THE BENEFITS OF INTEGRATED DECISIONS OVER SULPHUR CONTENT ALONG THE PROCESS CHAIN: PRODUCTION OF PIG IRON AND STEEL*

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Abstract

The definition of the chemical specification at multiple steps of the steelmaking process is very common in the industry. Among all elements and compounds, the Sulphur content has a special control over several stages, from the coal blend to the final products. Coke, iron and steelmaking specialists usually agree on a static specification for each intermediate product according to their local operation capacity and production cost. However, local decisions have major impacts on the whole production chain and many global factors should be considered in order to make the best decision. In this study, we will exemplify focusing on Sulphur content concepts and techniques that could be applied to many decisions in an integrated carbon steel plant. The variation of coal and coke prices, the desulphurization cost and time, the processes operating points, the hot metal rate at converters, prices and demands of low and ultra-low Sulphur steel grades are some of the integrated factors that are usually disregarded during the specification process. Mathematical modeling presents itself as a proper option into dealing with all the complexity that emerges from integrating all these processes' trade-offs and decisions. This study presents the results of a mathematical model that encompasses economic, thermal, chemical, and mass balances, physical quality of materials and productivity constraints of all processes of a hypothetical integrated carbon steel plant. It optimizes the iron and steelmaking process on a global and unique objective, dynamically defining targets for product quality to achieve the lowest steel production cost. This study details multiple market-plant scenarios in order to compare economic and operating results of a static vs dynamic specification practice.

Keywords: Processes integration; mathematical model; optimization; Sulphur content.

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1 INTRODUCTION

It is very common to have multiple production areas of an integrated steel plant debating about the Sulphur specification of products. High Sulphur content in steel has a large negative impact on its quality and properties, lowering its market price. However, raw materials with higher Sulphur content are cheaper and could be used to lower the production cost.

In the process chain, the first and biggest introduction of Sulphur happens at the coke plant with the coal blend. A part of the blend's Sulphur content is incorporated by the coke, determined by individual coal's yield. The blast furnace operators use process factors, like binary basicity of slag and hot metal temperature, to control the Sulphur equilibrium between the slag and the hot metal.

When desulphurization of hot metal is required prior to the converter, fluxes are injected to reduce the Sulphur content. This has a side effect of reducing the temperature of the hot metal. Additionally, processing time can become a critical factor to guarantee the rhythm of the steel shop.

At the converter, the Sulphur content can potentially increase due to the utilization of scraps.

Finally, the crude steel can pass by another desulphurization process, usually in a ladle furnace, with the same challenges as for the desulphurization of hot metal (time and cost).

Different mathematical modeling and optimization techniques could be used in the integrated steelmaking process depending on the problem being modeled. Due to the nature of the process being modelled in this study, we create a Non-Linear Mathematical Program (NLP). The mathematical model bringing the major complexity of the decision is then optimized using the commercial solver CONOPT, a solver for large-scale non-linear optimization based on The Generalized Reduced Gradient Method (GRG).

2 DEVELOPMENT

2.1 Model

The mathematical model presented in this paper optimizes the Sulphur strategy of a dummy plant. Its scope includes the coal coking process, the iron making at the blast furnace, the hot metal desulphurization and the primary refining. The secondary refining process is not considered in this model.

Also, the model simplifies a lot or completely disregards some decisions that are not directly related to the Sulphur strategy, such as iron-bearing materials, other chemical elements, coke physical quality, thermal balances, etc.

Here follow the decision variables that will determine the desulphurization strategy of an integrated steel plant and that are optimized by the model:

- the purchase of coal (different prices and Sulfur contents)

- the temperature of hot metal (within a realistic range)
- the binary basicity of slag (also within a realistic range)
- the flux consumption at the hot metal desulphurization

Other variables will be determined in function of those decision variables and input parameters.

