature (C^o)	2050	1998.75	2.5%
20	Top gas temperature (C^o)	312.86	310	1.1%
21	Heat Value of top gas (Kcal/Nm^3)	881	885.4	0.5%
22	The volume of bf top gas per ton HM (Nm^3)	1702	1719.02	1%
23	Blast air Consumption per ton HM (Nm^3)	1167	1207.84	3.5%
24	BF productivity (ton HM /day/m^3)	2.04	2.02	0.5%
25	Iron-making total CO_2 Emission per ton HM (Kg)	2019	2049.28	1%

Note: 1 US $ exchange with 42.500 Iranian Rls. in 2018

Table 5. Energy and raw materials prices

Row	Material	Unit	Price	Row	Material	Unit	Price
1	Coke	Rls./Kg	29803	10	Sinter	Rls./Kg	4404
2	Pulverized Coal	Rls./Kg	13500	11	Pellet	Rls./Kg	8298
3	Oil	Rls./Kg	36330	12	Lump	Rls./Kg	3269
4	Oxygen	Rls./Nm^3	2424	13	Scrap	Rls./Kg	25000
5	Natural Gas	Rls./Nm^3	3000	14	DRI	Rls./Kg	15693
6	Blast air	Rls./Nm^3	225	15	Mn-Ore	Rls./Kg	5960
7	Hot metal	Rls./Kg	25300	16	Lime-Ston	Rls./Kg	447
8	Slag	Rls./Kg	172	17	Dolomite	Rls./Kg	214
9	Quartzite	Rls./Kg	645				

Note: 1 US $ exchange with 42.500 Iranian Rls. in 2018

5. Conclusions

In this study, Zhang et al. model is extended in the sense that an optimization model is developed for the process of a blast furnace, with the objective of increasing production profit. The optimization results are obtained by adopting a sequential quadratic programming method in MATLAB to supply and purchase ferrous burden materials and energy of blast furnaces of steelmaking plants. This proposed model is run in MATLAB for the blast furnace 3 of Esfahan Steel Company. The outcomes of this model are compared with practical results for validation. Next to calculating the optimal blending of ferrous burden materials, coke and other carbon-bearing fuels this model obtains the maximum production profit,

In the current situation, steel production in the world is highly competitive. Reducing production costs only makes sustainable competition possible, and one of the most significant expenses in the steelmaking industry is the cost of purchasing coking coal and coke. The great price differences among coke, natural gas and pulverized coal, the complexity of the replacement of coke with other hydrocarbon fuels and its effect on the cost of raw materials, coke and energy consumption rate, and productivity of production, technical limitations, and carbon dioxide emissions issues are the reasons for running such study. Considering the prices and technical limitations, the software of this study model makes it possible to determine the optimal blending of the ferrous burden material among different options and replace pulverized coal, oil, and natural gas with coke; therefore, the maximum production profit can be yield by saving in coke consumption and decreasing the volume of carbon dioxide emissions. Here it is proved that, in spite of high subsidies and low prices for natural gas and oil in Iran, the injection of pulverized coal in the blast furnace for replacement with a portion of coke is significantly effective in increasing production profit in an environment-friendly sense. The results obtained here correspond to that of the economic conditions of Iran. The result of this study has convinced Esfahan Steel Company to draw the decision to invest € 20 million in establishing a pulverized coal injection plant, which will be come on stream at the end of the current year.

The following issues are suggested for future studies and can lead to an increase in the accuracy of the optimization model.

1-The study and modeling of the relation between pulverized coal injection rate in blast furnace and coke strength after reaction (CSR)

2-The study and modeling of the effect of injecting plastic waste materials in the blast furnaces on coke consumption, production profit, and contributing to environmental aspects

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