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Application of Advanced Process Control techniques to a pusher type reheating furnace

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Abstract. In this paper an Advanced Process Control system aimed at controlling and optimizing a pusher type reheating furnace located in an Italian steel plant is proposed. The designed controller replaced the previous control system, based on PID controllers manually conducted by process operators. A two-layer Model Predictive Control architecture has been adopted that, exploiting a chemical, physical and economic modelling of the process, overcomes the limitations of plant operators' mental model and knowledge. In addition, an ad hoc decoupling strategy has been implemented, allowing the selection of the manipulated variables to be used for the control of each single process variable. Finally, in order to improve the system flexibility and resilience, the controller has been equipped with a supervision module. A profitable trade-off between conflicting specifications, e.g. safety, quality and production constraints, energy saving and pollution impact, has been guaranteed. Simulation tests and real plant results demonstrated the soundness and the reliability of the proposed system.

1. Introduction

Steel industry is aimed to the production of quality products, based on various types of raw material as input, e.g. billets or slabs. Complex physical and chemical reactions take place in the production chain, requiring specific control and monitoring strategies. Final products consist in steel bars, e.g. iron rods that then can be used in different fields [1], [2].

In the last decades, the considerable development of technology resulted in a rising level of automation in the process industries. Traditional control systems, e.g. PID controllers manually run by plant operators, cannot guarantee optimality in this new context. Optimality call for finding a profitable trade-off between opposing specifications: product quality increasing and safety constraints meeting versus energy saving and pollution impact decreasing. In order to balance these conflicting requirements, Advanced Process Control (APC) solutions have been proposed and applied [3].

This work proposes an APC system design for the control and the optimization of a pusher type reheating furnace located in an Italian steel industry. A two-layer Model Predictive Control (MPC) strategy has been adopted that overcomes the limitations of plant operators' mental model. A suited cooperation between the two layers, together with their collaboration with a supervision module, assures a flexible and resilient control, able to manage most critical situations. Moreover, an ad hoc decoupling strategy has been implemented, allowing the inhibition of specific manipulated variables

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for the control of selected process variables. In particular, two equivalent mathematical approaches to obtain this feature are proposed and detailed.

The designed APC system has been tested on simulation and applied on the considered steel plant.

The present paper is organized as follows: a detailed description of the process, together with its control specifications, is given in section 2; section 3 explains the designed APC architecture, focusing on the adopted MPC solution. In section 4, the proposed decoupling strategy and its mathematical formulations are described while in section 5 simulations and practical results are resumed. Finally, conclusions are given in section 6.

2. Pusher type reheating furnace description and modelling

This section gives a detailed description of the considered unit of the Italian steel industry, i.e. its pusher type reheating furnace. In addition, control specifications and the consequent adopted modelling of the considered process are reported.

2.1. Focusing on the process features

The considered steel industry processes billets, that is small steel bars at an intermediate stage of manufacture. The production flow can be summarized as in figure 1.

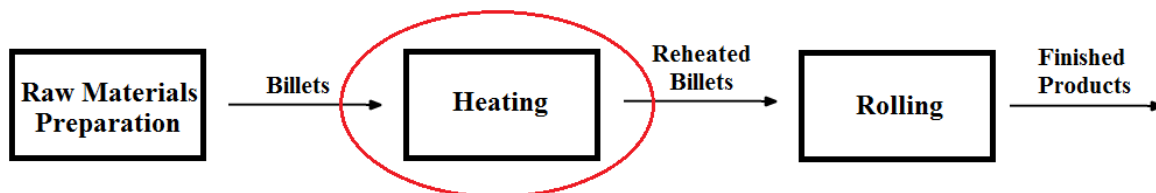


Figure 1. Schematic representation of the considered steel industry production chain.

In the initial phase, billets are prepared for their entry in a reheating furnace where the heating process takes place. In the furnace billets are reheated following a temperature profile guaranteeing a given exit temperature. After the exit from the furnace, the reheated billets are conveyed to the rolling mill stands. In this last stage of the production chain, the billets are subjected to a plastic deformation: in this way finished products, e.g. iron rods, are obtained.

This work is focused on the heating phase of the just described process (see figure 1). This production phase plays the most important role in steel industry, in terms of products quality, environmental impact and energy saving.

In figure 2, the reheating furnace is represented: the billets enter the furnace from the left side and they are moved along it by pusher tools, giving the name *pusher type* to the analyzed reheating furnace. Inside the furnace billets are subjected to a (re)heating process; conduction, convection and radiation heat exchanges occur in the furnace chambers where the billets transit. Oxy reactions are performed by fuel burners. The billets input temperature is variable, ranging from 50 °C to 300°C,