The model begins with the coke plant equations. The mass of coke produced is defined by the sum of purchased coals times their coking yield (removal of volatile matters).

$$\boldsymbol{M_{coke}} = \sum_{c}^{Coals} \boldsymbol{M_{coal}^{c}} \times \frac{\boldsymbol{\lambda^{c}}}{\mathbf{100}} \quad (1)$$

Where:

- $\boldsymbol{M_{coke}}$ is the mass of coke produced in kilotonne
- $\boldsymbol{M_{coal}^{c}}$ is the mass of coal “c” purchased in kilotonne
- $\boldsymbol{\lambda^{c}}$ is the coke yield of coal “c” in percent (parameter).

The demand of coke is defined by the coke rate at blast furnace (assumed to be constant, for simplicity).

$$\boldsymbol{M_{coke}} = \frac{\boldsymbol{M_{hm}} \times \boldsymbol{Rate_{coke}}}{\mathbf{1000}} \quad (2)$$

Where:

- $\boldsymbol{M_{hm}}$ is the mass of hot metal produced in kilotonne
- $\boldsymbol{Rate_{coke}}$ is the coke rate in kg/t (parameter).

For a given blend of coals matching the coke mass demand, the model determines the mass of Sulphur in the coke. It is equal to the sum of purchased coals times their Sulphur content times their coke yield times their Sulphur yield (different due to the nature of Sulphur).

$$\boldsymbol{M_{coke}^{S}} = \sum_{c}^{Coals} \boldsymbol{M_{coal}^{c}} \times \frac{\boldsymbol{P_{coal}^{S,c}}}{\mathbf{100}} \times \frac{\boldsymbol{\lambda^{c}}}{\mathbf{100}} \times \frac{\boldsymbol{\mu^{c}}}{\mathbf{100}} \quad (3)$$

Where:

- $\boldsymbol{M_{coke}^{S}}$ is the Sulphur mass in the coke in kilotonne
- $\boldsymbol{P_{coal}^{S,c}}$ is the coal’s Sulphur content in percent (parameter).
- $\boldsymbol{\mu^{c}}$ is the coal’s Sulphur yield in percent (parameter).

The coke’s Sulphur content is equal to the mass of Sulphur incorporated over the coke mass.

$$\boldsymbol{P_{coke}^{S}} = \frac{\boldsymbol{M_{coke}^{S}} \times \mathbf{100}}{\boldsymbol{M_{coke}}} \quad (4)$$

Where $\boldsymbol{P_{coke}^{S}}$ is the coke’s Sulphur content in percent.
The proportion of coal in the blend is defined by the procurement of the coal over the procurement of all coals.

$$\boldsymbol{P_{coal}^{c}} = \frac{\boldsymbol{M_{coal}^{c}} \times \mathbf{100}}{\sum_{cc}^{Coals} \boldsymbol{M_{coal}^{cc}}}, \quad \forall\, \boldsymbol{c\ in\ Coals} \quad (5)$$

Where $\boldsymbol{P_{coal}^{c}}$ is the proportion of coal “c” in the blend, expressed in percent.

Next, come the equations describing the blast furnace process. The first equation corresponds to the input mass of Sulphur in the furnace. Basically, it is equal to the sum of Sulphur mass from the coke and from the pulverized coal injected in the furnace.

$$\boldsymbol{M^{S}_{input}} = \boldsymbol{M^{S}_{coke}} + \boldsymbol{M^{S}_{inj}} \quad (6)$$

Where:

- $\boldsymbol{M^{S}_{input}}$ is the input mass of Sulphur at BF in kilotonne.
- $\boldsymbol{M^{S}_{inj}}$ is the mass of Sulphur from injection at BF in kilotonne.

