Fuzzy Control of a Sintering Plant

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Abstract: Within an integrated steelwork, the industrial priorities in the automation of the sinter plant comprise stable production rate at the highest productivity level and classical control scheme may fail due to the complexity of the sinter process. The paper describes an approach exploiting a fuzzy rule-based expert system to control the charging gates of a sinter plant. Two different control strategies are presented and discussed within an innovative advisory system that supports the plant operators in the choice of the most promising action to do on each gate. Through the proposed approach the operators are supported by the system in the control of the plant: through a suitable exploitation of real-time data, the system suggests the most promising action to do, by reproducing the knowledge of the most expert operators. Thus, this approach can also be used to train new technicians before involving them in the actual plant operations. The performance of the strategies and the goodness of the system have been evaluated for long time in the sinter plant of one of the biggest integrated steelworks in Europe, namely the ILVA Taranto Works in Italy.

1 INTRODUCTION

Within a steelwork, the sintering process is a central operation in the production cycle: the treatment is basically a high temperature process that starts from raw materials mixture (such as fine iron ores) and produces a particular form of agglomerate material known as sinter, which is one of the material fed to the blast furnace in order to produce the pig iron, which is subsequently refined in the steel shop to produce the liquid steel.

The sintering process is articulated into a series of standard operations. A first preliminary task is the acceptation and the storage of the iron-bearing raw materials in the ore stockyard followed by the crashing and the screening of these raw materials. Then, the following phases which are more specific of the sintering process can be pointed out: (I) raw materials are mixed together with water and then granulated into a pseudo-particles in a rotary mixer drum and then stocked in a feed hopper; (II) after the hopper, the moistened mix passes through the charging gates and it is accumulated just before a leveler that strips out the exceeding material; thus the moistened mixture is charging as a layer onto continuously moving pallet-cars called "strand"; (III) after the ignition of the material close to the charging zone, the burning process is propagated by chemical reaction thanks to the air sucked through the strand by the so-called *wind boxes*, that are depressurised air ducts mounted below the strand; (IV) at the end of the strand the solidified agglomerate is broken within a crusher and cooled within a cooler strand; (V) finally the cooled material is conveyed to a second crusher in order to obtain a suitable size of the particles of the final sinter.

The overall process must be controlled in order to ensure that all the mix is burned just earlier than being discharged into the crusher. The points at which the flame front reaches the base of the strand are called "burn-through points" (BTPs). Thus, among the aims of the control process of the plant, two of them are of considerable interest and can be summarized as follows: to ensure that the BTPs are aligned in the transversal direction of the strand and to ensure that this alignment happens just earlier than the discharge. As a matter of fact, a uniform flame front is guaranteed to the former condition while the latter one optimizes the production capacity of the plant. In fact there is an evident waste of productivity of the plant

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if the BTPs occur too early compared to the end of the process; analogously, the quality of the sinter lowers if the burning process is not completed before the discharge and this fact negatively affects the production rate of the overall steel plant and the following production stages.

Predictive capabilities have been used to develop control schemes controlling the speed of the strand. In (Kanjilal and Rose, 1986) the prediction of the waste gas temperature is used to manipulate the strand speed, while in (Hu and Rose, 1997) the same variable is controlled using a process model identified from the observed data. A different perspective is presented in (Arbeithuber et al., 1995), where the control scheme tries to keep the temperature distribution at the end of the plant on a pre-defined curve in order to yields a target BTP. Also in this case the manipulated variable is the strand speed.

The new approach presented in the paper is based on fuzzy rule-based expert systems and exploits the charging gates as controlled variables. Two different control strategies will be presented and discussed as well as an innovative advisory system that supports the plant operators in the control of the plant.

The paper is organized as follows. Section 2 describes the two control strategies while the advisory system is presented in Section 3. Section 4 presents the results of the on-the-plant tests and the Section 5 is devoted to the conclusion.