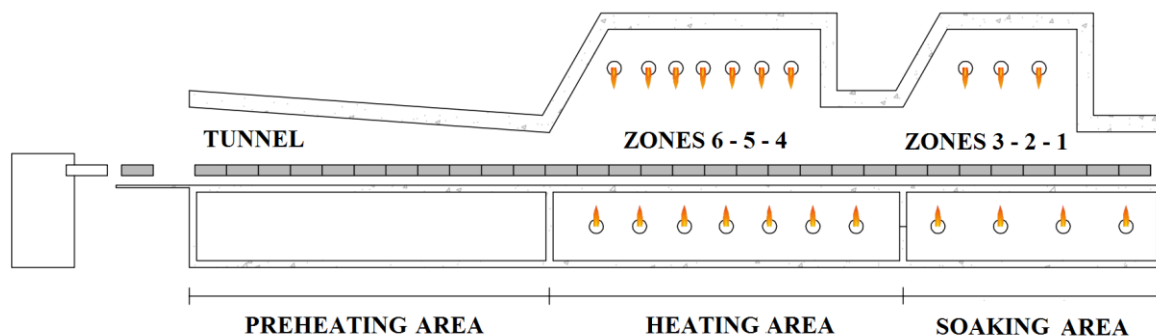


Figure 2. Schematic representation of the considered pusher type reheating furnace.

while their output temperature must be contained within the range 1000 °C – 1100 °C. On the basis of the local temperatures, the considered furnace can be divided into three different areas (see figure 2):

- *Preheating area*: this furnace area is the only one with no burners (see figure 2); hot gasses resulting from downstream areas are conveyed to this area, allowing the billets preheating. The chamber of this area, called *tunnel*, exhibits temperatures varying from 700 °C to 800 °C.
- *Heating area*: in this area, the most crucial phase of the billets reheating process takes place; here there are three chambers, named from the entry to the exit *zone 6*, *zone 5* and *zone 4*. Each of these chambers is equipped with an own burner; in this area, temperature may vary from 900°C to 1150 °C.
- *Soaking area*: it is the last furnace area, composed by three chambers, named from the entry to the exit *zone 3*, *zone 2* and *zone 1*. Each of these chambers is equipped with an own burner; in this area, temperature may vary from 1120°C to 1230 °C.

2.2. Process and control specifications

The most challenging requirement in a pusher type reheating furnace is the research of an optimal equilibrium between reheated billets quality and the binomial of energy saving and pollution impact decreasing, tied to fuel consumption minimization; billet quality requires homogeneous internal and external exit temperatures. Besides, safety constraints have to be fulfilled. Through several meetings with plant managers and engineers, these objectives have been converted into the following practical plant control specifications:

- minimization of air/fuel ratios, according to nominal stoichiometry; in this way a proper conduct of the process thermo-dynamical reactions is guaranteed;
- meeting of the assigned furnace temperature constraints, in order to assure a smooth billets heating process;
- compliance with safety constraints related to smoke-exchanger temperature, which is measured at beginning of the tunnel;
- minimization of fuel consumption.

For the regulation of the temperature of each zone of the furnace, an additional feature was required by plant engineers that consisted in the utilization of the zone own burner as sole control variable. This specification forces the neglecting of the physics of the process: in fact, the temperature of each zone is also influenced by the heat of the downstream zones. The only zone that is controlled acting on other zones burners is the tunnel, clearly due to the absence of power supplies: plant engineers required exploiting, as control variables, zone 6 and zone 5 burners. To fulfil this specific request, a decoupling strategy has been created, as will be detailed in section 4.

After this initial phase regarding control specifications, a key stage consisted in the selection of the input and output control variables together with measured disturbance input variables. These variables, in the industrial framework, are usually referred as Manipulated Variables (MVs), Controlled Variables (CVs) and Disturbance Variables (DVs), respectively. Fuel flow rate and stoichiometric ratio of each zone of the furnace have been selected as MVs. Temperature of each zone, fuel valves opening (per cent), temperature difference between adjacent zones and smoke-exchanger temperature have been chosen as CVs. Finally, furnace pressure, furnace production rate and air pressure have been selected as DVs. Based on the chosen MVs, CVs and DVs, an identification procedure with a black box approach has been fulfilled, in order to obtain reliable CVs-MVs and CVs-DVs dynamic models for the controller formulation: first order strictly proper linear models without delays have resulted from this phase [4], [5]. The obtained models consider deviations of MVs, DVs and CVs vectors from a vectors triplet (u_0, d_0, z_0 respectively), representing an operating point of the considered process. During the identification phase, the sampling time has been set to one minute; consistently, the APC cycle time has been set to one minute. The variables considered (see sections 4 - 5) for the proof of the proposed decoupling strategy are summarized in tables 1–2 –3.

Table 1. The selected MVs.

TAG	Variable Name	Acronym [Units]
PTRF_F06	Zone 6 Fuel	<i>Fuel 6 [Nm3/h]</i>
PTRF_F05	Zone 5 Fuel	<i>Fuel 5 [Nm3/h]</i>
PTRF_F04	Zone 4 Fuel	<i>Fuel 4 [Nm3/h]</i>
PTRF_F03	Zone 3 Fuel	<i>Fuel 3 [Nm3/h]</i>
PTRF_F02	Zone 2 Fuel	<i>Fuel 2 [Nm3/h]</i>
PTRF_F01	Zone 1 Fuel	<i>Fuel 1 [Nm3/h]</i>

Table 2. The selected CVs.

TAG	Variable Name	Acronym [Units]
PTRF_TU	Tunnel Temperature	<i>Tunnel [°C]</i>
PTRF_ZT06	Zone 6 Temperature	<i>Temp 6 [°C]</i>
PTRF_ZT05	Zone 5 Temperature	<i>Temp 5 [°C]</i>
PTRF_ZT04	Zone 4 Temperature	<i>Temp 4 [°C]</i>
PTRF_ZT03	Zone 3 Temperature	<i>Temp 3 [°C]</i>
PTRF_ZT02	Zone 2 Temperature	<i>Temp 2 [°C]</i>
PTRF_ZT01	Zone 1 Temperature	<i>Temp 1 [°C]</i>

Table 3. The selected DVs.