The mass of Sulphur from injection is determined by the injection rate and the coal Sulphur content.

$$\boldsymbol{M^{S}_{inj}} = \frac{\boldsymbol{Rate_{inj}} \times \boldsymbol{M_{hm}}}{\mathbf{1000}} \times \frac{\boldsymbol{P^{S}_{inj}}}{\mathbf{100}} \quad (7)$$

Where:

- $\boldsymbol{Rate_{inj}}$ is the injection rate in kg/t that is assumed constant (parameter).
- $\boldsymbol{P^{S}_{inj}}$ is the coal's Sulphur content in percent (parameter).

The input mass of Sulphur in the furnace separates into two products: hot metal and slag.

$$\boldsymbol{M^{S}_{input}} = \boldsymbol{M^{S}_{hm}} + \boldsymbol{M^{S}_{slag}} \quad (8)$$

Where:

- $\boldsymbol{M^{S}_{hm}}$ is the mass of Sulphur in hot metal in kilotonne
- $\boldsymbol{M^{S}_{slag}}$ is the mass of Sulphur in slag in kilotonne

The hot metal's Sulphur content is equal to the mass of Sulphur incorporated over the hot metal demand.

$$\boldsymbol{P^{S}_{hm}} = \frac{\boldsymbol{M^{S}_{hm}} \times \mathbf{100}}{\boldsymbol{M_{hm}}} \quad (9)$$

Where $\boldsymbol{P^{S}_{hm}}$ is the hot metal's Sulphur content in percent.

The hot metal demand is directly related to its specific consumption at primary refining and the crude steel demand.

$$\boldsymbol{M_{hm}} = \frac{\boldsymbol{M_{steel}} \times \boldsymbol{Rate_{hm}}}{\mathbf{1000}} \quad (10)$$

Where:

- $\boldsymbol{Rate_{hm}}$ is the hot metal specific consumption at primary refining, expressed in kg/t, that is assumed constant (parameter).
- $\boldsymbol{M_{steel}}$ is the crude steel demand, expressed in kilotonne (parameter).

The most sensitive equation of the model is the one that determines the Sulphur equilibrium between the Sulphur content of the hot metal and the slag. It is known to be impacted by the hot metal temperature and the slag basicity [1]. The equation is written as a linear regression.

$$\frac{\boldsymbol{P^{S}_{hm}}}{\boldsymbol{P^{S}_{slag}}} = \boldsymbol{a} + \boldsymbol{b}(\mathbf{ln}(\boldsymbol{T_{hm}}) - \mathbf{ln}(\boldsymbol{T^{*}_{hm}})) + \boldsymbol{c}(\boldsymbol{Bas_{slag}} - \boldsymbol{Bas^{*}_{slag}}) \quad (11)$$

Where:

- $\boldsymbol{P^{S}_{slag}}$ is the slag's Sulphur content in percent.
- $\boldsymbol{a}$ is the constant of equilibrium (parameter).

- $\mathbf{ln}(\boldsymbol{T_{hm}})$ is the natural logarithm of the hot metal temperature.
- $\mathbf{ln}(\boldsymbol{T^*_{hm}})$ is the natural logarithm of the hot metal temperature reference (parameter).
- $\boldsymbol{b}$ is the hot metal temperature's equilibrium impact coefficient (parameter).
- $\boldsymbol{Bas_{slag}}$ is the slag's binary basicity.
- $\boldsymbol{Bas^*_{slag}}$ is the slag's binary basicity reference (parameter).
- $\boldsymbol{c}$ is the slag binary basicity's equilibrium impact coefficient (parameter).

The binary basicity is defined by the mass of Calcium oxide over the Silica in slag.

$$\boldsymbol{Bas_{slag}} = \frac{\boldsymbol{M^{CaO}_{slag}}}{\boldsymbol{M^{SiO_2}_{slag}}} \quad (12)$$

The mass of CaO, $\boldsymbol{M^{CaO}_{slag}}$. expressed in kilotonne, comes from the lime added at the blast furnace (or at the sinter plant, if any). It has a cost associated with it, defined in equation 33.