2 CONTROL STRATEGIES

Some mathematical models have been developed in order to cope with the dynamic of the sintering process in an analytical way. A first attempt has been made in (Young, 1977) while a different perspective has been developed in (Augustin et al., 1995) and (de Castro et al., 2012). A different approach based on multiple-valued logic is the core of the present paper and concepts of fuzzy sets (Zadeh, 1965), fuzzy control (Lee, 1990) (Pedrycz, 1989) (Passino and Yurkovich, 1998) and expert systems (Jackson, 1998) (Durkin, 1998) are used to develop the strategies and to build the advisory system.

2.1 Overview of the Sintering Machine

The transversal direction of the strand can be divided into four segments denoted by A, B, C and D. Each of them covers the overall length of the machine and it is about one meter wide, so that they cover the overall

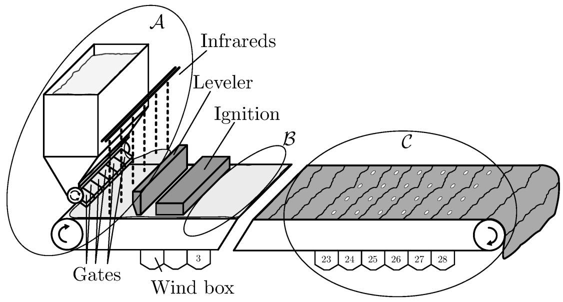

Figure 1: Sketch of the macro-zones $\mathcal{A}, \mathcal{B}$ and $\mathcal{C}$ of the plant.

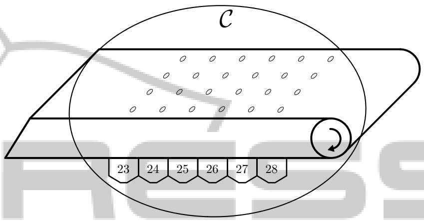

Figure 2: Sketch of the grid of thermocouples.

width of the strand. Regarding the longitudinal direction, three different macro-zones can be pointed out as depicted in Figure 1 and described in the following:

- charging zone ($\mathcal{A}$) at the very beginning of the strand;
- permeabilities zone ($\mathcal{B}$) after the ignition hood at the 3rd wind box;
- burn-through points zone ($\mathcal{C}$) at the end of the bed covering a wide area of about 48 m^2.

Within the macro-zone $\mathcal{A}$ the feed hopper, 6 charging gates and 6 infrared sensors can be found, while the permeability sensors, which take 4 different permeability measurements along the transversal direction of the strand and that are indicated in the following as K_A, K_B, K_C, K_D, are located within the macro-zone $\mathcal{B}$. Finally, in the last zone ($\mathcal{C}$) a regular grid of thermocouples has been installed, such as depicted in Figure 2 that measures 24 temperature values: among them, the maximum one of each segment is the associated BTP, thus finally there are 4 BTP values indicated as BTP_A, BTP_B, BTP_C, BTP_D.

From the point of view of the plant operational practice, it would be advisable that the maximum value of temperature is reached for all the segments in correspondence to approximately the same distance from the strand end, as this implies that the sintering process is quite homogeneous in all the portions of the strand itself.

A preparatory statistical analysis conducted on historical data coming from the plant has put into evidence that the transversal alignment of

$BTP_A, \dots, BTP_D$ is related to a specific configuration of $K_A, \dots, K_D$. Thus, the idea behind the strategies is to control the charging gates in order to obtain the suitable permeability configuration in the macro-area $\mathcal{B}$.

Indeed, as the permeability configuration is supposed to be symmetric, the difference between the external permeabilities (K_A, K_D) and the internal ones (K_B, K_C) can leads to crucial information about the suitable configuration to be obtained.