TAG	Variable Name	Acronym [Units]
PTRF_FP	Furnace Pressure	<i>FP [mbar]</i>
PTRF_FPR	Production Rate	<i>FPR [t/h]</i>
PTRF_AP	Air Pressure	<i>AP [mbar]</i>

Tables 4 and 5 depict the relationships between the selected CVs and the selected MVs/DVs as resulting from the identification phase: denoting by m the number of CVs, by l the number of MVs and by p the number of DVs, the CVs-MVs transfer matrix is a $(m \times l)$ matrix, while the CVs-DVs transfer matrix is a $(m \times p)$ matrix. The structure of table 5 is in accordance with the physical behaviour of the process where hot gases from downstream zones influence upstream zone temperatures, but not vice versa.

Table 4. The CVs-DVs mapping matrix.

Acronym	FP	FPR	AP
<i>Tunnel</i>	X	X	X
<i>Temp 6</i>	X	X	X
<i>Temp 5</i>	X	X	X
<i>Temp 4</i>	X	X	X
<i>Temp 3</i>	X	X	X
<i>Temp 2</i>	X	X	X
<i>Temp 1</i>	X	X	X

Table 5. The CVs-MVs mapping matrix.

Acronym	Fuel 6	Fuel 5	Fuel 4	Fuel 3	Fuel 2	Fuel 1
<i>Tunnel</i>	X	X	X	X	X	X
<i>Temp 6</i>	X	X	X	X	X	X
<i>Temp 5</i>		X	X	X	X	X
<i>Temp 4</i>			X	X	X	X
<i>Temp 3</i>				X	X	X
<i>Temp 2</i>					X	X
<i>Temp 1</i>					X	X

3. Advanced Process Control system design

In this section, the architecture of the designed APC system is analysed: all its functional blocks are described, focusing on the adopted MPC strategy.

3.1. APC system architecture

The proposed APC system architecture is depicted in figure 3.

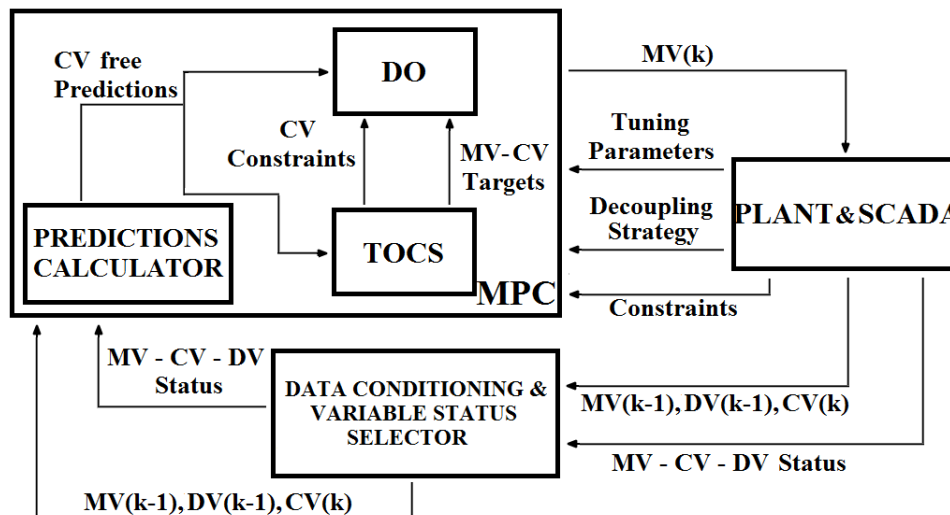


Figure 3. The proposed APC system architecture.

At a generic control instant k , updated MVs, DVs and CVs measurements are available from the plant: the communication between the process and the control system takes place through a Supervisory Control and Data Acquisition (*SCADA*) interface [6]. A *Data Conditioning & Variable Status Selector* module suitably processes new data, performing data conditioning if necessary (e.g. applying suitable filters): bad data (e.g. sensors spikes) or low level control loops faults are detected, contributing to the determination of the status of each MV, DV or CV, together with process management specifications. In this way, the selection of the variables subset to take into account in MPC formulation is performed. Together with this information, *MPC* block receives other fundamental data from the *SCADA* system: a set of tuning parameters, the settings for the adopted decoupling strategy implementation and the CVs and MVs constraints. In the following, these notions will be detailed.

MPC block, through an optimization strategy, computes a set of MVs moves: only the first of these control moves is forwarded to the plant and, at the next control instant, the entire procedure is repeated adding feedback from the process. In this way, a *receding horizon* strategy is performed [7]. *MPC* block is composed of three functional blocks: a two-layer scheme is supported by a *Predictions Calculator* module. The lower layer is constituted by a *Dynamic Optimizer (DO)* that dynamically calculates the MVs moves [7], [8]. The *Targets Optimizing and Constraints Softening (TOCS)* module lies on the upper layer: keeping into account economic and chemical objectives, it assures a coherency between DO steady state targets and constraints [9].