The mass of silica in the slag, $\boldsymbol{M^{SiO_2}_{slag}}$. expressed in kilotonne, is calculated by the balance of Si and SiO2:

$$\boldsymbol{M^{SiO_2}_{input}} = \boldsymbol{M^{Si}_{hm}} \times \boldsymbol{m^{Si}_{SiO_2}} + \boldsymbol{M^{SiO_2}_{slag}} \quad (\mathbf{13})$$

Where:

- $\boldsymbol{M^{Si}_{hm}}$ is the mass of Silicon in hot metal in kilotons.
- $\boldsymbol{m^{Si}_{SiO_2}}$ is the oxidation factor of Silicon to Silica
- $\boldsymbol{M^{SiO_2}_{slag}}$ is the mass of Silica in slag in kilotonne

The left-hand side corresponds to the input mass of Silica in the furnace. Basically, it is equal to the sum of Sulphur mass in coke and pulverized coals.

$$\boldsymbol{M^{SiO_2}_{input}} = \frac{\boldsymbol{M_{hm}} \times \boldsymbol{Rate_{iron}}}{\mathbf{1000}} \times \frac{\boldsymbol{P^{SiO_2}_{iron}}}{\mathbf{100}} + \boldsymbol{M^{SiO_2}_{coke}} + \boldsymbol{M^{SiO_2}_{inj}} \qquad (\mathbf{14})$$

Where:

- $\boldsymbol{Rate_{iron}}$ is the metallic charge rate in kg/t, that is assumed constant (parameter)
- $\boldsymbol{P^{SiO_2}_{iron}}$ is the Silica proportion in iron charge in percent (parameter)
- $\boldsymbol{M^{SiO_2}_{coke}}$ is the mass of Silica in coke in kilotonne
- $\boldsymbol{M^{SiO_2}_{inj}}$ is the mass of Silica in pulverized coal in kilotonne

The mass of Silica in coke is determined by the coke produced mass times its Silica proportion.

$$\boldsymbol{M^{SiO_2}_{coke}} = \boldsymbol{M_{coke}} \times \frac{\boldsymbol{P^{SiO_2}_{coke}}}{\mathbf{100}} \qquad (\mathbf{15})$$

Where $\boldsymbol{P^{SiO_2}_{coke}}$ is the coke's Silica content in percent (parameter).

The mass of Silica from the pulverized coal is determined by the injection rate and the coal's Silica content.

$$\boldsymbol{M^{SiO_2}_{inj}} = \frac{\boldsymbol{Rate_{inj}} \times \boldsymbol{M_{hm}}}{\mathbf{10^3}} \times \frac{\boldsymbol{P^{SiO_2}_{inj}}}{\mathbf{100}} \quad (\mathbf{16})$$

Where $P_{inj}^{SiO_2}$ is the powdered coal's Silica content, expressed in percent (parameter).

The mass of Silicon in hot metal is defined by the overall mass of hot metal times its Silicon content.

$$M_{hm}^{Si} = M_{hm} \times \frac{P_{hm}^{Si}}{100} \quad (17)$$

Where P_{hm}^{Si} is the hot metal's Silicon content in percent, assumed constant (parameter).

Also, the overall mass of slag is defined by the sum of its chemical elements.

$$M_{slag} = \sum_{c}^{Comp} M_{slag}^{c} \quad (18)$$

Where M_{slag}^{c} is the slag's compound "c" mass in kilotonne.

The model considers the following compounds in the slag: Sulphur, Silica, Calcium oxide, Aluminum oxide, and Magnesium oxide. Their contents in slag are defined by their mass over the slag mass.

$$P_{slag}^{c} = \frac{M_{slag}^{c} \times 100}{M_{slag}}, \quad \forall\, c \ in\ Comp_{slag} \ (19)$$

Where P_{slag}^{c} is the slag's compound "c" content in percent.