Thus, in order to pursue such investigation, the following 4 permeability ratios ($\mathbf{K}_r$) have been defined:

$$(r_1, r_2, r_3, r_4)^T = \left(\frac{K_A}{K_D}, \frac{K_B}{K_C}, \frac{K_A}{K_B}, \frac{K_D}{K_C}\right)^T. \tag{1}$$

2.2 Description of the Strategies

Two control strategies have been designed, which both aim at maximizing the increase of the average permeability. The first strategy ('a') takes into account only this target; the second one ('b') takes also into account the stress on the actuator and tries to minimize the movement of each gate, namely, if more actions involving different gates are equally physically feasible, this latter strategy suggests the action that produces the minimum displacement of the gates from their current position.

Variables and symbols for both strategies are summarized in Table 1 and a description of the first strategy ('a') is the following:

1. **Gates and Infrared Indices:** the gate and the infrared values are normalized using its operative limits ($G_{\min}$, $G_{\max}$, $IR_{\min}$, $IR_{\max}$);
2. **Control Coefficients:** four control coefficients that express the contribution of each couple of gates (i.e. 1,2 - 2,3 - 4,5 - 5,6) on each segment of the bed are computed using the above indices;
3. **Action Indices:** four "action-indices" that contain the information about the operations to perform on each couple of gates (e.g. a value less than zero indicates that the gates of a couple need to be closed) are computed and limited between suitable thresholds ($c_{\min}$, $c_{\max}$);
4. **Targets Computation:** four different target permeability profiles, namely 4 different vectors of 4 entries each, are obtained using the permeability ratios $\mathbf{K}_r$; the i-th element of the i-th vector is obtained by imposing $\mathbf{K}_{K_i}^{\text{target}}(i) = \mathbf{K}_t(i)$ while the other elements are calculated using $\mathbf{K}_r$; the equations (2) show the computations for the first ($i = 1$) profile:

$$\mathbf{K}_{K_1}^{\text{target}}(1) \stackrel{\text{def}}{=} K_A^{\text{target}} = \mathbf{K}_t(1) \equiv K_A \tag{2a}$$
$$\mathbf{K}_{K_1}^{\text{target}}(2) \stackrel{\text{def}}{=} K_B^{\text{target}} = K_A^{\text{target}}/r_3 \tag{2b}$$
$$\mathbf{K}_{K_1}^{\text{target}}(3) \stackrel{\text{def}}{=} K_C^{\text{target}} = K_B^{\text{target}}/r_2 \tag{2c}$$
$$\mathbf{K}_{K_1}^{\text{target}}(4) \stackrel{\text{def}}{=} K_D^{\text{target}} = K_A^{\text{target}}/r_1 \tag{2d}$$

where the relation (2a) concern the imposed elements ($i = 1$), while the formulas (2b)-(2d) concern the computed elements of the profile;

5. **Gaps Between Current and Target:** for each target profile the gaps between the current profile and the target is evaluated, obtaining 4 different vectors of 4 entries each that are computed according to the following equations, where $i = 1, \dots, 4$:

$$\mathbf{K}_{K_i}^{\text{gaps}}(1) = K_A - \mathbf{K}_{K_i}^{\text{target}}(1) \tag{3a}$$
$$\mathbf{K}_{K_i}^{\text{gaps}}(2) = K_B - \mathbf{K}_{K_i}^{\text{target}}(2) \tag{3b}$$
$$\mathbf{K}_{K_i}^{\text{gaps}}(3) = K_C - \mathbf{K}_{K_i}^{\text{target}}(3) \tag{3c}$$
$$\mathbf{K}_{K_i}^{\text{gaps}}(4) = K_D - \mathbf{K}_{K_i}^{\text{target}}(4) \tag{3d}$$

6. **Control Amount for Each Couple of Gates:** for each vector of gaps the control amount values to be applied on each couple of gates is calculated by obtaining four vectors with four elements each;
7. **Calculate the Feasibility:** for each target profile a feasibility coefficient is computed informing if the related action on the couple of gates are physically feasible or not (e.g. it is required to close a gate that it is already completely closed);
8. **Calculate the Increase of the Average Permeability:** for each target profile the gains of the average values are evaluated in order to use these values as performance indicators; each of them is related to a vector of control amount values so that the better the control on the gates the *higher* will be the index.
9. **Select the Actions:** among some target profile all equally physically feasible, it is selected the one which optimizes the performance indicator gaining the four control amount values denoted by u_{12}, u_{23}, u_{45} and u_{56}.

