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Model Predictive Control with horizons online adaptation: a steel industry case study

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Abstract— **This paper proposes a two-layer Model Predictive Control strategy based on linear models, where the horizons are online adapted. The developed horizons online adaptation law is governed by combination of different conditions concerning the controlled variables included in the controller formulation and feedback information from the plant. The control strategy has been introduced within an Advanced Process Control framework composed by several functional blocks, aimed at controlling and optimizing a pusher type billets reheating furnace located in an Italian steel plant. The synthesized control system replaced the control action performed by local standalone temperature controllers manually driven by plant operators. Significant improvements on process control have been obtained and the conflicting objectives have been successfully met. Optimal operating points for energy efficiency obtainment, production targets meeting and product quality specifications fulfillment have been achieved.**

I. INTRODUCTION

In process industries, energy efficiency and conservation are key components to respect the main purposes of *Green Economy* policies. These policies aim at a rational energy usage so to affect, as little as possible, the environment (e.g. CO_2 emissions reduction). To promote industrial technologies that match the new rigorous environmental and energy consumption standards, energy efficiency certificates (Italian acronym TEE) have been proposed [1].

Advanced Process Control (APC) solutions have shown their strong impact in the technological progress of process industries [2], [3]. Exploiting multivariable control strategies and/or adopting tailored architectures for standalone controllers, APC solutions are able to stabilize and improve the processes operations but guaranteeing, at the same time, a major approach to the optimal energy efficiency operating points. The choice of the control method to be adopted constitutes a crucial phase in an APC system design. Model Predictive Control (MPC) [4] represents an effective APC choice. MPC techniques exploit process variables predictions on a sliding time window (prediction horizon) and compute a future control inputs sequence based on (optionally) constrained optimization problems.

Among process industries, steel industries represent very energivorous ones. Benefit studies are performed so to highlight process phases where energy efficiency margins can be forecast. The reheating phase represents a critical phase in a steel industry: in this phase, steel bars at an intermediate stage of manufacture, e.g. billets or slabs, are reheated in a reheating furnace, following a defined heating profile. APC solutions can be designed in order to manage the multivariable and nonlinear time varying nature of this phase together with the presence of many conflicting specifications. In this field, different solutions have been proposed by researchers. In [5], a nonlinear optimization is formulated based on a genetic algorithms approach, taking into account fuel cost minimization and specifications about the bars discharge temperature. In [6], a double model is formulated for the heating process, together with a double model slab tracking control system. In [7], a recurrent neural network approach is proposed for zones temperature estimation and a heat transfer model for billets temperature prediction is formulated. An integrated intelligent control method based on the proposed models is then designed. In [8], the advantages of using a model-based control/optimization framework for steel reheating furnaces are discussed; among the proposed approaches, a control method based on a transient nonlinear furnace model is formulated. In [9], a nonlinear MPC strategy for controlling and optimizing a continuous steel slabs reheating furnace is proposed. A first principles mathematical model is proposed and the control action defines the local furnace temperatures able to guarantee the desired slabs discharging temperature.

In [10], the authors described an APC system for a steel industry billets reheating furnace located in an Italian steel plant. The APC system is based on two control modes that exploit different types of linear models for the furnace global modellization. The main control mode is formulated as an adaptive MPC strategy. In this paper, further details on the APC system are provided and the formulation of an adaptation methodology of the MPC horizons is motivated and presented. At this regard, significant simulation and field results are proposed. Energy efficiency aspects related to the installation of the developed controller on the real plant are described.

The paper is organized as follows: Section II resumes the main features of the considered process, together with the control specifications, the model and the developed APC modes. Section III describes the MPC-based APC framework. Section IV details the proposed adaptation methodology of the MPC horizons. A significant simulation example is discussed in Section V while field results are reported in Section VI. Section VII contains the conclusion.

II. STEEL BILLETS REHEATING FURNACES

In the production chain of a steel industry, raw materials are processed obtaining small steel bars, e.g. billets. Billets, at different temperatures, enter a reheating furnace where they are suitably reheated so to meet the specifications required for the subsequent rolling phase in a rolling mill [9]. The reheating phase represents a crucial step that strongly

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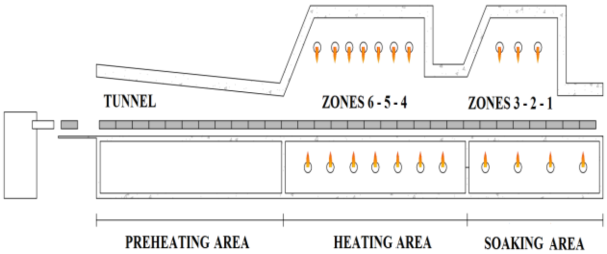

Figure. 1. Pusher type reheating furnace schematic representation.

