Value in Use of Lime in BOF Steelmaking Process

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Abstract

In the BOF steelmaking process, lime quality and quantity directly affect slag quality, affecting metallurgical results, liquid metal yield, productivity, and therefore the total cost and environmental impact of the steel production. In this paper, a value in use model based on mass balance and heat balance was developed and used to evaluate the impact of lime quality on the BOF process. The model is capable of calculating the consumption of scrap, lime, oxygen, the volume and composition of the slag and the volume and composition of off-gas and facilities to calculate the cost-benefit contributions and potential cost saving for a configured choice of various types of lime and operating parameters. The model has been successfully validated using the data of the Steel Plant. Then three types of lime with different qualities were used to elaborate on the impact of lime characteristics in optimizing the steelmaking process, metallurgical benefits, overall cost impact, potential savings, and environmental benefits. The calculation results show that good-quality lime could increase the scrap ratio, reduce the lime consumption, and reduce iron loss, accordingly, improve the steel quality, increase steel yield, reduce the smelting costs, stabilize smelting operations, and reduce CO_2 emissions.

Key Words

BOF process, Value in use model, Lime quality, Decarbonisation, Total cost of ownership.

1. Introduction

Despite the development of lime usage in many other industries, the steel industry today remains the largest market for lime usage followed by construction and environment—used as a flux in crude steel production.[1] Industrial lime production allows offering customized lime quality to answer the needs of different steel applications. The blast furnace-basic oxygen furnace (BF-BOF) is one of the most widely used routes for steel production. Lime and dolime play essential roles in this steel making process. Lime quality can significantly impact steel quality, metallurgical performance, productivity, and production costs. The steel industry indeed faces issues related to the growing demand for high-quality clean products, e.g., automotive applications. At the same time, the steel industry is leading carbon dioxide emissions and energy use reduction. Lime used in the steel industry with suitable quality is then a very important subject to produce good quality and sustainable steel.

The BOF steelmaking is a batch process that uses hot metal, scrap, fluxes and oxygen as input materials to produce steel with suitable composition and temperature. Conducting a mass balance and heat balance analysis with real-time operating conditions can optimize the input raw material configuration and provide an insight into the impact of raw material quality on process and cost. Based on this concept, static models were developed quickly by operators with the advent of oxygen steelmaking in the 1950s, but the first published model was in 1960 by Slatosky[2]. After that, Slatosky [3], Dauby et al.[4], and Katsura et al.[5] further improved the static model to calculate the thermodynamically balanced charge for a converter. However, only very few details are available in the open-source, and a few of them discussed the effect of lime quality on the process.

In this paper, a Value in Use (VIU) model based on the mass and heat balance analysis has been developed. The related parameters from publications combined with the semi-empirical equations from plant data are used to develop the realistic model, including properties estimation, performance prediction and cost-benefit analysis. The developed VIU model has been successfully validated using industrial operation data and employed to evaluate the impact of lime quality on the BOF process in terms of performance and cost benefits.

2. Model Description and Computation Method

The overall VIU model consists of three sub-modules: mass and heat balance module, properties prediction module, and cost-benefit module. The static mass and heat balance module plays a significant role in the computer-control system of the BOF process, which is the core of the current VIU model. The consumption of raw materials, fluxes and oxygen, and the volume and composition of the steel, slag and off-gas are calculated by a set of mass and heat balance equations. The slag properties have an important effect on the smelting process and the quality of steel products. The viscosity, density, De-S/Mn/P ability, lime dissolution time, and lime loss in dust can be estimated via the properties prediction module. Every company is racking its brains to reduce its operating costs and improve efficiency for maximizing profits. The quasi-fixed conversion cost, fluxes cost, materials cost, productivity gain, and CO_2 emission cost has been considered in the cost-benefit module. In addition, these modules are further developed in the form of a user-friendly interface for input setting and output displaying during calculation. The concept of the VIU model is illustrated as a flow chart in Figure 1. The model started with the mass and heat balance calculation and is followed by slag properties prediction, then the results of the calculation are used for the cost-benefit analysis. All the results are saved in the database and can be presented in the user interface.