In Figure 3 the conceptual diagram of control strategy 'a' is reported.

The description of strategy 'b' is similar to the one of the strategy 'a' where the point 8 is modified as follows:

8. **Calculate the Stress on the Actuator:** for each target profile, the stress produced on the actuator is evaluated by summing the overall gaps of the

Table 1: Symbols used within the control strategies.

Symbol	Meaning†
$\mathbf{G}_t$	Opening percentage of the gates
$\mathbf{IR}_t$	Measure of the height of the sinter bed along the transversal direction
$\mathbf{K}_t$	Permeability values i.e. $\mathbf{K}_t=(K_1,\ldots,K_4)^T \equiv (K_A,\ldots,K_D)^T$
$\mathbf{K}_r$	Permeability ratios i.e. $\mathbf{K}_r \equiv (r_1,r_2,r_3,r_4)^T$
$\mathbf{K}_{K_i}^{\text{target}}$	Permeability values computed using $\mathbf{K}_r$ by imposing $\mathbf{K}_{K_i}^{\text{target}}(i)=\mathbf{K}_t(i),\, i=1,\ldots,4$
$G_{\min}, G_{\max}$	Working range limits of the gates
$IR_{\min}$, $IR_{\max}$	Minimum and maximum allowed height of the sinter bed
$c_{\min}$, $c_{\max}$	Suitable thresholds
$\mathbf{Y}$	Selected control actions

†where $(\cdot)_t$ means that the values are taken at the current time instant i.e. they are on-line values.

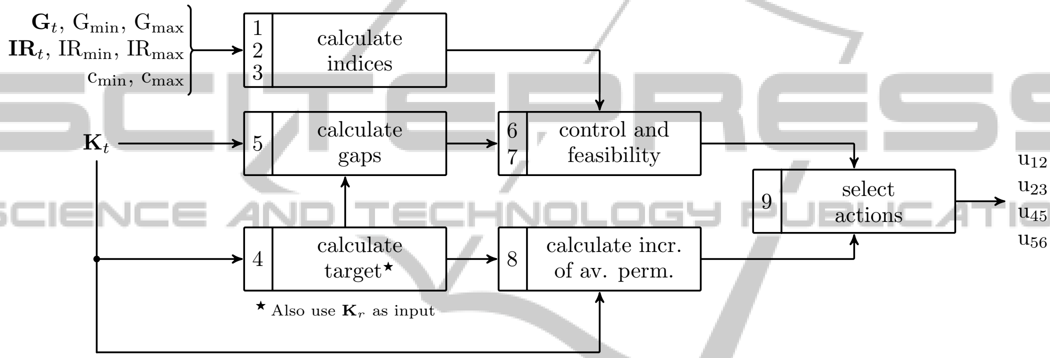

Figure 3: Conceptual scheme of the first control strategy.

profile[1] in order to use these values (one for each target profile) as performance indicators; each of them is related to a vector of control amount values so that the better the control on the gates the *lower* will be the index.

Thus, the conceptual diagram of the second control strategy is analogous to the one of the strategy 'a' except for the block number 8.