TABLE I. FURNACE AREAS FEATURES

Area	Billets Number	Temperature	Acronym [*Units*]
Preheating	38	Tunnel Temp.	*Tun* [°C]
Heating	64	Zone 6 Temp.	$Temp_6$ [°C]
		Zone 5 Temp.	$Temp_5$ [°C]
		Zone 4 Temp.	$Temp_4$ [°C]
Soaking	34	Zone 3 Temp.	$Temp_3$ [°C]
		Zone 2 Temp.	$Temp_2$ [°C]
		Zone 1 Temp.	$Temp_1$ [°C]

influences plant energy efficiency and products quality. A customized APC system for this phase, denoted "i.Process | Steel – RHF", has been developed [11].

In the reheating phase, billets are reheated during their path within a furnace. Pushers can move billets according to the defined production rate; in this case, the reheating furnace is denoted as *pusher type*. In the present paper, this furnace typology is proposed as case study (Fig. 1). Three main furnace areas can be observed in Fig. 1 (from left to right): *Preheating*, *Heating* and *Soaking*. Table I summarizes the furnace areas configuration and the related zones and billets maximum number. As can be noted in Table I, the maximum capacity of the analyzed furnace is 136 billets ($m_b = 136$).

Measurements of the temperature of each furnace zone (within each furnace area) and of the smoke-exchanger are acquired by thermocouples. Fuel (natural gas) and air flow rates are measured through flowmeters. Air and furnace pressures are measured by manometers. Billets transition at the furnace inlet and outlet is detected by photocells. Billets furnace inlet and outlet temperatures are measured by pyrometers located at the furnace inlet and shortly after the furnace outlet. No temperature measurements for the billets that are within the furnace were available. Before the introduction of the developed APC system, the furnace was controlled through local PID temperature controllers driven by plant operators. The lack of billets temperature measurements inside the furnace represents a key aspect. This aspect, together with the multivariable and strongly time varying nature of the process, required a strong effort to the plant operators in ensuring an acceptable billets heating; consequently, energy efficiency aspects were often ignored.

A. A first APC mode

The first step performed for the improvement of the process energy efficiency and control performances has been the substitution of the local standalone temperature controllers with a two-layer MPC based on linear models (Section III). In this way, a multivariable constrained approach has been guaranteed for the zones temperature control. For the setup of the two-layer MPC strategy, fuel flow rates and stoichiometric ratios of each furnace zone with an own burners set (all furnace zones except tunnel) have been selected as Manipulated Variables (MVs, $u \in \mathbb{R}^{l_u \times 1}$, $l_u = 12$), while measured input Disturbance Variables group (DVs, $d \in \mathbb{R}^{l_d \times 1}$, $l_d = 3$) includes the furnace production rate and the furnace and air pressures. The involved Controlled Variables (CVs) have been denoted as *zones* Controlled Variables (zCVs, $y \in \mathbb{R}^{m_y \times 1}$): furnace zones temperature and temperature difference between adjacent furnace zones are zCVs examples. Through an identification procedure, linear time invariant asymptotically stable zCVs-MVs/DVs models without time delays on the input-output channels have been obtained. The MPC strategy based on the obtained zCVs-MVs/DVs models has been denoted as *zones* APC mode (Section III).

B. The adaptive APC mode

In order to approach profitable process operating points, a virtual sensor has been formulated that estimates the billets temperature inside the furnace. It implements a first principles nonlinear model that takes into account heat phenomena and billets movement. The virtual sensor has been equipped with adaptation strategies of the related uncertain coefficients [11]. The virtual sensor model inputs are represented by linear combinations of the furnace zone temperatures (Table II). In Table II, the Mean Zones 2-1 Temperature variable indicates the mean between the temperatures of the last two zones that are vertically disposed (Fig. 1, *Soaking Area*, *zone 1* and *zone 2*). Fig. 2 shows the billets temperature measured by the furnace outlet pyrometer: a comparison between the pyrometer measurements (blue stars) and the virtual sensor estimations (green stars) is reported. The reliable performances of the developed virtual sensor have motivated the inclusion of the billets temperature as an additional CVs group (bCVs, $b \in \mathbb{R}^{m_b \times 1}$) in the control framework. A Linear Parameter Varying (LPV) model has been accordingly derived for each billet inside the furnace [11]. Through the identified zCVs-MVs/DVs models, bCVs have been directly tied to the selected MVs and DVs. The additional control mode that exploits also bCVs-MVs/DVs models has been denoted as *adaptive* APC mode and it represents the main control mode of "i.Process | Steel – RHF" APC system (Section III).