Silica and Calcium oxide contents are determined by their masses. While Aluminum oxide and Magnesium oxide contents are assumed constant (parameter)

The hot metal is treated in the desulphurization station in order to reach a target Sulphur content. This target is assumed to be constant and global for the whole production (the model does not consider several steel grades). The consumption of flux weighted by its efficiency is related to the logarithm of the ratio between the Sulphur contents.

$$K \times Rate_{flux} = log\left(\frac{P_{hm}^{S}}{P_{De[S]}^{S}}\right) \quad (20)$$

Where:

- K is the flux efficiency (parameter).
- $Rate_{flux}$ is the specific consumption of fluxes in kg/t.
- $P_{De[S]}^{S}$ is the targeted content of Sulphur, expressed in percent (parameter).

The overall mass of flux is defined by the specific consumption times the hot metal production.

$$M_{flux} = \frac{Rate_{flux} \times M_{hm}}{1000} \quad (21)$$

Where M_{flux} is the mass of flux purchased in kilotonne.

The desulphurization process takes a certain time which partially depends on the delta of Sulphur:

$$D_{De[S]} = D_{De[S]}^{fix} + D_{De[S]}^{var} \times (P_{hm}^{S} - P_{De[S]}^{S}) \quad (22)$$

Where:

- $D_{De[S]}$ is the average treatment time for a heat, expressed in min/heat.

- $D_{De[S]}^{fix}$ is a fixed time per heat (parameter).
- $D_{De[S]}^{var}$ is the variable treatment time of the desulphurization station, expressed in min/% (parameter).

It is well known that the desulphurization process can cause delays in the tap-to-tap time at the Basic Oxygen Furnace (BOF). The delay can be caused by a crane or by the desulphurization itself, depending on the layout of the steel shop.

From a global (average) perspective, we can estimate the overall process time of a set of facilities as the maximum of the time of each facility that operates in parallel. We can easily model this with two equations:

$$D_{PR} \geq D_{De[S]} \qquad (23)$$

Where D_{PR} is the average process time for a heat at the primary refining, expressed in min/heat.

And,

$$D_{PR} \geq D_{BOFs} \qquad (24)$$

Where D_{BOFs} is the average converting time for a heat at the primary refining, expressed in min/heat.
This time depends on the number of converters:

$$D_{BOFs} = \frac{D_{tap2tap}}{N_{BOFs}} \qquad (25)$$

Where:

- $D_{tap2tap}$ is the average process time for a heat at one converter, expressed in min/heat (parameter).
- N_{BOFs} is the number of converters (parameter).

The product of the average time of the primary refining with the number of heats define the total amount of process days in primary refining.

$$D_{total} = \frac{D_{PR} \times N_{heat}}{1440} \qquad (26)$$

Where:

- D_{total} is the total amount of process days in primary refining, expressed in days.
- N_{heat} is the number of heats for primary refining, expressed in heats.

The number of heats needed is determined by the production of crude steel and the mass per heat, assumed constant.

$$N_{heat} = \frac{M_{steel} \times 1000}{M_{heat}} \qquad (27)$$

Where M_{heat} is the mass per heat, expressed in t/heat.

It is necessary to constrain the total amount of process days in primary refining by the calendar days in the optimization horizon.

$$D_{total} \leq D_{horizon} \qquad (28)$$

Where $D_{horizon}$ is the calendar days available in the optimization horizon, expressed in days.

Since there are several combinations of the decision variables that generate a feasible desulphurization strategy and that satisfy the mass and chemical balances, the model will search for the one that minimizes the overall cost.

$$\min Cost_{total} \quad (29)$$

Where $Cost_{total}$ is the total production cost in MUS$.

The overall cost is a sum of the individual costs related to the production.

$$Cost_{total} = Cost_{coal} + Cost_{temp} + Cost_{lime} + Cost_{flux} \quad (30)$$

Where:

- $Cost_{coal}$ is the coal blend cost in MUS$.
- $Cost_{temp}$ is the hot metal's temperature cost in MUS$.
- $Cost_{lime}$ is the lime cost in MUS$.
- $Cost_{flux}$ is the desulphurization flux cost in MUS$.