3 ADVISORY SYSTEM

The new value of the gates, required to reach the target permeability profile, can be computed through the following relations:

$$\mathbf{G}^{\text{new}}(1) = \mathbf{G}_t(1) + 0.5u_{12} \ , \tag{4a}$$
$$\mathbf{G}^{\text{new}}(2) = \mathbf{G}_t(2) + 0.5u_{12} + 0.5u_{23} \ , \tag{4b}$$
$$\mathbf{G}^{\text{new}}(3) = \mathbf{G}_t(3) + 0.5u_{23} \ , \tag{4c}$$
$$\mathbf{G}^{\text{new}}(4) = \mathbf{G}_t(4) + 0.5u_{45} \ , \tag{4d}$$
$$\mathbf{G}^{\text{new}}(5) = \mathbf{G}_t(5) + 0.5u_{45} + 0.5u_{56} \ , \tag{4e}$$
$$\mathbf{G}^{\text{new}}(6) = \mathbf{G}_t(6) + 0.5u_{56} \tag{4f}$$

[1]In fact, the gaps are related to the distance between the current and the desired position of the gates.

where the coefficient of each term has been set heuristically using the knowledge of the technicians' expertise.

Comparing the new values of the gates with the current values, the advisory system is able to provide information about the actions to be performed on *all* of the charging gates. The actions are also related to a rank number in order to inform about the most promising of them.

The advisory system is an expert system (ES) founded on multiple-valued logic with a rule base that reproduce the knowledge of the plant operators. Thus the system belongs to the larger family of the Fuzzy Rule-Based Expert Systems (FRBES) (Geyer-Schulz, 1995).

The system is designed using the zero-order Takagi-Sugeno-Kang (TSK) model (Takagi and Sugeno, 1985) where the j-th fuzzy rule (R_j) of the form "IF $\langle$*premise*$\rangle$ THEN $\langle$*conclusion*$\rangle$" is given by:

$$R_j: \ \text{IF } (x \text{ is } A_i) \text{ AND/OR } (y \text{ is } B_i) \text{ THEN } z_j = c_j \tag{5}$$

where x and y are the inputs, A_i and B_i are fuzzy sets and c_j is a crisp adjustable parameter.

The system evaluates each rule (*implication*) collecting together the results (*aggregation*) in order to

Table 3: Characteristic parameters μ and σ of the linguistic terms.

	$FIS_{1,3,4,6}$		$FIS_{2,5}$		
	DG	DGN	DG	DGSx	DGDx
NEG	$-1, 0.34$	$-1, 0.34$	$-1, 0.34$	$-1, 0.34$	$-1, 0.34$
NUL	$0, 0.1$	$0, 0.1$	$0, 0.16$	$0, 0.14$	$0, 0.13$
POS	$1, 0.34$	$1, 0.34$	$1, 0.34$	$1, 0.34$	$1, 0.34$

Table 4: Rules for the $FIS_{1,3,4,6}$.

	DGN is NEG	DGN is POS	DGN is NUL
DG is NEG	-1	0	-1
DG is POS	0	1	1
DG is NUL	0	0	0

produce a unique output fuzzy set. The crisp value extracted from this fuzzy set (*defuzzification*) represents the output of the entire inference process.

The aggregation and the defuzzification tasks can be merged in a unique operation in the TSK model as follows:

$$z = \frac{\sum_{j=1}^{N} w_j c_j}{\sum_{j=1}^{N} w_j}, \text{ with } w_j = F(\mu_i, \nu_i) \tag{6}$$

where N is the number of rules, w_j is the firing strength of the j-th rule (i.e. the "degree of truth" of the $\langle premise \rangle$), F is the method that implements the AND operator (F is a t-norm) or the OR operator (F is a t-conorm), μ_i is the membership degree of x to A_i and ν_i is the membership degree of y to B_i.

The system is composed of 6 specialized fuzzy inference systems (FISs), one for each gate (FIS_i, $i = 1, \ldots, 6$), whose inputs are the differences $\Delta G_i = \mathbf{G}^{\text{new}}(i) - \mathbf{G}_t(i)$ (after a proper normalization stage forcing any crisp input to lie in the range $[-1, 1]$).

Moreover, ΔG_2 is in input to both the FIS_1 and the FIS_3 as additional input as well as ΔG_5 is in input to both the FIS_4 and the FIS_6. These additional gaps will be denoted by the DGN term within the rules.