III. THE APC FRAMEWORK

A. Focus on APC architecture

Fig. 3 depicts the "i.Process | Steel – RHF" APC architecture. At each control instant k, a Supervisory Control and Data Acquisition (*SCADA*) system supplies new measurements (*u(k-1)*, *d(k)*, *y(k)*) of the furnace process variables: the MVs set (u), the DVs set (d) and the zCVs set (y). The developed virtual sensor (Fig. 3, *Virtual Sensor*) supplies bCVs temperature estimations (*b(k)*). *Data Conditioning & Decoupling Selector* (*DC&DS*) block has been designed for checking bad conditions and local control

TABLE II. VIRTUAL SENSOR INPUTS VECTOR

Input Name	Acronym [*Units*]
Tunnel Temperature	*Tun* [°C]
Zone 6 Temperature	$Temp_6$ [°C]
Zone 5 Temperature	$Temp_5$ [°C]
Zone 4 Temperature	$Temp_4$ [°C]
Zone 3 Temperature	$Temp_3$ [°C]
Mean Zones 2-1 Temp.	$TempM_{21}$ [°C]

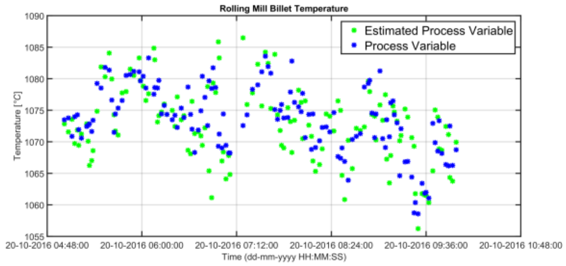

Figure 2. Example of virtual sensor performances.

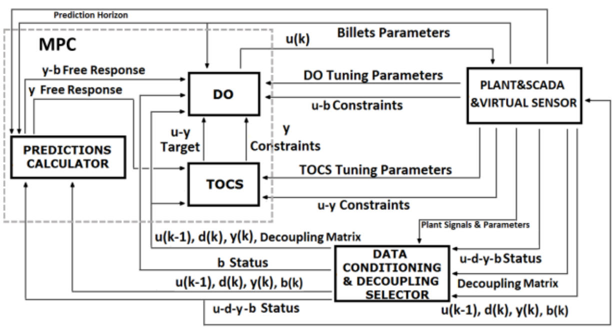

Figure 3. "i.Process | Steel – RHF" architecture.

loops faults, and for conditioning field data [12]. All this information is supplied to a two-layer MPC block that exploits linear models. This block is based on the solution of two subsequent optimization problems. At the upper layer, a steady-state module, called Targets Optimizing and Constraints Softening (*TOCS*) module, solves a preliminary optimization problem; hence, *TOCS* module results are forwarded to the lower layer, constituted by a Dynamic Optimizer (*DO*) module. This module, solving a second optimization problem, computes the MVs value $u(k)$ to be applied to the plant at the current control instant [10], [11]. The overall MPC computation is based on the *receding horizon* concept.

B. DO and TOCS modules

The overall MPC algorithm is based on the evaluation of process variables predictions over a prediction horizon H_p. $\hat{u}(k+i-1|k)$ and $\hat{y}(k+i|k)$ $(i = 1, \dots, H_p)$ indicate the predictions related to MVs and zCVs. Denote with jth $(j = 1, \dots, m_b)$ the billet (bCV) that at the current control instant k is located at the jth furnace place (the 1st place is assumed to be the place closer to the furnace entrance). Indicating with e_j the furnace exit predicted instant related to the jth billet $(j = 1, \dots, m_b)$, $\hat{b}_j(k+e_j|k)$ represents the associated temperature prediction. e_j has been defined as follows:

$$e_j = ceil\left(\frac{T_{fm} \cdot (m_b + 1 - j)}{T_s}\right) \qquad (j = 1, \dots, m_b) \tag{1}$$

where T_{fm} indicates the current furnace movement time $[s]$, defined as the elapsed time between the last two billets exited from the furnace. T_s indicates the MPC sampling time (60 $[s]$ for the case at issue). $ceil(x)$ rounds x to the nearest integer greater than or equal to x. At each control instant k, T_{fm} and the current furnace production rate (*Prod*, $[t/h]$) are related by the following expression:

$$T_{fm}\,[s] = \frac{3600\,[s] \cdot mass[t]}{1[h] \cdot Prod[t/h]} \tag{2}$$

where $mass$ indicates the mass of the last billet that exited the furnace.