The coal blend cost is determined by the product of the mass of coals with their price.

$$Cost_{coal} = \sum_{c}^{Coals} \frac{M_{coal}^{c} \times Price_{coal}^{c}}{1000} \quad (31)$$

Where $Price_{coal}^{c}$ is the coal's price in US$/t.

The hot metal's temperature cost accounts for all the costs involved in the thermal balance of the blast furnace.

$$Cost_{temp} = \frac{Price_{temp} \times (T_{hm} - T_{hm}^{*}) \times M_{hm}}{1000} \quad (32)$$

Where $Price_{temp}$ is the cost to increase the hot metal temperature by one ºC. It is expressed in US$/t/ºC.

The lime cost is associated to the consumption of lime:

$$Cost_{Llme} = \frac{Price_{Lime} \times M_{slag}^{CaO}}{1000} \quad (33)$$

Where $Price_{Lime}$ is the lime purchase price in US$/t.

The desulphurization flux cost is determined by the product of the flux with its price.

$$Cost_{flux} = \frac{M_{flux} \times Price_{flux}}{1000} \quad (34)$$

Where $Price_{flux}$ is the flux price in US$/t.

Note that we do not account for the other production costs as they are assumed constant, given all the assumptions described above.

2.2 Hypotheses

From the process perspective, for the sake of the simplicity, we made the following hypotheses in the model:

- Increasing the slag basicity does not increase the slag volume and consequently the coke rate,
- Increasing the hot metal temperature does not require a higher coke rate,

while, in reality, they do.

For the data (mentioned as 'parameter' in the model description), we used average values of prices, costs and physical properties from different plants around the world. The values are listed in the Appendix.

2.3 Results

The four main variables that we will focus are:

- The purchased mass of low sulfur coal. The coal blend at coke plant is fixed at 80%. The 20% remaining can be filled with a low Sulphur coal (0.40%), a high Sulphur coal (0.95%) or a blend of the two.
- The amount of lime used to adjust the basicity of the blast furnace slag.
- The hot metal temperature that can range from 1490ºC to 1520ºC.
- The consumption of desulphurization flux.

Assuming that the decision is purely economic, we can easily estimate the cost of the removal of 0.001% of Sulphur in hot metal from the different variables that have an impact on it. The values shown in the following table have been calculated by varying the respective variable and dividing the cost difference by the percentage of Sulphur in hot metal.

Table 1. Variable X Costs

Variable	Cost, in $ / tonne of steel / 0.001%
Fluxes at desulphurization	0.005*
BF slag basicity	0.015
HM temperature	0.110
Coal blend	0.554

** As the flux consumption evolves non-linearly with the Sulphur, we present here an average value of the cost. What really matters is the order of magnitude*

It clearly appears that the cheapest way to desulphurize the hot metal is with desulphurization flux at the steel shop. Then come the slag basicity, the temperature of hot metal and, finally, the usage of low Sulphur coal.
We now look at the impact of the Sulphur on the desulphurization time and its relation to the steel production.

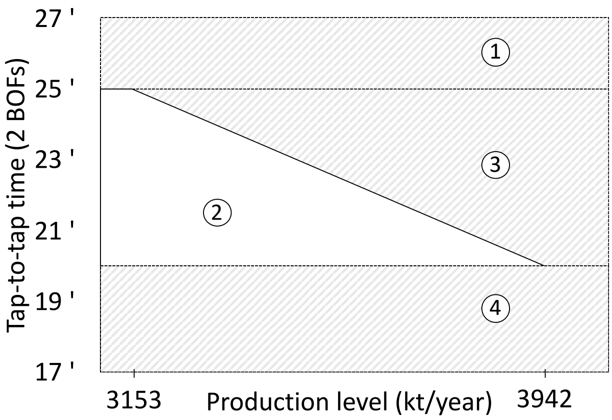

Figure 1. Average tap-to-tap time for two BOFs with respect to the production of crude steel