The FIS_2 has ΔG_1 and ΔG_3 as additional inputs as well as the FIS_5 receives ΔG_4 and ΔG_6. These additional gaps will be denoted, respectively, by the DGDx and DGSx terms within the rules. Table 2 summarizes the inputs of each FIS.

Table 2: Inputs of each fuzzy inference system.

	ΔG_1	ΔG_2	ΔG_3	ΔG_4	ΔG_5	ΔG_6
FIS_1	•	•				
FIS_2	•	•	•			
FIS_3		•	•			
FIS_4				•	•	
FIS_5				•	•	•
FIS_6					•	•

The inputs of the $FIS_{1,3,4,6}$ are 2 linguistic variables, while the inputs of the $FIS_{2,5}$ are 3 linguistic variables. For each input variable, 3 linguistic terms (i.e. fuzzy sets) are defined: 'Negative' (NEG), 'Null' (NUL) and 'Positive' (POS). The membership functions of all the fuzzy sets are bell-shaped functions whose parameters (μ, σ) have been heuristically set as described in Table 3.

The rule bases for the systems have been obtained after fruitful discussions with the plant operators and considering also the operative practices of the operators too.

All the rules for the $FIS_{1,3,4,6}$ are shown in Table 4 while in Table 5 to 7 are shown the rules for the $FIS_{2,5}$.

In all the rule bases the numerical value of the output means that the gate must be closed (-1) or opened (1) or, finally, that no operation must be performed on the gate (0). The $\prod(x, y) = x * y$ operator is the t-norm that implements the AND connection of each rule and the relation (6) is used to defuzzify the inferred output fuzzy set.

4 EXPERIMENTAL RESULTS

Two different scenarios have been considered for the plant tests. The first one ("short period scenario") takes into account a period of 4 hours using the strategy 'a' for the first 2 hours and the strategy 'b' during the last 2 hours.

Some characteristic conditions can be highlighted during the tests within this scenario: (a) no stoppage of the strand occurred; (b) the percentages of lime and limestone within the mix were fixed; (c) the ratio between the speed of the drum feeder and the speed of the strand was constant; (d) the moisture of the mix was kept as constant as possible.

The qualitative results of the first session showed that the strategy 'a' leads to an actual increment of the average permeability and thus to a better yield of

Table 8: Time intervals of the long period tests.

Test number	Duration (h)	Time interval	Control Strategy
1	12	Day 1 (from 00:00 to 12:00)	Technicians Expertise
2	12	Day 1 (from 12:00 to 00:00)	‘a’
3	12	Day 2 (from 00:00 to 12:00)	Technicians Expertise
4	12	Day 2 (from 12:00 to 00:00)	‘b’
5	12	Day 3 (from 00:00 to 12:00)	Technicians Expertise
6	12	Day 3 (from 12:00 to 00:00)	‘a’
7	12	Day 4 (from 00:00 to 12:00)	‘b’

Table 5: Rules for the $FIS_{2,5}$ when DGSx is POS.

DGSx is POS			
	DGDx is NEG	DGDx is POS	DGDx is NUL
DG is NEG	0	0	-1
DG is POS	0	1	0
DG is NUL	0	0	0

Table 6: Rules for the $FIS_{2,5}$ when DGSx is NUL.

DGSx is NUL			
	DGDx is NEG	DGDx is POS	DGDx is NUL
DG is NEG	0	-1	-1
DG is POS	1	0	1
DG is NUL	0	0	0

Table 7: Rules for the $FIS_{2,5}$ when DGSx is NEG.

DGSx is NEG			
	DGDx is NEG	DGDx is POS	DGDx is NUL
DG is NEG	-1	0	0
DG is POS	0	0	1
DG is NUL	0	0	0

the plant: this can be assessed considering the lower Internal Return Fines (IRFs) consumption and thus a lower wet coke consumption.