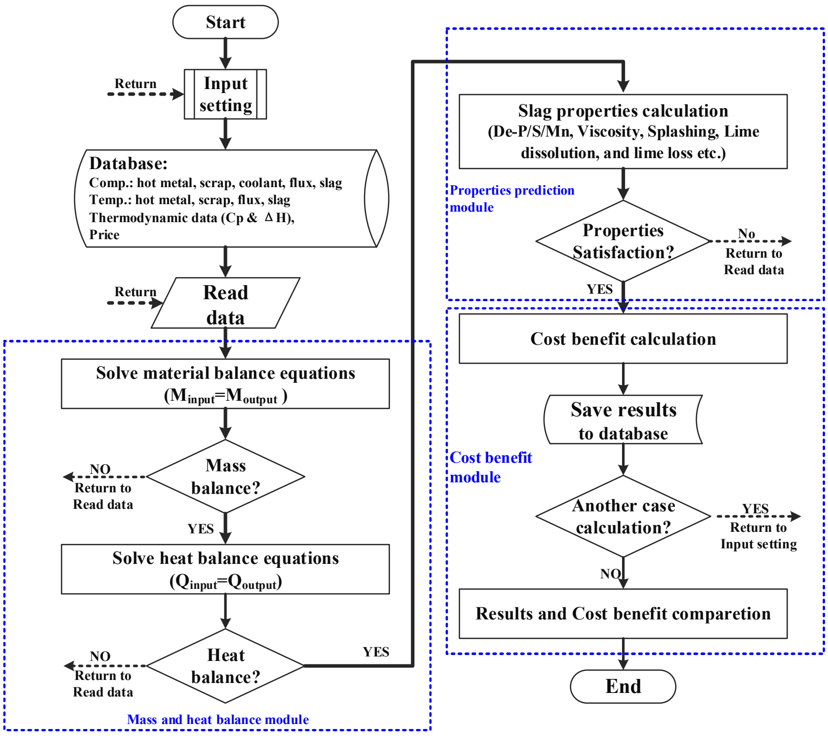

Fig. 1. Flow chart of the VIU model.

2.1 Mass balance and heat balance module

2.1.1 Mass balance

In the BOF process, the vessel is a batch reactor where the vessel is emptied in between heats. The mass balance compares materials inputs and outputs (Eq.1) and can be considered global balances, specific entities balances (gas, slag, steel. Etc.), and elementary balances (Fe, C, O, P, etc.). For instance, the balance for element X can be written as Eq.2. Table 1 presents the input and output materials in the BOF process.

$$\sum input = \sum output \tag{1}$$

$$\sum_i Q_{input,i} \times \%X_{input,i} = \sum_j Q_{output,j} \times \%X_{output,j} \quad (2)$$

Depending on the context, Eq.2 can be used for evaluating the amount $Q_{\text{input,i}}$ or $Q_{output,j}$ of an input or output, and evaluating the composition $\%X_{\text{input,i}}$ or $\%X_{\text{output,j}}$ of an input or output. First of all, the mass balance equations of Fe, C, Si, P, S, CaO, MgO, and Al_2O_3 are considered to estimate the weights and composition of steel and slag, and the consumption of fluxes (lime and dolime). It is followed by oxygen balance to calculate the volume of oxygen and off-gas composition. Establishing accurate mass balances is always the crucial first step to guarantee the validity of the energy balance.

Table 1: Input and output materials from the Basic Oxygen Furnace Process

Input	Hot metal	Weight fixed (M_{HM}), composition and temperature are known
	Scrap	Weight fixed or unknown (M_{Scrap}), composition and temperature are known; If the weight is unknown, then it can be determined by the tapping temperature (T_{tap})
	Coolants	Including DRI, ore, pig iron, sinter, pellet. Weight fixed ($M_{coolant}$), composition and temperature are known
	Fluxes	Lime: weight fixed or unknown(M_{Lime}), composition and temperature are known, If the weight is unknown, then it can be determined by binary basicity (B2) of slag Dolime: weight fixed or unknown(M_{Dolime}), composition and temperature are known, If the weight is unknown, then it can be determined by the fixed MgO content in slag Limestone: weight fixed ($M_{Limestone}$), composition and temperature are known Dolostone: weight fixed (M_{Dolo}), composition and temperature are known Fluorspar: weight fixed (M_{Fluor}), composition and temperature are known
	Oxygen	Volume unknown (V_{Oxygen}), calculated based on oxygen balance, composition and temperature are known
Output	Steel	Weight unknown (M_{Steel}), calculated based on Fe balance. The endpoint carbon content is known, Mn/S/P content in steel calculated via the capacity property of slag. temperature fixed or calculated via heat balance
	Slag	Weight unknown (M_{Slag}), FeO content is known, temperature fixed or calculated via heat balance
	Gas	Weight unknown (M_{Gas}), temperature fixed
	Dust	Weight unknown (M_{Dust}), temperature fixed

2.1.2 Heat balance

Heat balance is important for the correct temperature prediction. The first law of thermodynamics states that the heat of reaction depends only on the initial and final states and not on the intermediate states through which the system may pass. Thus, the components of heat balance are shown in Figure 2. The heat input is through the sensible heat of materials and the heat of exothermic reactions. The heat goes out as sensible heat of steel/slag/gas/dust, endothermic heat of melting/ decomposition, and some heat loss to the atmosphere.