The tap-to-tap time at the converter is restricted by many factors. For this set of data, it has the shape shown in Figure 1. Based on it, we can distinguish four zones:

1. Above 25 min/heat, the process is too slow to guarantee a continuous casting.
2. In this zone, any tap-to-tap time is possible and fulfill all the restrictions.
3. The tap-to-tap times in this zone are not compatible for the production level (a minimum pace is required).
4. 20 min/heat, corresponding to 40 min/heat per BOF, is the minimum time for executing the main operations (charging, blowing, sampling and tapping).

This tap-to-tap has to be consistent with the desulphurization time that depends on the Sulphur content of hot metal (Figure 2).

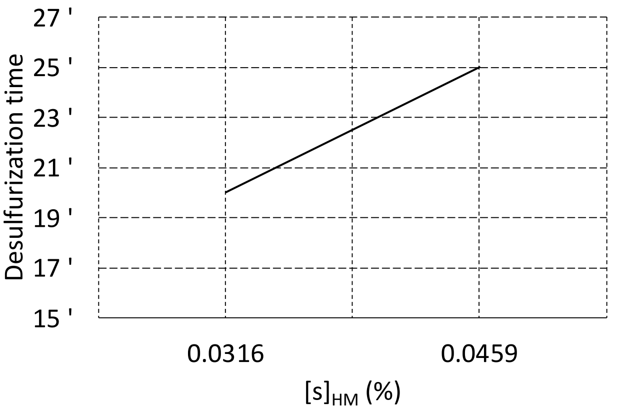

Figure 2. Desulfurization time with respect to Sulphur content in hot metal

Given the data and more specifically the cost of Sulphur removal and the process times presented above, the model suggested the strategy described in the Figure 3. The strategy varies with the production. Five ranges of production are observed:

1. Below that production level, the tap-to-tap time is constant and hence the strategy remains uniform: maximum of cheap/high Sulphur coal, low hot metal temperature and low basicity.
2. From there, the tap-to-tap time has to decrease (for production pace). The time reduction at desulphurization is obtained by increasing the slag basicity.
3. The slag basicity reached its maximum allowed. The hot metal temperature leaves its minimum value and increase progressively.
4. The HM temperature reached its maximum allowed. In order to reduce the desulphurization time, the cheap high Sulphur coal is progressively substituted by the expensive low Sulphur coal, in order to reduce the coke and hence hot metal Sulphur content.
5. It is not possible to produce more than that level, independently of the Sulphur content or any other variable.

These results guarantee the lowest production cost.

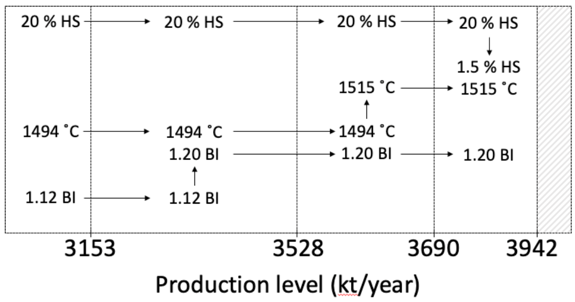

Figure 3. Sulphur strategy per production level

As a consequence of this strategy, we observe an evolution of the Sulphur content in coke and in hot metal, as shown in Figure 4.

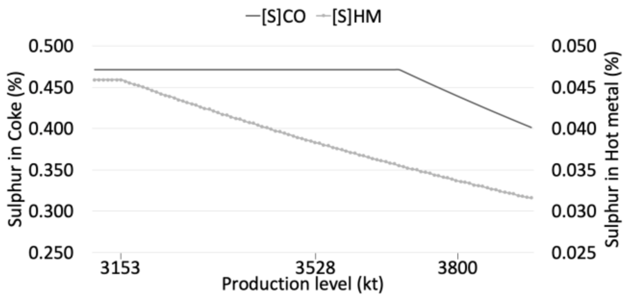

Figure 4. Sulphur content of coke and hot metal per production level

3 CONCLUSION

The results presented in this paper only have the purpose to illustrate the methodology of the mathematical model. They must not be used as conclusions to be implemented in any steel plant as they are. They highly depend on the data and on the coefficients of the equations used to represent the desulphurization in the blast furnace and the cost of temperature.