During the tests, the plant operators confirmed that: (i) the actions proposed by the system have been always fully safe despite the change of the operational conditions in which each decision has been taken; (ii) the operations have been always coherent with the personnel's expertise. Thus, in the short period the advisory system proved to behave according to the best practice of the operators. Therefore, it is expected that, in the long period, the automatic implementation of such system will lead to improvement of the process performances with a reduction of the operators' effort.

The second scenario (“long period scenario”) considers a period of 84 hours and compares the system behavior during intervals when one of the developed control strategies was applied to intervals when none of them was used and the plant was controlled by exploiting only the expertise of the plant technicians. The detailed description of each period of time is summarized in Table 8.

The long period of eighty-four hours is the best one that can be obtained minimizing the external influences such as, for example, a different chemical composition in the mix caused by a different Blend Iron Ore (BIO) in the mix. In Taranto, in fact, the typical amount of BIO is of 160000-180000 tonnes and they are used within the mix during a typical period of five days. Thus, the tests have been performed after a suitable stabilization period after the change of the BIO. Moreover, during the first day of the long period test a significant stoppage of the strand occurred. In order to take this fact into account, the results have been computed by using only the data deriving from a stable condition of the process (i.e. about 90 min. after the restart).

Let ΔS be the amount of the produced sinter (in tonnes), σ_C the specific coke consumption (i.e. the amount of the coke consumption - measured in Kg - per tonne of produced sinter) and σ_{IRF} the specific IRF production (i.e. the amount of produced IRFs production - measured in Kg - per tonne of produced sinter); 3 significant Key Performance Indicators (KPIs) can be defined as follows (where $(\cdot)/h$ means “per hour”):

$$\mathrm{KPI}_1 \text{ i.e. Sinter Production } = \frac{\Delta S}{h} \ , \tag{7a}$$

$$\mathrm{KPI}_2 \text{ i.e. Wet Coke Consumption } = \frac{\sigma_C}{h} \ , \tag{7b}$$

$$\mathrm{KPI}_3 \text{ i.e. IRF Production } = \frac{\sigma_{IRF}}{h} \ . \tag{7c}$$

In order to evaluate the goodness of the results the trends of the KPIs have been evaluated. In particular, the IRFs production that can be related directly to the yield of the plant through the following equation:

$$\mathrm{Yield}(\%) = 100 - 0.1\,\sigma_{IRF} \ . \tag{8}$$

The results of the long period tests are numerically described in Table 9: using the strategy ‘a’ an average increment of the produced sinter and an average

Table 9: Experimental results.

Control Strategy	KPI_1	KPI_2	KPI_3
Expertise	4.25	-0.019	6.60
Strategy ‘a’	2.38	-0.236	-6.75
Expertise	-6.25	0.208	4.66
Strategy ‘b’	1.45	-0.062	-2.50
Expertise	-1.18	0.048	2.17
Strategy ‘a’	3.92	-0.015	-0.43
Strategy ‘b’	-5.76	-0.231	-0.93
Expertise (mean)	-1.06	0.08	4.48
Strategy ‘a’ (mean)	3.15	-0.13	-3.59
Strategy ‘b’ (mean)	-2.16	-0.15	-1.72

reduction of the coke consumption as well as of the IRFs production have been gained. The strategy ‘b’, on the other hand, led to comparable results regarding the coke consumption and the IRFs production, but caused an average decrement of the productivity.

During both the short and the long period tests the opinions of the technicians have been taken into account in order to evaluate the practical goodness of the strategies as well as the KPI’s variations.

The behaviour most frequently used by the plant experts was very similar to that of the strategy ‘b’ and in contrast with the strategy ‘a’. Indeed, the strategy ‘a’ takes into account only the average permeability and whenever a variation of the gates position is required in order to improve the permeability, the variation is reported to the gates. This leads to frequent variation in the gates positions and sometimes in abrupt changes. The technicians, on the other hand, use a more conservative approach that tends to perform slight modification in the gates position and rarely abrupt changes.