The main balances calculation are defined by the following equations:

The sensible heat of materials Q_{sh}:

$$Q_{sh} = \sum_i (M_i \times \Delta T \times C_P + H_{trans,i} \times M_i) \quad (3)$$

where Mi is the reactant amount, kg; ΔT is the temperature difference, K; C_p is the specific heat capacity of substance i, J/(kg·K), and $H_{trans,i}$ is the enthalpy of phase change of substance i, J/kg.

According to the reactant amount (Mi) from mass balance calculation and the reaction thermal effects (ΔH_i), the heat of reactions Q_{rh} can be expressed:

$$Q_{rh} = \sum_i M_i \times \Delta H_i \quad (4)$$

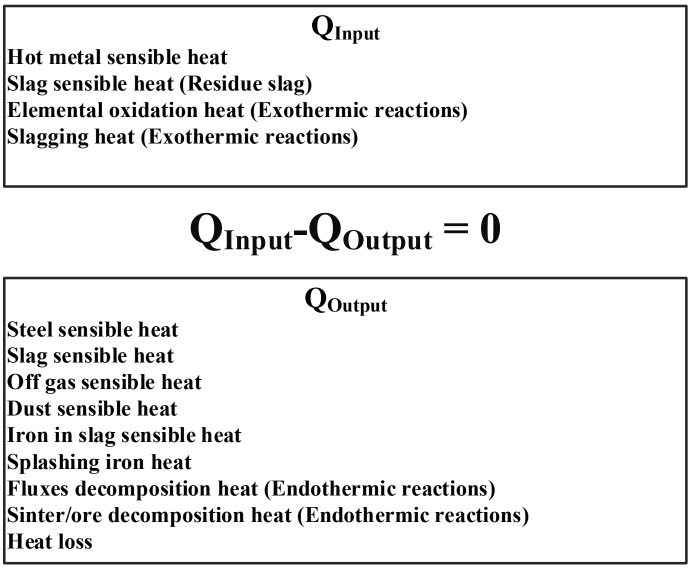

Fig.2. components of heat balance during BOF process.

2.2 Properties prediction module

2.2.1 Phosphorous, Manganese and Sulphur prediction

There are several de-phosphorus prediction models and well documented by Deo et al.[6]. Healy's model[7] and Suito's model[8] are widely used for phosphorous prediction. However, these models are based on thermodynamic equilibrium. Thus, an empirical model developed from steel plant practice is employed:

$$\lg\{\frac{P}{[P]}\} = 18837/(T^{\circ}C+273) + 0.067*(wt(\%CaO)*100+0.3*wt(\%MgO)*100) - 0.55*wt\%[C]*100+12 \quad (5)$$

Numerous semi-empirical and empirical models have been established for calculating the slag sulphide capacities. The KTH model[9-10] is based on thermodynamics but requires many parameters in the calculation process when the interactions of components are considered. The concept of optical basicity Λ was developed by Duffy and Ingram[11-12], then first proposed by Sosinsky and Sommerville[13-14] to estimate a sulphide capacity model, whereas the results are less accurate, and then modified by Young et al. [15]. Young's model was divided into two sections taking the optical basicity value 0.8 as the boundary, and the accuracy was greatly improved. The sulphide capacity of slag is predicted using Young's model, and the sulphur in steel can be calculated based on the relationship between sulphide capacity and sulphur distribution[16], which is as follows:

$$for\ \Lambda < 0.8: log\ Cs = -13.913 + 42.84\Lambda - 23.82\Lambda^2 - \frac{11710}{T} - 0.02223(\%SiO_2) - 0.2275(\%Al_2O_3) \quad (6)$$

$$for\ \Lambda \geq 0.8: Cs = -0.6261 + 0.4808\Lambda + 0.7197\Lambda^2 + \frac{1697}{T} - \frac{2587\Lambda}{T} + 0.0005(\%FeO) \quad (7)$$

$$\log\{\frac{(S)}{[S]}\} = logCs - loga_O + logf_S - \frac{936}{T} + 1.375 \quad (8)$$

The manganese prediction is done by using Suito [17] model as follows:

$$logC_{Mn} = -0.0188[(\%CaO) - 0.21(\%SiO_2) + 0.12(\%MgO) + 0.31(\%FeO) + 1.65(\%P_2O_5)] + \frac{14200}{T} - 3.685 \quad (9)$$

The coefficients of these three models can be estimated and modified by performing regression analysis with the plant data.

2.2.2 Viscosity and density prediction

The liquid slag viscosity is calculated by using the model developed by Zhang et al.[18] The model is a structure-based viscosity model, which is proposed to represent the viscosity of oxide melts as a function of both temperature and composition. The model provides a good description of the variations in viscosity with composition and temperature in the molten stage. When the solid phase (can be calculated via thermodynamic software) exists in the slag, the Einstein equation is used[19]:

$$\eta = \eta_L * (1 + 2.5\theta) \quad (10)$$

where, η is the apparent viscosity, η_L is the liquid viscosity, θ is the volume fraction of the solid phase.