Also, due to the dependence on the production time, we expect the results to be highly sensitive to the layout of the steel shop.
The main conclusion of this paper is that the right desulphurization strategy of a plant should consider both the cost and the impact on the production time (hence the production level). It also shows that intermediate product quality should not be restricted by static specifications. The usage of a mathematical model is recommended to optimize this decision.

It is also important to emphasize that the variables that we used in this simplified model to illustrate their impact on the desulphurization strategy play a role in other strategic decisions. For instance, coke/coke oven gas production impacting the overall energy balance of the plant, slag basicity limited by alkalis in the furnace, HM temperature impacting the BOF thermal balance, Sulphur target in crude steel depending on the steel grades in the order book, etc.

4 ABBREVIATIONS

Table 2. Abbreviations

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CO	Coke
HM	Hot Metal
HS	High Sulfur coal
BI	Basicity Index

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APPENDIX

Parameter	Value	Unit
a	0.053	-
b	-0.6	-
$\boldsymbol{Bas^*_{slag}}$	1.1	-
c	-0.1	-
$\boldsymbol{D^{fix}_{De[S]}}$	10	min/heat
$\boldsymbol{D^{var}_{De[S]}}$	350	min/% S
$\boldsymbol{D_{horizon}}$	365	day
$\boldsymbol{D_{tap2tap}}$	40	min
K	0.31	-
$\boldsymbol{\ln(T^*_{hm})}$	3.17	-
$\boldsymbol{M_{heat}}$	150	t/heat
$\boldsymbol{m^{Si}_{SiO_2}}$	2.139	-
$\boldsymbol{M_{steel}}$	3000-3942	kt
$\boldsymbol{N_{BOFs}}$	2	-
$\boldsymbol{P^{S,\text{HIGH S}}_{coal}}$	0.95	%
$\boldsymbol{P^{S,\text{LOW S}}_{coal}}$	0.40	%
$\boldsymbol{P^{S,\text{MED S}}_{coal}}$	0.65	%
$\boldsymbol{P^{SiO_2}_{coke}}$	5	%
$\boldsymbol{P^{S}_{De[S]}}$	0.003	%
$\boldsymbol{P^{Si}_{hm}}$	0.5	%
$\boldsymbol{P^{S}_{inj}}$	0.36	%

$P_{inj}^{SiO_2}$	3	%
$P_{iron}^{SiO_2}$	3.5	%
$P_{slag}^{Al_2O_3}$	13	%
P_{slag}^{MgO}	8	%
$Price_{coal}^{\mathrm{HIGH}\,S}$	245	US$/t
$Price_{coal}^{\mathrm{LOW}\,S}$	285	US$/t
$Price_{coal}^{MED\,S}$	265	US$/t
$Price_{flux}$	80	US$/t
$Price_{Lime}$	20	US$/t
$Price_{temp}$	1	US$/t/°C
$Rate_{coke}$	350	kg/t
$Rate_{hm}$	950	kg/t
$Rate_{inj}$	150	kg/t
$Rate_{iron}$	1600	kg/t
T_{hm}^{*}	1500	°C
$\lambda^{\mathrm{HIGH}\,S}$	70	%
$\lambda^{\mathrm{LOW}\,S}$	72	%
$\lambda^{MED\,S}$	65	%
$\mu^{\mathrm{HIGH}\,S}$	80	%
$\mu^{\mathrm{LOW}\,S}$	80	%
$\mu^{MED\,S}$	80	%

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