Summing up the results of the tests of the two control strategies: strategy ‘a’ gives better automatic results, but it is less coherent to the technicians’ standard operating practice, thus they can experience higher efforts in order to follow the plant behavior when this control strategy is applied. Strategy ‘b’ leads to fairly good results, but it is more coherent to the standard operating practice.

Finally, it can be noticeable that the advisory system has been designed to be improved through its use, as the overall software system supports data collection and analysis. After a longer period of use it will be possible to refine the performances of the proposed system using the same statistical parameters that supplied the system.

5 CONCLUSION

A new approach based on fuzzy rule-based expert systems and a new advisory system to control the charging gates of a sinter plant is presented. Two new control strategies have been developed and tested on the field.

Strategy ‘a’ is more invasive within the process operational conditions, as it aims at maximizing the productivity without any kind of trade-off. It can be used when the plant is characterized by lower productivity (e.g. the plant is restarted after a stoppage): in these cases the greater the control amount, the shorter the time elapsed before reaching fair operating conditions.

On the other hand, strategy ‘b’ is more conservative, as it aims at maximizing the productivity but considers also the stress on the gates’ actuators and produces less perturbation in the operating conditions with respect to the other strategy. It can be used when the plant is characterized by higher productivity and the machine shows a higher sensitivity to the changes on the gates.

Real-time tests are still ongoing at the sintering plant of ILVA S.p.A. (Taranto Works, Italy) and satisfactory results confirm the goodness of the automatic control system.

Future work will deal with the development of a new strategy combining the strong points of the two developed ones. In detail, this strategy can select automatically the use of the strategy ‘a’ during the lower productivity phase of the plant switching on the other strategy (‘b’) during the phase with high productivity and vice-versa. In this way a single strategy can take the best advantages from the two developed ones achieving good results during all the production phase of the plant.

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REFERENCES

Arbeithuber, C., Jörgl, H. P., and Raml, H. (1995). Fuzzy control of an iron ore sintering plant. *Control Engi-*

neering Practice, 3(2):1669–1674.

Augustin, M., Arbeithuber, C., and Jörgl, H. P. (1995). Modeling and simulation of an iron ore sinterstrand. In *EUROSIM*, pages 873–878.

de Castro, J. A., Sazaki, Y., and Yagi, J. (2012). Three dimensional mathematical model of the iron ore sintering process based on multiphase theory. *Materials Research*, 15(6):848–858.

Durkin, J. (1998). *Expert Systems: Design and Development*. Macmillan Publishing Company.

Geyer-Schulz, A. (1995). *Fuzzy Rule-Based Expert Systems and Genetic Machine Learning*. Physica-Verlag.

Hu, J. Q. and Rose, E. (1997). Predictive fuzzy control applied to the sinter strand process. *Control Engineering Practice*, 5(2):247–252.

Jackson, P. (1998). *Introduction to Expert Systems*. Addison Wesley, 3rd edition.

Kanjilal, P. P. and Rose, E. (1986). Application of adaptive prediction and control method for improved operation of the sintering process. *Ironmaking and Steelmaking*, 13(6):289–293.

Lee, C. C. (1990). Fuzzy logic in control systems: Fuzzy logic controller - parts 1 and 2. *IEEE Transactions on Systems, Man and Cybernetics*, 20(2):404–435.

Passino, K. M. and Yurkovich, S. (1998). *Fuzzy Control*. Addison Wesley.

Pedrycz, W. (1989). *Fuzzy Control and Fuzzy Systems*. Research Studies Press Ltd.

Takagi, T. and Sugeno, M. (1985). Fuzzy identification of systems and its applications to modelling and control. *IEEE Transactions on Systems, Man and Cybernetics*, 15(1):116–132.

Young, R. W. (1977). Dynamic mathematical model of a sintering process. *Ironmaking and Steelmaking*, 4(6):321–328.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, 8:338–353.