The density of slag can be estimated to a reasonable accuracy (~2%) by the Mills model[20]. This model calculates the density through the molar volume (V_{mol}) and molecular weight of slag (M_{mol}).

2.2.3 Slag splashing

The amount of slag required for slag splashing (Q_{slag}) (in tonnes) for satisfactory coverage was dependent upon the size (in tonnes) of the vessel (W). The relationship is given as following [21]:

$$Q_{slag} = 0.301W^n \tag{11}$$

where n=0.583 to 0.650. The target composition of splash slag: MgO=16 wt.%, FeO < 20 wt.%, Basicity < 5. Generally speaking, the MgO content in slag is the key factor for slag splashing practice. If the MgO content is lower than the target value, then the MgO-bearing material is needed to add in the slag for splashing practice.

2.2.4 Lime dissolution time and oxygen blow time

In oxygen steelmaking, flux is added in the solid form to form a basic slag that will limit the degradation of the refractory lining and remove oxidation products such as phosphorus and silicon. The progress of flux dissolution determines the efficiency of fluxing of impurities and prolongs contact time with refractory lining. Since the top blowing process takes only 15–20 minutes to decarburize and remove impurities from the steel, full utilization of flux added requires fast-flux dissolution in the slag. Therefore, the rate of flux dissolution is of crucial interest for understanding the progress of slag–metal reactions in the oxygen steelmaking system. Many researchers investigated the lime dissolution into different slag systems, and well documented by Du et al.[22] and Chen et al.[23]. Most of them are idealistic and difficult to apply in practice directly.

Here, an approach has been proposed that uses the modified specific surface area (S m^2/g) by considering the particle size distribution to calculate the dissolution time of lime. For a given lime, assuming the lime consists of standard spheres with the number of particles (n). According to the specific surface area, the equivalent diameter r (m) can be calculated:

$$S * M = 4n\pi r^2, M = n\rho_l * \frac{4}{3}\pi r^3;\ r = 3/(\rho_l S) \tag{12}$$

The dissolution rate V_r (m/s) can be calculated by the model suggested by Maruoka et al. [24].

$$V_r = -\frac{dr}{dt} = (1 + a)\, k * \rho_s/(100\, \rho_l) * \Delta(\%CaO) \tag{13}$$

here, a is an acceleration factor due to CO_2, $a=0.53\times(\%CO_2)$; ρ_l is the lime density, 3.35*10^{6}g/m^3; ρ_s is the slag density, which can be calculated by Mills model[20]; *(%CaO)* is the difference between the concentration of CaO in the slag phase and its solubility in the slag phase (in mass%); k is the mass transfer coefficient of CaO in the slag (m^2/s), here the value is 2.7*10^{-9}.

It can be seen that for a given quantity of lime, the specific surface is inversely proportional to the radius of the powder grains. This model is simplistic since the grains are generally neither spherical nor of the same size. Moreover, they can be agglomerated (which reduces the free surface). According to the equivalent diameter r, and the dissolution rate V_r, then the dissolution time t_{dis} (min) of lime can be calculated:

$$t_{dis} = \frac{r}{60 * V_r} \tag{14}$$

The oxygen blow time is calculated via oxygen needed from mass balance and oxygen blow rate from practice.

$$t_{blow} = \frac{Volume\ of\ Oxygen}{Oxygen\ blow\ rate} \tag{15}$$

2.2.5 Lime loss in dust

The movement of particles in the gas flow is simplified here. The force analysis of a lime particle in the descending process after adding to the converter is shown in Figure 3. Fk is the drag force from the fluid gas flow. Fs and Fw are the buoyant force and gravitational force, respectively. The Stokes law is used to calculate the lime loss in dust:

$$\pi r^2 \left(\frac{1}{2}\rho V^2\right) f + \frac{4}{3}\pi r^3 \rho_{gas} g = \frac{4}{3}\pi r^3 \rho_l g \tag{16}$$

here, ρ_{gas} is the density of gas; r is the lime particle radius; V is the relative velocity of particles and flow; and f is the drag coefficient. Based on the calculation, maximum particle size Ø = 4-5 mm in diameter can be taken up into an off-gas system. Lime particle size is usually measured at the lime plant. Due to the transportation for the increase in small particles, a degradation factor α is introduced allowing to calculate the increase of fine particles and the change of particle size distribution hence the real specific surface used for the lime dissolution time. Assuming about 60% particles with a size less than 5mm are taken into the off-gas system. The lime loss into off-gas can be calculated by:

$$M_{Lime\ loss} = M_{Lime} * (1+ \alpha) * (\% < 5mm) * 60\% \quad (17)$$

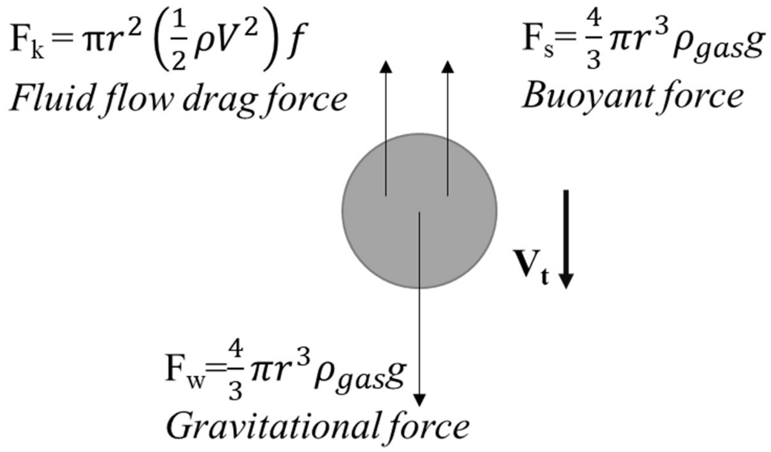

Fig.3. Force analysis of a lime particle.

2.3 Cost-benefit module

The cost-benefit module calculates the cost and saving based on a reference case by considering the quasi-fixed conversion cost, fluxes cost, materials cost, productivity gain, and CO_2 emission cost. The tap-to-tap time affects productivity. The oxygen blow time and re-blow time may differ due to the difference in lime quality, thus affecting the tap-to-tap time. Based on the reference case, considering the difference of oxygen blow time and re-blow time (if implemented), the tap-to-tap time of using different types of lime can be calculated. The main cost items are listed as below:

Quasi-fixed conversion cost = estimated labour cost + overheads and maintenance;
Fluxes cost = Lime/Dolime/limestone/dolostone consumption cost;
Materials cost = hot metal cost + scrap cost + oxygen cost + refractory cost;
Energy cost = electricity cost + Ar gas cost + off-gas cost;
Productivity gain/loss = productivity gain tons * productivity gain saving;
Slag cost = slag handing cost + slag landfill cost;
Dust cost = dust handing cost + dust landfill cost;
CO_2 emissions cost = CO_2 emissions * price.
Here, CO_2 emissions only consider the CO_2 in off-gas, mainly from carbon oxidization and fluxes. The CO in the off-gas can be used in subsequent processes.

3. Results and Discussion

The VIU model developed in this work is validated with plant data. The reference case is calculated based on the actual factory data and compared with the other two cases with different lime qualities. Figure 4 shows the mass flow sheet of the reference case. The calculation conditions are defined based on a particular customer that the temperature of final slag/steel is 1670°C, the temperature of off-gas/dust is 1450°C, the charge amount of hot metal is 110 tons, the MgO content in slag is 8 wt%, the FeO content in slag is 18 wt%, and the slag basicity is 3.4. Under steady-state, the consumption of scrap, flux (lime, dolime), and oxygen were calculated with the static process module. Under this condition, 256.50 kg scrap, 37.38 kg lime, 16.70 kg dolime, and 57.89 Nm^3 oxygen are required for producing 1 t steel. It should be noted that the hot metal contains 2.12 wt.% Mn and slag contains 20.46 wt.% MnO, which is not a typical case of BOF steelmaking. Because the particular customer uses a cheap and poor quality iron ore, which results in unstable hot metal chemistry in terms of Mn, Si, P and S content. The steel grades produced by the customer contain Mn 0.2 - 0.6%, so they have to "burn" the high Mn content in the hot metal (2.12% Mn) to meet the steel specifications. Therefore, the MnO content in the steelmaking slag is high (20.46% MnO). Because of the operating practice in this particular customer, the high amount of MnO in slag is not considered a loss. Table 2 shows three types of lime with different qualities. The content of CaO increases from lime 1 to lime 3, while impurities like, e.g. SiO_2 content decreases. Prices per ton of lime 2 and 3 are set respectively 4% and 8% higher than lime 1.