The developed MPC strategy exploits two main modules, i.e. *DO* and *TOCS*. They are supported by a *Predictions Calculator* module, which computes the zCVs *free response* on the prediction horizon and the *free response* of each bCV at the related furnace exit predicted instant e_j (Fig. 3, *y-b Free Response*). DVs future information (e.g. production rate future information) is assumed to be unknown, so DVs future values are considered constant at the last plant value *d(k)*.

Based on the process variables predictions, MPC modules solve an optimization problem formulated as Quadratic Programming (QP) or Linear Programming (LP) problem. *DO* cost function (to be minimized) and constraints related to the *adaptive* APC mode are represented by (3)-(4).

$$\begin{aligned} V_{DO}(k) = & \textstyle\sum_{i=0}^{H_p-1} \|\hat{u}(k+i|k) - u_t(k+i|k)\|^2_{\mathcal{S}(i)} + \\ & + \textstyle\sum_{i=1}^{H_p} \|\hat{y}(k+i|k) - y_t(k+i|k)\|^2_{\mathcal{Q}(i)} + \\ & + \textstyle\sum_{i=1}^{H_u} \|\Delta\hat{u}(k+M_i|k)\|^2_{\mathcal{R}(i)} + \left\|\varepsilon_y(k)\right\|^2_{\rho_y} + \\ & + \textstyle\sum_{j=1}^{m_b} \left\|\hat{b}_j(k+e_j|k) - lb_{b\_DO_j}\right\|^2_{T_j} + \|\varepsilon_b(k)\|^2_{\rho_b} \end{aligned} \tag{3}$$

subject to

$$\begin{aligned} &\text{i. } lb_{du\_DO}(i) \le \Delta\hat{u}(k+M_i|k) \le ub_{du\_DO}(i), i = 1, \dots, H_u \\ &\text{ii. } lb_{u\_DO}(i) \le \hat{u}(k+M_i|k) \le ub_{u\_DO}(i), i = 1, \dots, H_u \\ &\text{iii. } lb_{y\_DO}(i) - \gamma_{lby\_DO}(i) \cdot \varepsilon_y(k) \le \hat{y}(k+i|k) \le \\ &\qquad \le ub_{y\_DO}(i) + \gamma_{uby\_DO}(i) \cdot \varepsilon_y(k), i = 1, \dots, H_p \\ &\text{iv. } lb_{b\_DO_j} - \gamma_{lbb\_DO_j} \cdot \varepsilon_{b_j}(k) \le \hat{b}_j(k+e_j|k) \le \\ &\qquad \le ub_{b\_DO_j} + \gamma_{ubb\_DO_j} \cdot \varepsilon_{b_j}(k), j = 1, \dots, m_b \\ &\text{v. } \varepsilon_y(k) \ge 0;\ \varepsilon_b(k) \ge 0 \end{aligned} \tag{4}$$

DO module takes into account MVs and zCVs predictions over the entire H_p (see (3)-(4)), while *TOCS* module considers the related steady-state predictions [10], [11]. Furthermore, also bCVs predictions are considered in (3)-(4). The future MVs moves are $\Delta\hat{u}(k+M_i|k)$ on a control horizon H_u $(0 < H_u \le H_p)$ in (3)-(4). *DO* module takes into account MVs and zCVs constraints (see (4)): MVs constraints are considered as inviolable (*hard*) constraints, while zCVs (*soft*) constraints can be relaxed in critical conditions. For this purpose, a slack variables vector $\varepsilon_{y\_DO}(k)$ has been introduced in (3). Furthermore, bCVs (*soft*) constraints are considered in (3)-(4). Finally, tracking terms related to MVs, zCVs and bCVs have been included in (3). *TOCS* module, taking into account minimization and/or maximization goals for MVs, solves the designed LP problem [10], [11]. Optimal steady-state targets and constraints for *DO* module are thus obtained (Fig. 3, *u-y Target* and *y Constraints*). In the proposed APC architecture, the same *TOCS* formulation is adopted for the *zones* and the *adaptive* APC modes [10], [11]. On the other hand, the *zones* APC mode *DO* formulation does not take into account the terms related to bCVs in (3)-(4). In both control modes, the choice of the horizons (H_p and H_u), together with the choice of the prediction instants related to the MVs future moves (M_i; $M_1 = 0,\ 0 < M_i \le H_p - 1$), play a fundamental role.

IV. MPC Horizons Adaptation Methodology

DC&DS block (see Section III) represents an auxiliary block that, among its functions, defines the process variables subset that has to be included in the MPC formulation at each control instant. This function is performed through the definition of a status value for each process variable. Thus, *DC&DS* block determines the final status value of each of the variables of the bCVs group. For each bCV, two status values have been introduced: “1” and “0”. The status value “1” related to a generic bCV indicates that the MPC scheme must control that variable, i.e. the bCV is *active*. Conversely, the bCV status value equal to “0” indicates that the bCV is *inactive*: at the current control instant, the MPC scheme has not in control that bCV, i.e. MVs must not act for satisfying its specifications (see the related terms in (3)-(4)). The initial bCVs status value takes into account plant management specifications and requirements, together with particular bCVs plant conditions. For example, plant management specifications and requirements may refer to the need of a temporary furnace stop, while particular bCVs plant conditions may refer to bad estimations of the virtual sensor or to failures related to the optical pyrometers. In these cases, the status value of all bCVs is set to “0”, i.e. all bCVs are considered as *inactive*. In the developed APC architecture, the *adaptive* APC mode is considered as the main control mode: in this control mode, at least a bCV is *active*. When all bCVs are *inactive*, “i.Process | Steel – RHF” APC system switches to the *zones* APC mode. When the *zones* APC mode is active, *TOCS* and *DO* modules exploit the same zCVs-MVs/DVs linear time invariant model. In this case, the prediction horizon H_p is maintained constant to guarantee steady-state approaching to the obtained models; the control horizon H_u is consequently tuned in order to ensure the desired degrees of freedom to *DO* QP problem. Finally, the MVs moves prediction instants are assumed as the first H_u prediction instants ($M_i = i - 1, i = 1, \dots, H_u$). According to the obtained zCVs-MVs/DVs model, the following *zones* APC mode parameters have been chosen:

$$H_p = 60\ [min]; \quad H_u = 8; \quad M_i = i - 1\ (i = 1, \dots, 8) \tag{5}$$

When the *adaptive* APC mode is active, also bCVs-MVs/DVs LPV models are considered. Each billet within the furnace is characterized by “an own steady-state condition”, related to the associated e_j instant (see (1)). For this reason, bCVs-MVs/DVs LPV models have not been included in the *TOCS* formulation. In order to consider the furnace exit temperature prediction of all the billets located in the furnace at each control instant, the prediction horizon $H_p$within the *adaptive* APC mode is set as e_1 value (see (1)), i.e. the number of sampling instants required by the 1st billet to traverse the entire furnace. Accordingly, the prediction horizon H_p within the *adaptive* APC mode changes whenever the furnace movement time (and the furnace production rate) changes: a direct relationship between H_p and the furnace movement time (and the furnace production rate) has been defined. For example, when the furnace movement time decreases (and the furnace production rate increases), H_p decreases. For the definition of the control horizon H_u within the *adaptive* APC mode, the following relationship has been introduced:

$$H_u = ceil\left(\frac{H_p}{r_{H_p - H_u}}\right) \tag{6}$$

where $r_{H_p - H_u}$ represents the desired ratio between H_p and H_u ($r_{H_p - H_u} = 5$ in the considered case study). Accordingly, the *adaptive* APC mode requires an online adaptation law also for M_i ($i = 1, \dots, H_u$) instants, based on the adapted values of H_p and H_u. The formulated M_i online adaptation law is:

$$\begin{aligned} M_1 &= 0 \\ M_2 &= 1 \\ &\vdots \\ M_\mu &= \mu - 1 \\ M_{\mu+1} &= \mu + \alpha \\ M_{\mu+2} &= \mu + \alpha + \beta \\ M_{\mu+3} &= \mu + \alpha + 2 \cdot \beta \\ &\vdots \\ M_{H_u} &= (\mu + \alpha) + (H_u - (\mu + \alpha)) \cdot \beta \end{aligned} \tag{7}$$

where

$$\mu \leq H_u; \qquad \alpha \in \mathbb{N}; \\ \beta = fix\left(\frac{(H_p - \omega) - (\mu + \alpha)}{(H_u - \mu)}\right); \\ \omega \in \mathbb{N} \tag{8}$$

In (8), $fix(x)$ rounds x to the nearest integer less than or equal to x. The adaptation law reported in (7)-(8) defines the prediction instants M_i related to the MVs future moves in order to ensure several MVs control moves in the first prediction instants and to ensure the required number of MVs control moves over the current prediction horizon. In the considered case study, the following parameters in (7)-(8) have been selected:

$$\mu = 5; \quad \alpha = 1; \quad \omega = 0 \tag{9}$$

V. Simulation Results

In order to better clarify the proposed adaptation procedure of the MPC horizons within the designed “i.Process | Steel – RHF” APC system, a simulation example about the *adaptive* APC mode is reported. The zCVsMVs/DVs plant model exploits the identified zCVs-MVs/DVs model and no measurement noise is assumed. The plant model for simulating the relationships between billets and furnace zones temperature exploits the billets temperature nonlinear model that has been formulated for the virtual sensor. At the initial control instant of the simulation, the *adaptive* APC mode is requested to be activated. The virtual sensor estimation gives reliable results and bCVs (billets temperature) can be included in the control problem. The zCVs reported in Table I, the temperature differences between the bCVs model inputs (Table II) and all fuel flow rates represent additional process variables that are considered in the simulation. The other MVs and all DVs are considered constant, so not influencing the proposed scenario. The MVs and the zCVs are constrained by physical limits. The temperature differences between the bCVs model inputs are constrained to ensure an increasing monotonicity of the temperatures along the furnace. The temperature of the 136 billets that initially lie within the furnace is in the range 20 [°*C*] - 1140 [°*C*], while the billets that will enter the furnace during the simulation are characterized by a temperature of about 550 [°*C*]. The *Rolling Phase* specifications require the billets temperature in the rolling area to be in the range 1030 [°*C*] - 1045 [°*C*]. The furnace production rate is equal to about 110 [*t/h*], which corresponds to a furnace movement time equal to 75 [*s*]. In order to guarantee the predicted reaching of the furnace outlet to the billet closer to the furnace inlet, a prediction horizon H_p equal to 170 [*min*] is set. Consequently, the control horizon H_u is set equal to 34 moves (see (6)) suitably spaced over the prediction horizon H_p (see (7)-(9)).

In the first 25 simulation instants, "i.Process | Steel – RHF" *adaptive* APC mode ensures that billets temperature detected by the optical pyrometer in the rolling mill area converges towards the minimum required temperature (1030 [°*C*]), despite the very high furnace production rate, as can be observed in Fig. 4. Without the controller action, the billets temperature could violate the imposed constraints: to avoid this undesired behavior, the cooperative action between *TOCS* and *DO* modules increases the furnace zones temperature (Fig. 5) manipulating the related fuel flow rates. At instant 26, a sudden and unforeseen change of the furnace movement time (and of the furnace production rate) is simulated. The updated furnace movement time is equal to 120 [*s*]; the associated furnace production rate is equal to about 70 [*t/h*]. Thanks to the developed MPC horizons online adaptation methodology, H_p, H_u and M_i parameters are adapted by "i.Process | Steel – RHF" APC system. In order to guarantee to the billet closer to the furnace inlet the reaching of the furnace outlet at the end of the prediction horizon H_p, an H_p equal to 272 [*min*] is set. The control horizon H_u is set equal to 55 moves (see (6)) suitably spaced over the prediction horizon H_p (see (7)-(9)).

Without the controller action, the billets temperature could increase: in order to maximize the energy efficiency, this situation must be avoided. For this purpose, the controller, acting on fuel flow rates, immediately reverses the trend of the zones temperature (Fig. 5). In this way, after a brief transient, the billets temperature, measured by the optical pyrometer in the rolling mill area, converges again towards the minimum required temperature (Fig. 4).

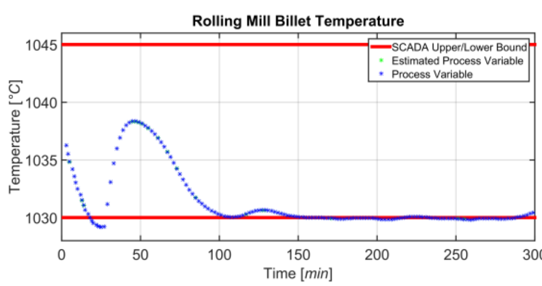

Figure 4. Simulation results: bCVs trends.

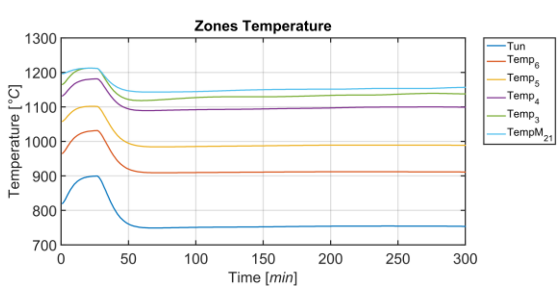

Figure 5. Simulation results: bCVs model inputs trends.

VI. Field Results

The study and design phases of the project related to the considered process began in January 2015 and ended in May 2015. The APC system has been installed on the considered Italian steel plant in early June 2015, substituting the local PID temperature controllers managed by plant operators. The developed control method aimed at steel industry billets reheating furnaces control and optimization has been awarded with an Italian patent [12].

A. Approaching the process operating constraints

Fig. 6-9 represent a plant configuration under "i.Process | Steel – RHF" control. A period of about seven hours is taken into account. Fig. 6 shows the bCVs trends: virtual sensor estimation (green stars) and optical pyrometer measurements (blue stars) are depicted, together with the defined constraints in the rolling mill area (1125 [°*C*] - 1075 [°*C*], red lines). The furnace production rate is shown in Fig. 7, while the billets furnace inlet temperature is shown in Fig. 8. The inputs related to the bCVs model are depicted in Fig. 9. All MVs and DVs are considered in the control problem, together with some zCVs (for example furnace zones temperatures and temperature differences between adjacent furnace zones) and the bCVs (some process variables have not been shown for brevity). The billets that are already present in the furnace at the beginning of the considered plant scenario are characterized by temperatures in the range 430 [°*C*] – 1100 [°*C*] and the inlet temperature of the billets that will enter the

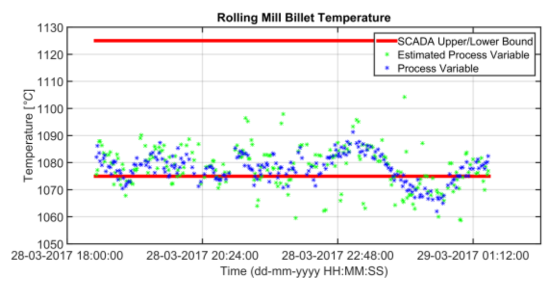

Figure 6. Field results: bCVs trends.

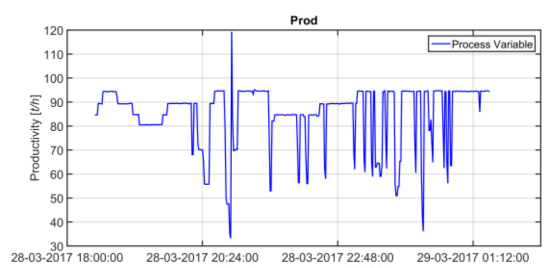

Figure 7. Field results: furnace production rate trends.

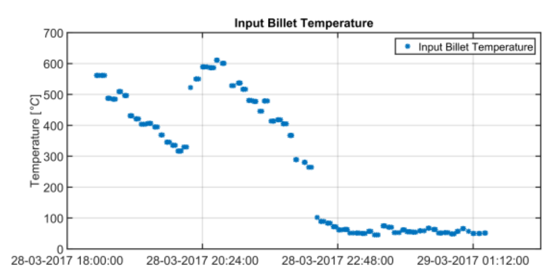

Figure 8. Field results: billets furnace inlet temperatures trends.

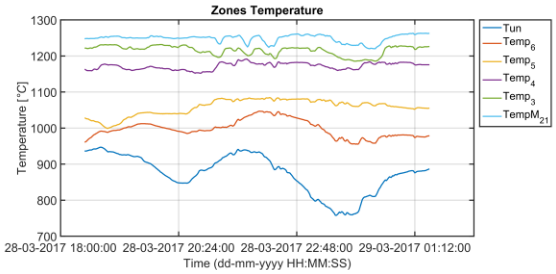

Figure 9. Field results: bCVs model inputs trends.

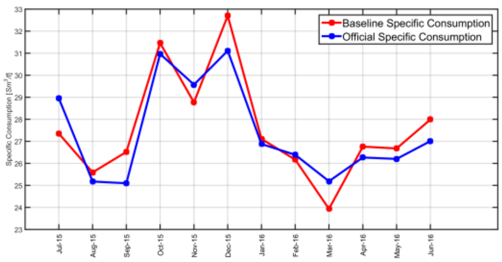

Figure 10. Field results: comparison between baseline and official specific consumption.

furnace is in the range 40 [°*C*] – 610 [°*C*] (Fig. 8). Besides the inlet temperature of the billets, also the furnace production rate is not constant (Fig. 7): it assumes values in the range 30 [*t/h*] - 120 [*t/h*]. The controller does not know future information about inlet temperature and furnace production rate. "i.Process | Steel – RHF" APC system ensures that the billets temperature detected by the optical pyrometer in the rolling mill area (see Fig. 6) converges towards the minimum required temperature (1075 [°*C*]). The developed controller profitably manages the furnace zones temperature (see Fig. 9) that is directly tied to the manipulation of the fuel flow rates. All imposed constraints and specifications are fulfilled, despite the not constant furnace production rate and billets furnace inlet temperature. The developed MPC horizons online adaptation methodology ensures the needed adaption of H_p, H_u and M_i parameters.