3.2. Predictions Calculator

The two-layer MPC architecture (see subsections 3.3 - 3.4) is assisted by a *Predictions Calculator* module. In the present case, based on a linear state space model, this block computes the CVs *free predictions* over a *prediction horizon* H_p , i.e. the CVs future trends keeping constant the MVs at the last value $MV(k-1)$ and exploiting all information available up to the time instant k . In the present case study, no future knowledge about DVs is available, so that in the CVs *free predictions* their value is kept constant to the last value $DV(k-1)$. According with the absence of delays in the considered case study, the CVs *free predictions* over the prediction horizon H_p can be formulated as follows [7]:

$$Z_{free}(k) = \begin{bmatrix} \hat{z}_{free}(k+1|k) \\ \hat{z}_{free}(k+2|k) \\ \vdots \\ \hat{z}_{free}(k+H_p|k) \end{bmatrix} = M \cdot \hat{x}(k|k) + N \cdot u_{past}(k) + T \cdot d_{past}(k) + Z_0 \quad (1)$$

$$Z_0 = \text{ones}(H_p, 1) \otimes z_0 \quad (2)$$

$$u_{past}(k) = \text{ones}(H_p, 1) \otimes (MV(k-1) - u_0) \quad (3)$$

$$d_{past}(k) = \text{ones}(H_p, 1) \otimes (DV(k-1) - d_0) \quad (4)$$

where $Z_{free}(k)$ is a $(m \cdot H_p \times 1)$ vector and $\hat{z}_{free}(k+i|k)$ is a $(m \times 1)$ vector, representing the CVs *free predictions* in the future control instant $k+i$. $\hat{x}(k|k)$ is the $(n \times 1)$ state estimation vector at the present instant k and M , a $(m \cdot H_p \times n)$ matrix, resumes the influence of this vector on CVs *free predictions*. Z_0 is a $(m \cdot H_p \times 1)$ vector containing the repetition of z_0 ($m \times 1$) vector, $\text{ones}(H_p, 1)$ is a $(H_p \times 1)$ vector composed by elements all equal to 1 and \otimes represents the Kronecker product [10]. $u_{past}(k)$ is a $(l \cdot H_p \times 1)$ vector containing the variation vectors of $MV(k-1)$ from u_0 . $d_{past}(k)$ is a $(p \cdot H_p \times 1)$ vector containing the variation vectors of $DV(k-1)$ from d_0 . N and T are $(m \cdot H_p \times l \cdot H_p)$ and $(m \cdot H_p \times p \cdot H_p)$ matrices, respectively: they represent the relationships between the deviations of $MV(k-1)$ and $DV(k-1)$ from their operating point and the CVs *free predictions* over the prediction horizon H_p .

3.3. Dynamic Optimizer

The Dynamic Optimizer, together with *Predictions Calculator* block, constitutes the basic scheme of a Model Predictive Controller. In the present work, the *DO* represents the lower layer of the proposed architecture. It is based on a Quadratic Programming (QP) problem, subject to linear inequality constraints. Consistently with the considered case study, no delays are assumed on MVs-CVs and DVs-CVs channels.

The *DO* objective function to minimize at each control instant k is:

$$V(k) = \sum_{i=0}^{H_p} \|\hat{u}(k+i|k) - u_{target}(k+i|k)\|_{S(i)}^2 + \sum_{i=0}^{H_u-1} \|\Delta\hat{u}(k+i|k)\|_{R(i)}^2 + \|\varepsilon(k)\|_{\rho}^2 \quad (5)$$

subject to

- i. $lb_{du}(i) \leq \Delta\hat{u}(k+i|k) \leq ub_{du}(i)$, $i = 0, \dots, H_u - 1$
- ii. $lb_u(i) \leq \hat{u}(k+i|k) \leq ub_u(i)$, $i = 0, \dots, H_u - 1$
- iii. $lb_z(i) - ECR_{lbz}(i) \cdot \varepsilon(k) \leq \hat{z}(k+i|k) \leq ub_z(i) + ECR_{ubz}(i) \cdot \varepsilon(k)$, $i = 1, \dots, H_p$
- iv. $\varepsilon(k) \geq 0$

where $\hat{z}(k+i|k)$, $\hat{u}(k+i|k)$ are, respectively, the CVs and MVs prediction and $u_{target}(k+i|k)$ is the MVs reference trajectory at the future instant $k+i$. $\Delta\hat{u}(k+i|k)$ represents the future control moves that are assumed to be performed in the first H_u control steps. H_u is the *control horizon*, and it indicates the designed number of MVs moves available for the resolution of the *DO* problem. $S(i)$ is a positive (semi-)definite matrix, containing the tracking error weights for MVs at the future instant $k+i$. $R(i)$ is a positive definite matrix, that allows control efforts monitoring. The terms lb_{du} and ub_{du} are the lower and upper constraints for MVs moves while lb_u and ub_u indicate the lower and upper bounds for MVs. The terms lb_z and ub_z are the lower and upper constraints for CVs. MVs constraints can never be violated while CVs constraints may be possibly relaxed. In the proposed *DO* formulation, as a common MPC practice, these violations are allowed through the introduction of a non-negative slack variables vector $\varepsilon(k)$. $\varepsilon(k)$ is a $(m \times 1)$ vector, containing a slack variable for

each CV. This vector has been introduced in the DO constraints through *Equal Concern for the Relaxation (ECR)* parameters, i.e. ECR_{lbz} and ECR_{ubz} in inequalities (6.iii) [11]. The importance of each single element of vector $\varepsilon(k)$ in the cost function (5) is tuned by a positive definite ρ matrix: this matrix, in cooperation with ECR parameters, defines a CVs priority ranking in DO constraints relaxation [12], [13]. According to CVs *free predictions* calculated by *Predictions Calculator* module (see equation (1)), the CVs (forced) predictions over the prediction horizon H_p are formulated as in the following:

$$Z(k) = \begin{bmatrix} \hat{z}(k+1|k) \\ \hat{z}(k+2|k) \\ \vdots \\ \hat{z}(k+H_p|k) \end{bmatrix} = Z_{free}(k) + F \cdot \Delta U(k) \quad (7)$$

where the $(l \cdot H_u \times 1)$ vector of MVs moves has the form:

$$\Delta U(k) = \begin{bmatrix} \Delta \hat{u}(k|k) \\ \Delta \hat{u}(k+1|k) \\ \vdots \\ \Delta \hat{u}(k+H_u-1|k) \end{bmatrix} \quad (8)$$

As can be noticed, CVs (forced) predictions can be expressed as a sum of two terms: CVs *free predictions* and an additional contribution, which depends on the dynamical relations between CVs and the MVs moves. These dynamical relations are explained by the F ($m \cdot H_p \times l \cdot H_u$) matrix. Exploiting the information of equations (1) and (7), the CVs prediction in a future control instant $k+i$ becomes:

$$\hat{z}(k+i|k) = \hat{z}_{free}(k+i|k) + F((i-1) \cdot m + 1 : i \cdot m, :) \cdot \Delta U(k) \quad (9)$$

where $\hat{z}_{free}(k+i|k)$ derives from equation (1), while the symbolism $F((i-1) \cdot m + 1 : i \cdot m, :)$ indicates a $(m \times l \cdot H_u)$ sub-matrix of F , composed by the same number of columns and including the F matrix rows between $((i-1) \cdot m + 1)$ th and $(i \cdot m)$ th rows (extremes included): it details the dynamic relationship between $\hat{z}(k+i|k)$ and $\Delta U(k)$ [7].

In figure 3, the terms H_p , H_u , S , R , ECR_{lbz} , ECR_{ubz} and ρ are among the *Tuning Parameters*, while lb_{du} , ub_{du} , lb_u , ub_u , $lb_{z_{op}}$ and $ub_{z_{op}}$ represent the *Constraints*. An important remark is the possible modification of $lb_{z_{op}}$ and $ub_{z_{op}}$ by TOCS module determining lb_z and ub_z (see *CV Constraints* in figure 3), as will be shown in subsection 3.4.

3.4. Targets Optimizing and Constraints Softening

In the previous subsection DO module has been described: among its parameters, the definition of $u_{target}(k+i|k)$ terms has not been treated. A proper setting of these terms, representing the MVs reference trajectory, can guarantee the reaching of a profitable economic/chemical operating point for the process: in order to overcome the limitations of plant operators' mental models, an optimization approach for the computation of their end terms, i.e. $u_{target}(k+H_p|k)$, has been introduced. This is performed by TOCS module. In the present work, all $u_{target}(k+i|k)$ over the prediction horizon terms will be set equal to the target calculated by TOCS module.

During the driving of a process, in some abnormal situations, e.g. caused by improper operators' manoeuvres and settings, the CVs constraints set through *SCADA* interface (see figure 3) may result not coherent with the plant chemical principles [12], [13]. A protection against these unexpected events is provided by TOCS module that, as additional feature, relaxes DO constraints.

In the designed APC system, a Linear Programming (LP) problem, subject to linear constraints, constitutes the core of the TOCS module. The TOCS cost function to minimize at a generic control instant k is:

$$V_{ss}(k) = c_u^T \cdot \Delta u_{ss} + \rho_{ss_min}^T \cdot \varepsilon_{ss_min} + \rho_{ss_max}^T \cdot \varepsilon_{ss_max} \quad (10)$$

subject to

- i. $lb_{du_ss} \leq \Delta u_{ss} \leq ub_{du_ss}$
- ii. $lb_{u_ss} \leq u_{ss} \leq ub_{u_ss}$
- iii. $u_{ss} = u_{target}(k + H_p | k) = MV(k - 1) + \Delta u_{ss}$ (11)
- iv. $z_{ss} = \hat{z}_{free}(k + H_p | k) + \Delta z_{ss}$
- v. $lb_{z_ss} - ECR_{lb_ss} \cdot \varepsilon_{ss_min} \leq z_{ss} \leq ub_{z_ss} + ECR_{ub_ss} \cdot \varepsilon_{ss_max}$
- vi. $\varepsilon_{ss_min} \geq 0; \varepsilon_{ss_max} \geq 0$

In these expressions, Δu_{ss} and Δz_{ss} represent the steady state moves for MVs and CVs; making use of $MV(k - 1)$ and $\hat{z}_{free}(k + H_p | k)$, they provide u_{ss} and z_{ss} , i.e. the MVs and CVs steady state targets. c_u is the MVs economic(/chemical) cost vector. The consistency between TOCS and DO modules is granted by the TOCS terms lb_{du_ss} , ub_{du_ss} , lb_{u_ss} and ub_{u_ss} , i.e. the steady state constraints for MVs steady state move and MVs steady state value, respectively:

- i. $lb_{du_ss} = \sum_{i=0}^{H_u-1} lb_{du}(i)$
- ii. $ub_{du_ss} = \sum_{i=0}^{H_u-1} ub_{du}(i)$ (12)
- iii. $lb_{u_ss} = lb_u(H_u - 1)$
- iv. $ub_{u_ss} = ub_u(H_u - 1)$

Moreover, in equation (11.v) lb_{z_ss} and ub_{z_ss} terms correspond to the unchanged CVs bounds $lb_{z_op}(H_p)$ and $ub_{z_op}(H_p)$ (see *Constraints* in figure 3). According to DO module, violations on CVs steady state constraints are permitted in the proposed TOCS architecture: this feature is performed by the introduction of the non-negative slack variables vectors ε_{ss_min} and ε_{ss_max} . The interaction between TOCS-ECR parameters, i.e. ECR_{lb_ss} and ECR_{ub_ss} , and positive vectors ρ_{ss_min} and ρ_{ss_max} allows the creation of a CVs priority ranking in steady state constraints relaxation [12], [13]. An additional cooperation feature between TOCS and DO modules is represented by the relationship between lb_{z_ss} , ub_{z_ss} and $lb_z(i)$, $ub_z(i)$ ($i = 1, \dots, H_p$):

- i. $lb_z(i) = \min(lb_{z_op}(i), lb_{z_ss} - ECR_{lb_ss} \cdot \varepsilon_{ss_min})$ (13)
- ii. $ub_z(i) = \max(ub_{z_op}(i), ub_{z_ss} + ECR_{ub_ss} \cdot \varepsilon_{ss_max})$

where min and max indicate minimum and maximum vector operators. According to CVs *free predictions* calculated by *Predictions Calculator* module (see equation (1)), the steady state CVs (forced) predictions exploited in the TOCS module have been formulated as in equation (11.iv). Exploiting the CVs-MVs ($m \times l$) gain matrix (indicated with G), derived from the identification CVs-MVs transfer matrix, Δz_{ss} (the CVs steady state moves vector) can be expressed as:

$$\Delta z_{ss} = G \cdot \Delta u_{ss} \quad (14)$$

Substituting this relation in the equation (11.iv), CVs steady state predictions become:

$$z_{ss} = \hat{z}_{free}(k + H_p | k) + G \cdot \Delta u_{ss} \quad (15)$$

Terms c_u , ρ_{ss_min} , ρ_{ss_max} , ECR_{lb_ss} and ECR_{ub_ss} are part of *Tuning Parameters* of the figure 3.

4. MPC decoupling strategy

In this section, the proposed decoupling approach introduced in the MPC formulation is described, and two equivalent mathematical implementations are presented.

4.1. Mathematical approaches

As stated in the previous sections, to deal with a specific request of plant engineers, i.e. to regulate each zone temperature exploiting only its own burner, a decoupling strategy has been introduced in the MPC formulation. Typically, the control of a generic CV can be performed through the MVs related to that CV: this information is contained in the identification CVs-MVs transfer matrix; table 5 summarizes these relations for the case at issue. Thus, the decoupling strategy should enable a selection on which manipulated variables to move for controlling each of the controlled variables: in this way, an inhibition of the action of certain MVs on such CVs is obtained, that is not dependent on the tuning parameters. In the following, two equivalent approaches for the fulfilment of this objective are described.

The first approach modifies the setup of the MPC problem. Considering the $(m \times l)$ CVs-MVs mapping matrix, the number of MVs to be inhibited for the control of at least one CV is determined (each MV can be counted maximum once), denoted by b . An MV j can be inhibited if in the j th column of G matrix there is at least a row i (related to i th CV) for which both the following conditions hold:

- the (i, j) element of G matrix is nonzero;
- the control specification requires the inhibition of the j th MV moves for the i th CV.

After the determination of the b number, together with all pairs CV-MV to inhibit, the initial CVs-MVs transfer matrix (and consequently also G matrix) is modified by zeroing each (i, j) element to inhibit. Then, the b selected MVs are duplicated as DVs, thus resulting in a $(m \times (p + b))$ CVs-DVs transfer matrix and the removed MV-CVs transfer functions are restored in each of the added b columns. In this way, the original transfer matrices CVs-MVs and CVs-DVs are modified, and a new MPC problem is obtained. For the case at issue, starting from initial CVs-MVs (7×6) and CVs-DVs (7×3) transfer matrices, being b number equal to 5, the tables 4-5 are modified as follows:

Table 6. The CVs-MVs modified mapping matrix.

Acronym	Fuel 6	Fuel 5	Fuel 4	Fuel 3	Fuel 2	Fuel 1
Tunnel	X	X				
Temp 6	X					
Temp 5		X				
Temp 4			X			
Temp 3				X		
Temp 2					X	
Temp 1						X

Table 7. The CVs-DVs modified mapping matrix.

Acronym	FP	FPR	AP	Fuel 5	Fuel 4	Fuel 3	Fuel 2	Fuel 1
Tunnel	X	X	X		X	X	X	X
Temp 6	X	X	X	X	X	X	X	X
Temp 5	X	X	X		X	X	X	X
Temp 4	X	X	X			X	X	X
Temp 3	X	X	X				X	X
Temp 2	X	X	X					X
Temp 1	X	X	X				X	

The new setup of the MPC problem gives rise to a modified CVs-MVs (7×6) transfer matrix and a new CVs-DVs (7×8) transfer matrix.

Alternatively, a different approach that exploits the structure of the matrices F and G , not changing the original setup of the MPC problem, is proposed. The definition of a *Decoupling Matrix* D_E is performed: an (i, j) element of the D_E $(m \times l)$ matrix is set to 0 if both the following conditions hold:

- the (i, j) element of G matrix is nonzero;
- the control specification requires the inhibition of the j th MV moves for the i th CV.

The remaining elements of D_E matrix are set to 1. From D_E an additional $(m \times l \cdot H_u)$ matrix is constructed:

$$D_E^{ext} = ones(1, H_u) \otimes D_E \quad (16)$$

where $ones(1, H_u)$ indicates a row vector composed of elements all equal to 1. These matrices have been inserted in equations (9) - (14) - (15), resulting in:

$$\hat{z}(k+i|k) = \hat{z}_{free}(k+i|k) + (F((i-1) \cdot m + 1:i \cdot m, :) \circ D_E^{ext}) \cdot \Delta U(k), \quad i = 1, \dots, H_p \quad (17)$$

$$\Delta z_{ss} = (G \circ D_E) \cdot \Delta u_{ss} \quad (18)$$

$$z_{ss} = \hat{z}_{free}(k+H_p|k) + (G \circ D_E) \cdot \Delta u_{ss} \quad (19)$$

where \circ indicates the element-wise multiplication.

For the case at issue, the D_E matrix has been reported in table 8.

Table 8. The decoupling matrix.

Acronym	Fuel 6	Fuel 5	Fuel 4	Fuel 3	Fuel 2	Fuel 1
Tunnel	1	1	0	0	0	0
Temp 6	1	0	0	0	0	0
Temp 5	1	1	0	0	0	0
Temp 4	1	1	1	0	0	0
Temp 3	1	1	1	1	0	0
Temp 2	1	1	1	1	1	0
Temp 1	1	1	1	1	0	1

The equivalence of the two mathematical approaches for the required decoupling strategy can be proved. This proof is not reported here, for brevity.

5. Simulation and field results

In this section, first a simulation example of the proposed decoupling approach is provided. Then, field results deriving from the implementation of the APC system on the real plant are depicted. Before showing the simulation example, a brief description of the design and tuning parameters is provided.

Tuning of S , R and ρ matrices of DO formulation has been performed in such a way that major importance to the CVs constraints meeting is assured, while considering MVs targets and monitoring control efforts. DO-ECR matrices and ρ matrix have been set so to guarantee the desired priority ranking on CVs constraints. For example, the meeting of smoke exchanger temperature bounds has been considered as a top priority objective compared to the compliance with zone temperatures constraints. The prediction horizon H_p has been set at 60 minutes, assuring steady state reaching for all CVs, while the control horizon H_u has been set at 8 control moves [14]. Tuning of TOCS module parameters has been performed according to DO one: c_u , ρ_{ss_min} and ρ_{ss_max} have been set in order to guarantee the fulfilment of CVs steady state constraints, while searching for economic and chemical objectives. The desired priority ranking in CVs steady state constraints relaxation is assured by the cooperation between ρ_{ss_min} , ρ_{ss_max} and ECR parameters, while for attaining fuel minimization c_u has been designed as positive vector.

In the simulation example, only zone 5 and zone 6 temperatures are considered in the APC control (no changes are made on the other MVs and DVs) and a typical operator's manoeuvre is simulated: a variation on both constraints of zone 6 temperature is performed, because of the entry of cold billets in the furnace. The effectiveness of the proposed decoupling strategy is proved by comparing the system performances without and with its introduction.

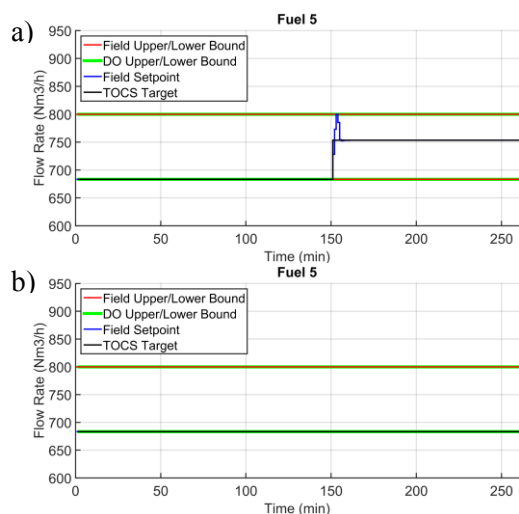


Figure 4. Zone 5 Fuel trends - a) without - b) with decoupling strategy.

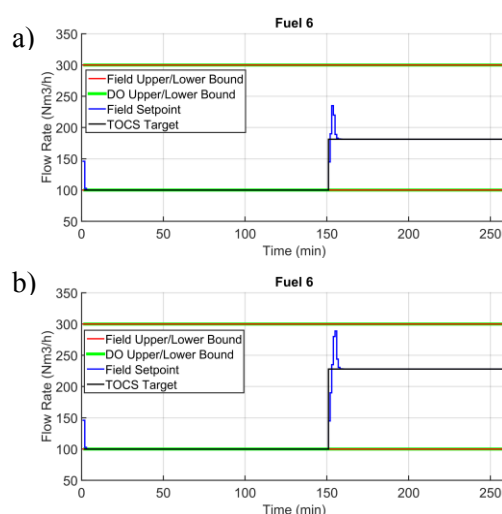


Figure 5. Zone 6 Fuel trends - a) without - b) with decoupling strategy.

In the presented simulation, as starting point a typical operating condition has been chosen: zone 6 fuel, zone 6 and zone 5 temperatures are inside their bounds, while zone 5 fuel lies on its lower limit. DO module, supported by TOCS module action, saves energy minimizing fuels flow rate. At time instant 150, as shown in figure 6, after the operator's move, the lower and upper constraints of zone 6 temperature are subjected to +20 °C and +30 °C change, respectively. Figures 4-5 show zone 5 and zone 6 fuel flow rates (zone 5 temperature has not be shown for brevity). In figures 4-6.a the control results without the decoupling strategy are reported, while figures 4-6.b refer to the decoupling approach. In the first control solution, when the operator performs the constraint change, TOCS module, in order to fulfil the request, modifies both zone 6 and zone 5 fuel targets (black dotted lines) and no steady state relaxation is required (cyan, red and green lines in figure 6 overlap). Consequently, DO module moves both fuel flow rates (blue line in figures 4-5), driving the entire subsystem towards a new operating point. In this way, zone 6 temperature (blue line in figure 6), after a brief transient, that causes a DO relaxation (magenta lines in figure 6), approaches its new lower constraint. In the second control solution, thanks to the decoupling strategy, when the constraints change is performed, TOCS module moves only zone 6 fuel target, leaving unchanged zone 5 fuel target. No steady state relaxation is required also in this second case. DO module, because of the inhibition of zone 5 fuel flow rate action for zone 6 temperature, acts on zone 6 fuel flow rate only, thus fulfilling the required management specification. Zone 6 temperature, after a transient (longer than in the first case but equally satisfactory), approaches its new lower constraint.

The designed APC system has been installed in an Italian steel plant, substituting the manual driving of PID control systems. In figure 7, comparisons of the system performances before and after the APC introduction are reported. In particular, zone 4 and zone 3 temperatures probability density functions (PDF) are shown: both situations refer to a three weeks period, with similar average boundary conditions, e.g. billets input temperature and furnace production rate.

After two years since the first start-up of the proposed APC system, the following results have been obtained:

- reduction of 3% average value and 8% variance of zones temperatures;
- reduction of 2.5% average specific consumption, computed considering fuel usage and productivity of the furnace.

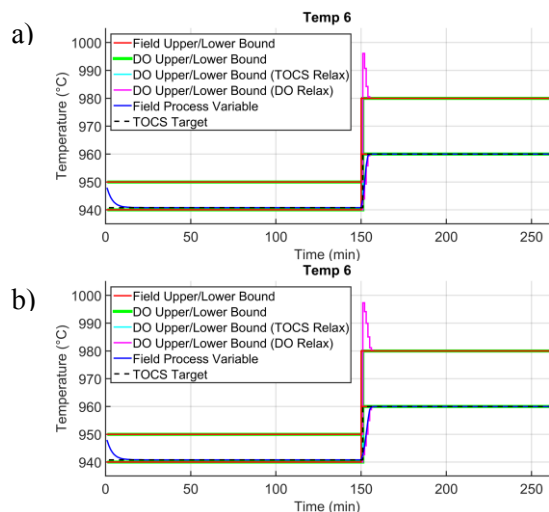


Figure 6. Zone 6 Temperature trends - a) without - b) with decoupling strategy

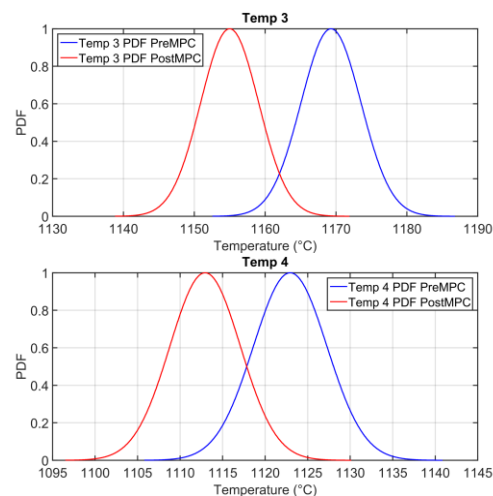


Figure 7. Zone 3-4 Temperature PDF pre and post MPC

6. Conclusion

In this work an APC system aimed at controlling a pusher type reheating furnace located in an Italian steel plant has been proposed. An architecture based on the interaction between a two-layer Model Predictive Controller and a supervisory block assures overcoming the limitations of plant operators' mental model in local PID control loops management. In addition, through a decoupling strategy, a selection on which MVs to use for controlling each CV has been introduced. In this way, a mathematical compromise between conflicting objectives, regarding quality, safety, pollution and energy aspects, has been guaranteed. With respect to the previous control system, a reduction of the variance of the main controlled variables has been observed, allowing to operate closer to the operating limits.

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