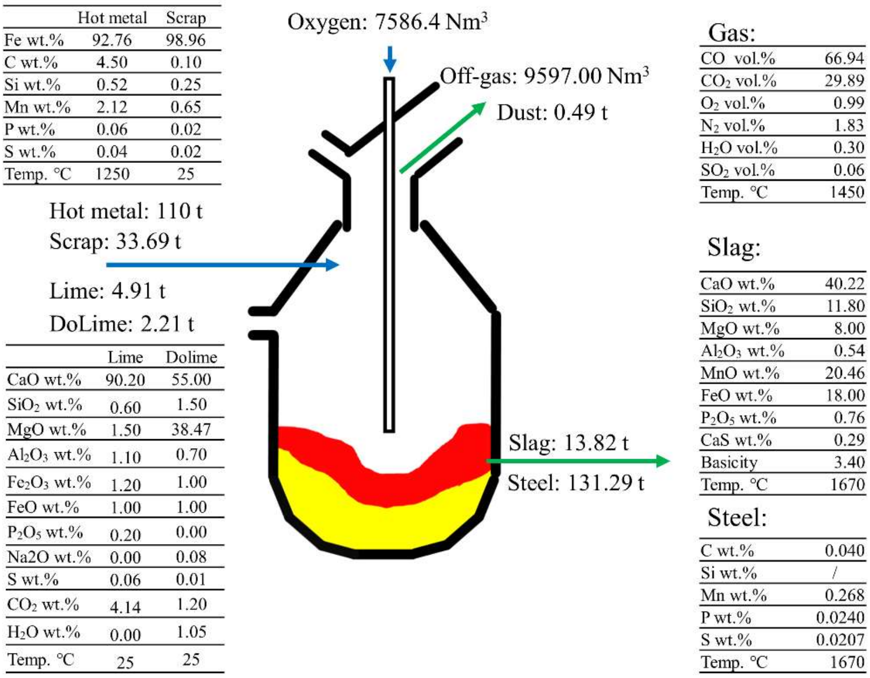

Fig. 4. Specific mass flow of the reference case

Table 2: Quality of three types of lime (wt.%)

	Lime 1	**Lime 2**	**Lime 3**
CaO	90.20	93.50	95.05
SiO_2	0.60	0.40	0.29
MgO	1.50	1.10	1.13
Al_2O_3	1.10	0.20	0.13
Fe_2O_3	1.20	0.20	0.05
FeO	1.00	1.00	0.00
P_2O_5	0.20	0.10	0.20
S	0.06	0.03	0.01
CO_2	4.14	3.26	3.14
< 5mm	5%	5%	5%
Modified Specific surface area (m^2/g)	0.840	0.896	0.896

3.1 Materials consumption

The influence of three types of lime with different qualities on material consumption is shown in Table 3. The calculation results show that the lime consumption per ton of liquid steel using lime 3 is about 2.5kg lower than that of lime 1. The content of CaO in lime increases, and the SiO_2 content decreases as the quality of lime gets better. When the basicity (CaO wt%/SiO_2 wt%) is fixed at 3.4, the consumption of lime decreased as uses lime 3 with higher CaO content. As the amount of lime is reduced when using better quality lime, slag volume is decreased as well. More heat can be used to melt the scrap when fixed the tapping temperature. Therefore, the scrap ratio is increased by about 1%, resulting in the increase of steel production of each heat; in other words, the productivity has increased. In order to protect the refractory materials, the MgO content of the slag is fixed at 8%, so the consumption of dolime is slightly increased due to the MgO content of Lime 3 is lower than that of Lime 1 and Lime 2. The increase of scrap introduces more carbon into the heat, which needs to be oxidized, resulting in an increase in oxygen consumption. Since the proportion of the three types of limes whose particle size is less than 5mm is the same (5%), there is no obvious difference in the lime lost in the dust.

Table 3: Effect of lime quality on materials consumption and output

	Unit	Lime 1	Lime 2	Lime 3
Hot metal	kg/t steel	837.84	832.51	831.63
Scrap	kg/t steel	256.53	261.48	262.56
Scrap ratio	%	30.62%	31.41%	31.57%
Lime	kg/t steel	37.38	35.55	34.94
Dolime	kg/t steel	16.87	17.09	17.03
Oxygen	Nm^3/t steel	57.89	57.60	57.60
Steel	tons/heat	131.29	132.13	132.27
Slag	tons/heat	13.82	13.76	13.74
	kg/t steel	105.28	104.14	103.86

3.2 Steel quality

As it is well known, sulphur and phosphorus are harmful impurities in steel products, and slag plays a significant role in removing these kinds of impurities. However, in these cases, the composition of the final slag is similar, and the smelting operation conditions are the same. Thus, the main factors affecting the sulphur and phosphorus content in steel are the sulphur/ phosphorus load and slag volume. A large sulphur/ phosphorus load means that the amount of sulphur and phosphorus introduced by the raw materials is large. When the thermodynamics (slag composition and temperature) and kinetics (operating conditions) of slag in desulphurization and dephosphorization are similar, the greater the sulphur and phosphorus load, the higher the sulphur and phosphorus content in the steel. The decrease in slag volume results in a decrease in the amount of sulphur and phosphorus absorbed in the slag. From table 2, the phosphorus content in lime 2 is less than that of the other two types of lime, which response to the phosphorus decrease in steel. The sulphur content decreases from lime 1 to lime 3, resulting in a significant decrease of sulphur load, which response to the decrease of sulphur in steel. In addition, good quality lime with high activity and a large specific surface area has a fast slagging rate, which is beneficial to remove the impurities in the steel.