B. *Focusing on the fuel specific consumption*

The processes control improvements after the installation of "i.Process | Steel – RHF" APC system allowed working closer the operating limits. This key aspect has been also registered from a fuel specific consumption point of view. The fuel specific consumption, that takes into account the fuel usage and the furnace production rate, represents a significant indicator for the evaluation of the energy efficiency performances of an APC system. A project baseline for the fuel specific consumption has been computed, that varies with the furnace hot charge. Fig. 10 shows the monthly fuel specific consumption ([Sm^3/t]) related to the first year of "i.Process | Steel – RHF" APC system performances. The specific consumption is represented though a blue line, while the defined project baseline is shown through a red line. After about two years from the installation of "i.Process | Steel – RHF" APC system on the described pusher type billets reheating furnace, about 2 [*%*] reduction of the fuel specific consumption with respect to the defined project baseline has been pursued. A controller service factor about equal to 95 [*%*] has been observed.

VII. Conclusion

In this paper, a two-layer Model Predictive Control (MPC) strategy with horizons online adaptation has been proposed. A tailored horizons online adaptation law has been developed that takes into account controlled variables conditions and plant feedback information. The MPC strategy, based on linear models, represents the core of an Advanced Process Control (APC) framework aimed at steel reheating furnaces control and optimization. The APC system has been installed on a billets reheating furnace located in an Italian steel plant. The benefits deriving from the proposed multivariable predictive approach led the controller to conduct the plant to very profitable operating regions. An energy efficiency improvement has been obtained with respect to the previous furnace conduction, based on local PID temperature controllers driven by plant operators. The steel customer accepted the developed technology and, thanks to the energy efficiency improvement, Italian energy efficiency certificates have been obtained. Future work will be focused on specific studies about new modellization procedures. Furthermore, an attempt for the extension of the steel process phases under the control of "i.Process | Steel – RHF" APC system will be performed.

References

[1] www.enea.it

[2] M. Bauer and I. K. Craig, "Economic assessment of advanced process control – A survey and framework," *Journal of Process Control*, vol. 18, no. 1, pp. 2-18, 2008.

[3] W. M. Canney, "Are you getting the full benefit from your advanced process control system?," *Hydrocarbon Processing*, vol. 84, no. 6, pp. 55-58, 2005.

[4] M. G. Forbes, R. S. Patwardhan, H. Hamadah, and R. B. Gopaluni, "Model Predictive Control in Industry: Challenges and Opportunities," *IFAC-PapersOnLine*, vol. 48, no. 8, pp. 531-538, 2015.

[5] H. S. O. Santos, P. E. M. Almeida, and R. T. N. Cardoso, "Fuel Costs Minimization on a Steel Billet Reheating Furnace Using Genetic Algorithms," *Modelling and Simulation in Engineering*, vol. 2017, Article ID 2731902, 11 pages, 2017.

[6] Z. Yi, Z. Su, G. Li, Q. Yang, and W. Zhang, "Development of a double model slab tracking control system for the continuous reheating furnace," *International Journal of Heat and Mass Transfer*, vol. 113, pp. 861-874, 2017.

[7] Y. X. Liao, J. H. She, and M. Wu, "Integrated Hybrid-PSO and Fuzzy-NN Decoupling Control for Temperature of Reheating Furnace," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 7, pp. 2704-2714, 2009.

[8] A. Steinboeck, *Model-based Control and Optimization of a Continuous Slab Reheating Furnace*. Aachen, Germany: Shaker Verlag GmbH, 2011.

[9] A. Steinboeck, D. Wild, and A. Kugi, "Nonlinear model predictive control of a continuous slab reheating furnace," *Control Engineering Practice*, vol. 21, no. 4, pp. 495-508, 2013.

[10] G. Astolfi, L. Barboni, F. Cocchioni, C. Pepe, and S. M. Zanoli, "Optimization of a pusher type reheating furnace: an adaptive Model Predictive Control approach," in *Proc. 6th International Symposium on Advanced Control of Industrial Processes (AdCONIP)*, Taipei, 2017, pp. 19-24.

[11] S. M. Zanoli and C. Pepe, "Two-Layer Linear MPC Approach Aimed at Walking Beam Billets Reheating Furnace Optimization," *Journal of Control Science and Engineering*, vol. 2017, Article ID 5401616, p. 15, 2017.

[12] G. Astolfi, L. Barboni, F. Cocchioni, and C. Pepe, "Metodo per il controllo di forni di riscaldo," Italian Patent n. 0001424136 awarded by Ufficio Italiano Brevetti e Marchi (UIBM), 2016.