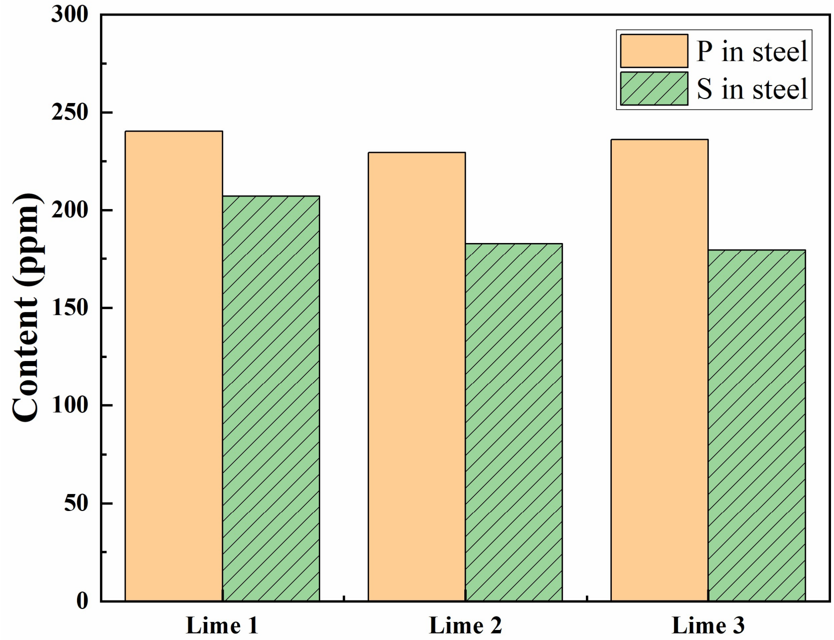

Fig. 5. The sulphur and phosphorus content in steel

3.3 Cost and CO_2 reduction benefit

Cost is a topic that every company cares about most and endeavours to reduce operating costs and improve production efficiency. Table 4 shows a brief summary of the effect of lime quality on the cost-benefit. According to the oxygen blow rate and oxygen required, the oxygen blow time can be calculated. The use of good quality lime increases productivity and increases oxygen consumption per heat. Thus, the oxygen blow time slightly increased, as well as the tap-to-tap time. It should be noted that according to equations (11) to (13), the lime dissolution time decreases from 12.4 min to 11.8, mainly due to the increased specific surface area. The decrease of lime dissolution time may reduce the smelting time, but there is no evidence yet to prove that it will reduce the tap-to-tap time, then this parameter has not been considered in the calculation of tap-to-tap time. The Quasi-fixed conversion cost is fixed for each heat while slightly decreases when considering the cost per ton of steel. The fluxes cost depends on the price of fluxes (lime/dolime); good quality lime can have a higher price but reduces consumption. Materials cost increases each heat due to the increase of scrap consumption but decrease when considering the cost per ton of steel. Iron is mainly lost in slag as FeO and metallic iron, splashing and dust. As the decrease of slag volume, the iron loss is reduced accordingly, which means an extra saving. The slag and dust include handing cost and landfill cost, which also decreased due to the decrease of slag volume.

CO_2 emission of the steel industry is currently accounted for 6% of the total global anthropogenic CO_2 emissions. It is about 1.8 tons per ton of crude steel produced through the BF-BOF route[25]. Although it is mainly produced from the BF process, the BOF part also contributes to the total emission. Changing the lime quality allows increasing the scrap ratio, which helps to reduce carbon emissions in the BOF process. According to the calculation, the CO_2 emission decreases from 43.35 to 41.96 kg/ton (-3.2%) when changing from lime 1 to lime 3, and the cost for CO_2 emission decreases as well.

In summary, even if the price of lime 2 and lime 3 is higher than lime 1, the cost saving is calculated to be 0.89 € and 0.98 € per ton of steel when using lime 2 and lime 3 compared to lime 1, respectively. When considering 320 working days a year, the total saving can be more than 0.9 million euros in one operating set.

Table 4: Effect of lime quality on cost.

	Units	lime 1	lime 2	lime 3
Oxygen blow time /heat	min	19.00	19.03	19.05
Tap-to-tap time	min	60.00	60.03	60.05
Quasi-fixed conversion cost /ton	EUR (€)	7.50	7.47	7.46
Fluxes cost /ton	EUR (€)	3.23	3.22	3.25
Materials cost /ton	EUR (€)	265.97	265.30	265.23
Fe loss cost /ton	EUR (€)	8.53	8.45	8.43
Slag cost /ton	EUR (€)	6.32	6.25	6.23
Dust cost /ton	EUR (€)	0.22	0.22	0.22
CO_2 emissions cost /ton	EUR (€)	1.08	1.05	1.05
Cost /ton	EUR (€)	292.86	291.96	291.88
Saving/ton	EUR (€)	0.00	0.89	0.98
Saving/heat	EUR (€)	0.00	117.99	129.12
Saving/year	EUR (€)	0.00	905,748	990,885

4. Conclusions

A Value in Use model has been developed in this work to elaborate the impact of lime quality on the BOF process. The properties prediction module and cost-benefits module are added in the basic of static mass balance and heat balance module, and complemented by a friendly user interface. The model can calculate the consumption of scrap, lime, oxygen, and the volume and composition of the slag/off-gas as well as the cost-benefit contributions and cost savings for a configured choice of limes and operating parameters. After successfully validating using the steel plant data, three types of lime with different quality were used to analyze the effect of lime characteristics on optimizing the steelmaking process, metallurgical benefits, overall cost-benefits, and potential environmental benefits. The calculation results show that good-quality lime could increase the scrap ratio, reduce the lime consumption, and reduce iron loss, accordingly, improve the steel quality, increase steel yield, reduce the smelting costs, stabilize smelting operations, and reduce CO_2 emissions.

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Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 1: Input and output materials from the Basic Oxygen Furnace Process

Input	Hot metal	Weight fixed (M_{HM}), composition and temperature are known
	Scrap	Weight fixed or unknown (M_{Scrap}), composition and temperature are known; If the weight is unknown, then it can be determined by the tapping temperature (T_{tap})
	Coolants	Including DRI, ore, pig iron, sinter, pellet. Weight fixed ($M_{coolant}$), composition and temperature are known
	Fluxes	Lime: weight fixed or unknown(M_{Lime}), composition and temperature are known, If the weight is unknown, then it can be determined by binary basicity (B2) of slag Dolime: weight fixed or unknown(M_{Dolime}), composition and temperature are known, If the weight is unknown, then it can be determined by the fixed MgO content in slag Limestone: weight fixed ($M_{Limestone}$), composition and temperature are known Dolostone: weight fixed (M_{Dolo}), composition and temperature are known Fluorspar: weight fixed (M_{Fluor}), composition and temperature are known
	Oxygen	Volume unknown (V_{Oxygen}), calculated based on oxygen balance, composition and temperature are known
Output	Steel	Weight unknown (M_{Steel}), calculated based on Fe balance. The endpoint carbon content is known, Mn/S/P content in steel calculated via the capacity property of slag. temperature fixed or calculated via heat balance
	Slag	Weight unknown (M_{Slag}), FeO content is known, temperature fixed or calculated via heat balance
	Gas	Weight unknown (M_{Gas}), temperature fixed
	Dust	Weight unknown (M_{Dust}), temperature fixed

Table 2: Quality of three types of lime (wt.%)

	Lime 1	Lime 2	Lime 3
CaO	90.20	93.50	95.05
SiO_2	0.60	0.40	0.29
MgO	1.50	1.10	1.13
Al_2O_3	1.10	0.20	0.13
Fe_2O_3	1.20	0.20	0.05
FeO	1.00	1.00	0.00
P_2O_5	0.20	0.10	0.20
S	0.06	0.03	0.01
CO_2	4.14	3.26	3.14
< 5mm	5%	5%	5%
Modified Specific surface area (m^2/g)	0.840	0.896	0.896

Table 3: Effect of lime quality on materials consumption and output

	Unit	Lime 1	Lime 2	Lime 3
Hot metal	kg/t steel	837.84	832.51	831.63
Scrap	kg/t steel	256.53	261.48	262.56
Scrap ratio	%	30.62%	31.41%	31.57%
Lime	kg/t steel	37.38	35.55	34.94
Dolime	kg/t steel	16.87	17.09	17.03
Oxygen	Nm^3/t steel	57.89	57.60	57.60
Steel	tons/heat	131.29	132.13	132.27
Slag	tons/heat	13.82	13.76	13.74
	kg/t steel	105.28	104.14	103.86

Table 4: Effect of lime quality on the cost.

	Units	lime 1	lime 2	lime 3
Oxygen blow time /heat	min	19.00	19.03	19.05
Tap-to-tap time	min	60.00	60.03	60.05
Quasi-fixed conversion cost /ton	EUR (€)	7.50	7.47	7.46
Fluxes cost /ton	EUR (€)	3.23	3.22	3.25
Materials cost /ton	EUR (€)	265.97	265.30	265.23
Fe loss cost /ton	EUR (€)	8.53	8.45	8.43
Slag cost /ton	EUR (€)	6.32	6.25	6.23
Dust cost /ton	EUR (€)	0.22	0.22	0.22
CO_2 emissions cost /ton	EUR (€)	1.08	1.05	1.05
Cost /ton	EUR (€)	292.86	291.96	291.88
Saving/ton	EUR (€)	0.00	0.89	0.98
Saving/heat	EUR (€)	0.00	117.99	129.12
Saving/year	EUR (€)	0.00	905,748	990,885

Figure list: