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Energy saving and environmental impact decreasing in a walking beam reheating furnace

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Abstract

In this work, an Advanced Process Control system aimed at the control and the optimization of a walking beam billets reheating furnace has been designed. In particular, a two-layer linear Model Predictive Control strategy has been adopted. A billets reheating first principles model has been formulated, in order to obtain accurate relationships between furnace zones temperature and billets temperature. To model the effect of the fuel flow rates on the furnace zone temperature, a black-box approach has been adopted. The cooperation between the control architecture and several supervision modules assures a flexible and resilient control, capable to cope with the most critical situations. Simulation tests and real plant results have demonstrated the soundness and the reliability of the proposed approach. With respect to the previous control system, manually operated by plant operators, the designed Advanced Process Control system allows the process to be maintained closer to its variables operating limits. In this way, energy saving and environmental impact decreasing have been obtained.
Keywords: Model Predictive Control, reheating furnace, billet, walking beam, energy saving, environmental impact decreasing.

1 Introduction

In the last decades, relevant technological improvements, together with the need to observe increasing restrictive environmental constraints, have resulted in the growth of the automation levels in the process industries. In this context, the research of an optimum equilibrium point between conflicting objectives is a key point: product quality and production maximization versus energy saving and environmental impact decreasing. In particular, plant engineers and managers are looking for minimum payback time solutions, in order to maximize the return on investment (Boe *et al.* [1]). At this regards, a preferred solution to new hardware acquisitions is to take full advantage from the existent devices while introducing Advanced Process Control (APC) systems (Bauer and Craig [2], Latour *et al.* [3]).

In this work an APC system project for the optimization and the control of a walking beam billets reheating furnace (subsection 2.1), located in an Italian steel industry is proposed. In order to limit the economic burdens and to allow the required customization of the overall system, a proprietary APC package has been developed. The control algorithm has been based on a two-layer linear Model Predictive Control (MPC) technology (Qin and Badgwell [4]). Various models typologies have been exploited, in order to manage all process conditions. Furthermore, consistency and cooperation strategies within the MPC module and between the MPC module and several functional blocks assure flexibility of the whole control system. The resilience and the reliability of the designed APC system have been proved in simulation and with its putting into practice on a real steel process.

The paper organization is the following: the considered reheating furnace is descripted and detailed in section 2, together with control specifications and process model. In section 3, the proposed APC system is depicted, focusing on the adopted MPC strategy. In section 4 the real results are discussed, comparing them to the performances of the previous control system. Finally, conclusions are resumed in section 5.

2 Case study: a walking beam reheating furnace

In this section, the considered walking beam reheating furnace is described detailing its location in the production chain of the corresponding steel industry. Control requirements and the developed mathematical models are illustrated.

2.1 Process features description

The analysed steel industry produces angle bars, iron rods or tube rounds, processing billets, i.e. steel bars at an intermediate stage of manufacture. In this specific case the billets are characterized by either a rectangular or quadratic section (160 [mm] x 160 [mm], 200 [mm] x 160 [mm] or 150 [mm] x 150 [mm]), and their length varies from 9 [m] to 4.5 [m]. The production workflow has been depicted in fig. 1. As can be observed, billets require an initial raw materials preparation phase. Then they are introduced in a reheating furnace: the considered furnace has a maximum capacity of 80 billets with a total length of 24 [m]. At the furnace entrance, billets temperature could be very different, from 30 [°C] to 700 [°C]. In the furnace, billets are reheated according to a specific temperature profile. After they exit the furnace, billets are transported to the rolling mill stands: here billets, through stands cylinders, are submitted to a plastic deformation, obtaining the final products. Billets' temperature at the furnace exit varies, according to the requirements for the subsequent processing.

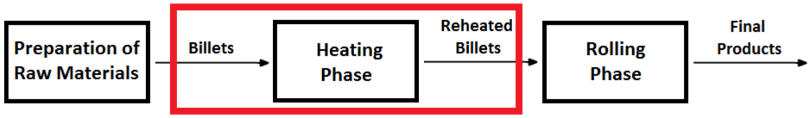

Figure 1: The production workflow of the considered steel industry.

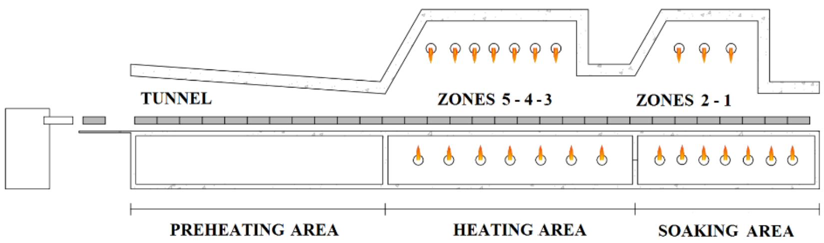

Figure 2: The analysed walking beam reheating furnace.

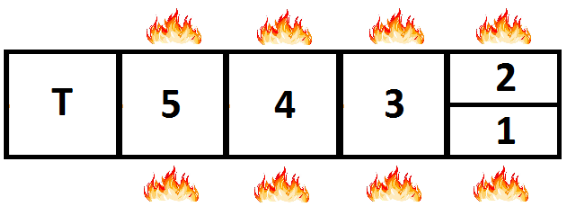

Figure 3: Detail on the furnace zones' disposition.

The proposed work focuses on the reheating phase. This step is the most significant phase in a steel industry, in terms of environmental impact, energy consumption and final products quality. Fig. 2 shows a scheme of the considered reheating furnace. The billets are introduced in the furnace from the left side and here they are placed on stationary ridges. A revolving beam moves the billets along the furnace up to the furnace exit. This movement type names the considered reheating furnace as *walking beam* (Trinks *et al.* [5], von Starck *et al.* [6]). During billets movement along the furnace, thermal energy is transferred to them through air/fuel combustion. Burners are located on the furnace walls and fuel is constituted by natural gas; fuel combustion gives rise to conduction, convection and radiation phenomena. Based on local temperatures and according to the role played on the billets reheating process, three main areas are identified along the furnace; each area is characterized by one or more zones. Starting from the furnace entrance, on the left side of fig. 2, they are:

- *Preheating area*: in this area there are no burners. Through hot gasses from downstream areas, a billets preheating process takes place. The only zone of this area is named as *tunnel* (fig. 3, "T"): it has a length of 7 [m] and its temperature varies approximately from 600 [°C] to 800 [°C].
- *Heating area*: this area is the most important for the billets reheating process; it is composed by three zones, denotes as (from the left side to the right side) *zone 5*, *zone 4* and *zone 3* (fig. 3). Each of these three zones has a length of 4 [m] and is equipped with 12 burners. In this area, temperature varies approximately from 800 [°C] to 1150 [°C].
- *Soaking area*: this is the last furnace area, where the billets heating is completed. It is composed by a single chamber, vertically divided into two zones, denoted as *zone 2* and *zone 1* (fig. 3). The total length of this chamber is 5 [m]; the two zones are equipped with 24 burners. In this area, temperature varies approximately from 1100 [°C] to 1210 [°C].

Billets, during their path toward the exit of the furnace, are subjected to monotonically increasing temperatures. The combustion air supplied to each burner is preheated by a heat exchanger (denoted also as *smoke-exchanger*): it is located near the beginning of the tunnel and it exploits the combustion smokes.

2.2 Sensors equipment and control requirements

Each furnace zone and the smoke-exchanger are equipped with a thermocouple, in order to measure their temperature. In the furnace zones, air and fuel (natural gas) flow rates are measured by flowmeters. Near the furnace chimney, a manometer measures air pressure. An optical pyrometer detects the billets temperature at their entrance in the furnace. At the exit of first stage of rolling mill stands, an additional optical pyrometer measures the processed billets temperature. Finally, a trigger detects each furnace step (entrance of a new billet) and photocells detect the billets transition.

Before the introduction of the designed APC system, plant operators, based on their experience, conducted the combustion of the furnace manually setting the zones temperature targets of the local Proportional-Integral-Derivative (PID) controllers (Astrom and Hagglund [7]).

The considered reheating phase is a high energivorous process. Averagely, before installing the designed APC system, the natural gas consumption (per year) was about 9 million [Sm^3], with a production of about 350000 [ton]. In order to increase the energy efficiency of the furnace, the fuel specific consumption has to be minimized, while assuring the desired billets temperature at the exit of the furnace. In particular, the following specifications have to be satisfied (Martensson [8], Shinskey [9]):

- guarantee the desired billets exit temperature, suitably managing the furnace zones temperature; the desired billets temperature at the exit of the furnace may vary depending on the final product typology;
- guarantee an uniform heating profile along the internal billets layers;

- minimization of air/fuel ratios, meeting the nominal stoichiometry; in this way the involved thermodynamic reactions are properly conducted;
- minimization of the fuel consumption, handling situations with varying furnace production rate.

The fulfilment of all the above requirements is not easily achievable by a manual furnace conduction and typically plant operators were able to guarantee the suitable billets heating at the expense of energy saving and environmental impact decreasing aspects. In this way, with the previous control system, the billets' temperature at the exit of the furnace was often greater than the temperature needed for the subsequent plastic deformation.

2.3 Process modelling

In order to improve the process energy efficiency, an APC system has been designed. For this purpose, the process modelling played a fundamental role. A billets reheating first principles model has been formulated, in order to obtain accurate relationships between furnace zones temperature and billets temperature. To model the effect of the air and fuel flow rates on furnace zones temperature and on other significant process variables, a black-box approach has been adopted. Furthermore, a suitable model for the air/fuel ratios has been formulated.

2.3.1 Billets first principles model

For the development of the billets first principles model, two modules have been developed: a so-called *tracking* module and a *thermodynamic* module. The tracking module models the movement of each billet inside and outside the furnace. This module takes into account all the furnace operations and features, such as the download of a billet, the furnace production rate and sensors information (subsection 2.2). The thermodynamic module estimates the billets temperature inside and outside the furnace taking into account tracking module information. To model the thermodynamic behaviour of each billet, thermal diffusion equations of the different billet layers have been considered. In particular, convection boundary conditions have been taken into account for the outside of the furnace, while radiation boundary conditions have been adopted for the furnace interior (Cengel [10]). As it is well known in literature, the following conduction model can be considered:

$$\dot{Q}_{cond} = -\lambda A \frac{dT}{dx} \quad [W] \tag{1}$$

where A [m^2] represents the area related to the billet section that is normal to the heat transfer direction, λ [W/(m·K)] is the billet thermal conductivity and dT/dx [K/m] is the temperature variation along the considered layer direction. The conduction model can be customized with the required number of billet layers. The well-known convection (eqn (2)) and radiation (eqn (3)) models govern the above mentioned boundary conditions:

$$\dot{Q}_{conv} = hA(T_{bill} - T_{env}) \quad [W] \tag{2}$$

$$\dot{Q}_{rad} = \varepsilon\sigma A(T_{bill}^4 - T_{env}^4) \quad [W] \tag{3}$$

where A [m^2] represents the area related to the exposed surface, h [W/(m^2·K)] is the convection heat transfer coefficient, T_{bill} [K] is the billet temperature and T_{env} [K] is the environment temperature of the fluid around the considered billet.

ε represents the emissivity coefficient, while σ is the Stefan-Boltzmann constant.

The heat transfer coefficients exploited in these models are online adapted by the thermodynamic module so as to face not modelled uncertainties. In particular, for each billet that exits the furnace, a constrained optimization problem is solved: a nonlinear cost function minimizes the difference between the real exit temperature and the estimated one. In this problem, the optical pyrometer measurements of the billets final temperature and all the temperature profile of the last billet that exited the furnace are exploited. The computed coefficients are then applied for the temperature estimation of billets that are in the furnace. A linear approximation of the obtained model is finally exploited in the adopted linear MPC strategy.

In fig. 4 the performances of the described estimator are shown: the estimated surface temperature of the exit billets (red line) are compared to the pyrometer measurements (blue line).

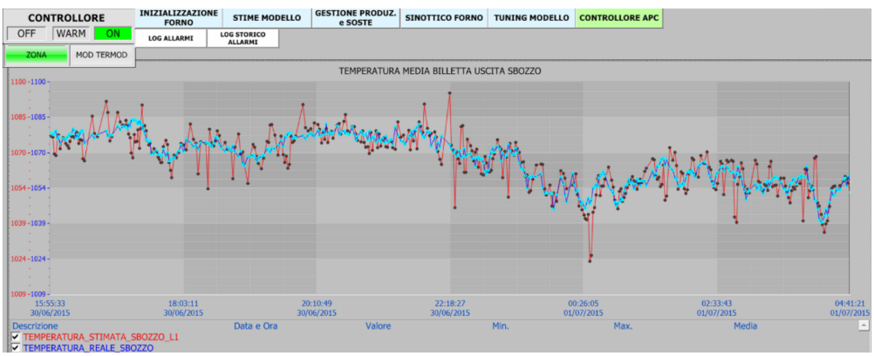

Figure 4: Comparison between estimated (red line) and real (blue line) exit billets temperature.

2.3.2 Furnace model identification

In order to meet the selected control objectives (subsection 2.2), fuel and air flow rates of each furnace zone (with burners) have been selected as Manipulated Variables (MVs). Furthermore, to exploit additional field information, furnace production rate, air pressure and furnace pressure have been selected as Disturbance Variables (DVs). The Controlled Variables (CVs) have been distinguished into two groups. The first CVs group is related to all the billets that at each control instant are in the furnace (this group is denoted as *BILL-CV*). Among second CVs group (denoted as *ZONE-CV*) there are the six zone temperatures, the temperature difference between zone 1 and zone 2, the smoke-exchanger temperature, the total air flow rate and the fuel and air valves opening (per cent). Linear dynamic models between the variables of the second group and MVs/DVs have been derived through an identification procedure based on a black box approach (Ljung [11], Liu *et al.* [12]). Discrete time first order strictly proper linear models without delays have been obtained. Air/fuel ratios modelling required an ad hoc MVs mathematical manipulation. Air/fuel ratios have been included into *ZONE-CV* group.

Table 1: The main ZONE-CV group controlled variables.

Controlled variable name	**Acronym [units]**
Tunnel Temperature	*Tun [°C]*
Zone *i* Temperature (*i*=1,…,5)	*Temp i [°C]*
Zone 1 – Zone 2 Temp. Difference	*Diff 12 [°C]*
Total Air Flow Rate	*AirTot* $[Nm^3/h]$
Smoke-Exchanger Temp.	*SE [°C]*
Zone *i* Air/Fuel Ratio (*i*=1,…,5)	*R-i*

Table 2: The manipulated variables.

Manipulated variable name	**Acronym [units]**
Zone *i* Fuel (*i*=1,…,5)	*Fuel i* $[Nm^3/h]$
Zone *i* Air (*i*=1,…,5)	*Air i* $[Nm^3/h]$

Table 3: The disturbance variables.

Disturbance variable name	**Acronym [units]**
Furnace Production Rate	*Prod [t/h]*
Furnace Pressure	*Furnace Press* $[mm/H_2O]$
Air Pressure	*Air Press [mbar]*

Billets' temperature has been directly tied to fuel and air flow rates through the black box models. The main *ZONE-CV* group CVs have been summarized in table 1, while MVs and DVs have been reported in tables 2 and 3, respectively.

3 Advanced Process Control system description

In this section the designed APC system is detailed, focusing on its main functional blocks and describing the adopted MPC strategy.

The architecture of the designed APC system is shown in fig. 5. At a generic control instant k, updated field measurements are available through a Supervisory Control and Data Acquisition ($SCADA$) system, that collects them from the real plant [13]. Among this information, there are MVs and DVs values ($MV(k-1), DV(k-1)$), together with the actual values of the *ZONE-CV* group CVs ($Zone-CV(k)$). These information are provided to the

$Billets\ Virtual\ Sensor$ block that, based on the theoretical aspects described in section 2, exploiting some suitable parameters ($Billets\ Parameters$), computes the best estimation of the temperature of the billets inside the furnace ($Bill - CV(k)$). $CV(k)$ term groups *ZONE-CV* values and *BILL-CV* values. A $Data\ Conditioning\ and\ Variables\ Status\ Selector$ block processes field data, preconditioning them when necessary: bad data (e.g. sensors spikes), bad billets temperature estimation or low level control loops faults are detected. This detection procedure contributes to the definition of the status of each process variable, also based on the status provided by SCADA (Pepe and Zanoli [14]). In this way the subset of MVs, DVs and CVs to be considered in the MPC formulation at the current control instant is defined. Additional parameters (e.g. tuning parameters) and the constraints related to MVs and CVs are supplied to MPC block ($MPC\ Parameters$, $Constraints$). Based on an optimization strategy, MPC block calculates a sequence of future MVs values. The first term ($MV(k)$) of the computed sequence is then applied to the plant, and, at the next control instant, the whole procedure is repeated, exploiting feedback information. This technique is denoted as *receding horizon* strategy (Maciejowski [15], Camacho and Bordons [16]). Three modules compose the proposed MPC block: a $Predictions\ Calculator$ module supports a two-layer architecture, constituted by a Dynamic Optimizer (DO) module and a Targets Optimizing and Constraints Softening ($TOCS$) module.

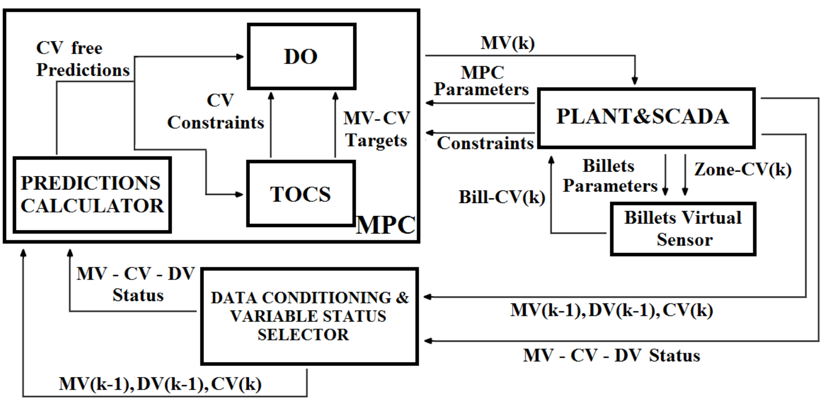

Figure 5: Advanced Process Control architecture.

3.1 Predictions calculator module and TOCS module

$Predictions\ Calculator$ module, according to the linear models described in section 2, computes the CVs *free predictions* along a *prediction horizon* H_p (Maciejowski [15]). These predictions represent the future CVs behaviour, calculated by keeping constant the MVs and the DVs values at their last values $MV(k-1)$ and $DV(k-1)$ (fig. 5). At each control instant, based on the variables set included in the control problem, the prediction horizon H_p (among $MPC\ Parameters$ of fig. 5) may vary.

$TOCS$ module is at the upper layer of the proposed two-layer MPC strategy: it computes MVs and CVs targets, based on $SCADA$ and $Predictions\ Calculator$ modules information. These targets take into account the steady state behaviour of the system that is assumed to be reached at the end of H_p. In the designed MPC block, $TOCS$ module has been based on a Linear Programming (LP) problem: a suitable linear cost function is minimized, subject to linear constraints. The constraints exploited in the $TOCS$ optimization problem belong to $Constraints$ group of fig. 5. The $TOCS$ optimization problem may change at different control instants, for example due to the variables set included in the control problem. $TOCS$ module provides DO module with MVs and CVs targets (fig. 5, $MV - CV\ Targets$) and with CVs constraints (fig. 5, $CV\ Constraints$). A mathematical consistency between the formulations of the two layers is imposed and a cooperation between them is defined (Pepe and Zanoli [14]).

3.2 DO module

DO module is at the lower layer of the proposed MPC strategy. At each control instant, it computes the sequence of future MVs values on a *control horizon* H_u based on $SCADA$, $Predictions\ Calculator$ and $TOCS$ modules information (Maciejowski [15], Camacho and Bordons [16]). In the designed MPC block, DO module has been based on a Quadratic Programming (QP) problem: a suitable quadratic cost function is minimized, subject to linear constraints. The constraints exploited in the DO optimization problem belong to $Constraints$ and $CV\ Constraints$ groups of fig. 5. The DO optimization problem (including the H_u parameter) may change at different control instants, e.g. due to the variables set included in the control problem. For example, when billets temperature is controlled through the zones temperature handling, the DO cost function to minimize is:

$$\begin{aligned} V_{DO}(k) = &\sum_{i=0}^{H_p-1} \left\| \widehat{MV}(k+i|k) - \widehat{MV}_{TOCS}(k+i|k) \right\|_{\mathcal{S}(i)}^2 + \\ &+ \sum_{i=0}^{H_u-1} \left\| \Delta\widehat{MV}(k+i|k) \right\|_{\mathcal{R}(i)}^2 + \\ &+ \sum_{i=1}^{H_p} \left\| \widehat{CV}(k+i|k) - \widehat{CV}_{TOCS}(k+i|k) \right\|_{Q(i)}^2 + \|\varepsilon(k)\|_{\rho}^2 \end{aligned} \quad (4)$$

subject to

$$\begin{aligned} &\text{i.} \quad lb_{dMV}(i) \le \Delta\widehat{MV}(k+i|k) \le ub_{dMV}(i), \quad i = 0, \dots, H_u - 1 \\ &\text{ii.} \quad lb_{MV}(i) \le \widehat{MV}(k+i|k) \le ub_{MV}(i), \quad i = 0, \dots, H_u - 1 \\ &\text{iii.} \quad lb_{CV}(i) - ECR_{lbCV}(i) \cdot \varepsilon(k) \le \widehat{CV}(k+i|k) \le \\ &\qquad \le ub_{CV}(i) + ECR_{ubCV}(i) \cdot \varepsilon(k), i = 1, \dots, H_p \\ &\text{iv.} \quad \varepsilon(k) \ge 0 \end{aligned} \quad (5)$$

where $\widehat{MV}(k+i|k)$ and $\widehat{CV}(k+i|k)$ are, respectively, the MVs and the *ZONE-CV* group CVs predictions at the future instant $k+i$. $\widehat{MV}_{TOCS}(k+i|k)$ and $\widehat{CV}_{TOCS}(k+i|k)$ are, respectively, the MVs and the *ZONE-CV* group CVs reference trajectories at the future instant $k+i$, obtained from $TOCS$ targets. $\Delta\widehat{MV}(k+i|k)$ terms represent the future MVs control moves. $\mathcal{S}(i)$ and $Q(i)$ are positive (semi-)definite matrices, containing, respectively, the tracking error weights for MVs and for *ZONE-CV* group CVs at the future instant $k+i$. Control moves are weighted by $\mathcal{R}(i)$ positive definite matrices. The terms $lb_{dMV}(i)$ and $ub_{dMV}(i)$ are the lower and upper constraints for MVs moves while $lb_{MV}(i)$ and $ub_{MV}(i)$ indicate the lower and upper bounds for MVs. The terms $lb_{CV}(i)$ and $ub_{CV}(i)$ are the lower and upper constraints for *ZONE-CV* group CVs. MVs constraints violation is not allowed, while CVs constraints violation is allowed in critical situations. As is well known in MPC practice, these violations are allowed through the introduction of a non-negative slack variables vector $\varepsilon(k)$. This vector has been introduced in the DO constraints through *Equal Concern for the Relaxation (ECR)* parameters, contained in $ECR_{lbCV}(i)$ and $ECR_{ubCV}(i)$ matrices in inequalities (5.iii) (Bemporad *et al.* [17]). The importance of $\varepsilon(k)$ vector elements in the cost function (4) is tuned by a positive definite ρ matrix: this matrix, in cooperation with ECR parameters, defines a CVs priority ranking in DO constraints relaxation (Pepe and Zanoli [14]). Terms H_u, $\mathcal{S}(i)$, $\mathcal{R}(i)$, $Q(i)$, $ECR_{lbCV}(i)$, $ECR_{ubCV}(i)$ and ρ belong to $MPC\ Parameters$ of fig. 5.

4 Real results of the designed APC system

The project for the development of the described APC system has been performed through a cooperation between Università Politecnica delle Marche and i.Process S.r.l.. The study and design phases began in August 2013 and ended in May 2014. In early June 2014, the system has been installed, substituting operators' manual driving of local PID controllers. In fig. 6, the performances of the proposed system are compared with the previous one. In particular, the optical pyrometer measurements of billets final temperature are shown. A 15-hour period is considered: the first 4 hours refer to the previous control system ($APC\ OFF$), while the remaining 11 hours are related to the proposed APC system ($APC\ ON$). The billets temperature constraints (straight lines, 1055 [°C]–1080 [°C]) in the two situations are the same and similar furnace boundary conditions, e.g. billets input temperature and furnace production rate, have been preserved. When the APC system is off, the billets temperature is always very close to its upper bound and energy saving and environmental impact decreasing aspects are neglected. With the activation of the APC system, billets final temperature decreases approaching its lower bound thanks to the optimized usage of fuel and air flow rates.

In fig. 7, the fuel specific consumption ([m^3/ton]) before and after the introduction of the designed control system is depicted. It is computed considering natural gas usage and furnace production rate. A period of four and half years is taken into account. The period from January 2011 to July 2013 (at the left of fig. 7) refers to the previous control system, while the one from June 2014 to May 2015 (at the right of fig. 7) is related to the proposed APC system. In this figure about 5% reduction is observed when the designed control system is active. Up to June 2016, the reduction has become greater than 7%. Furthermore, after two years from the first start-up, a service factor greater than 95% has been registered.

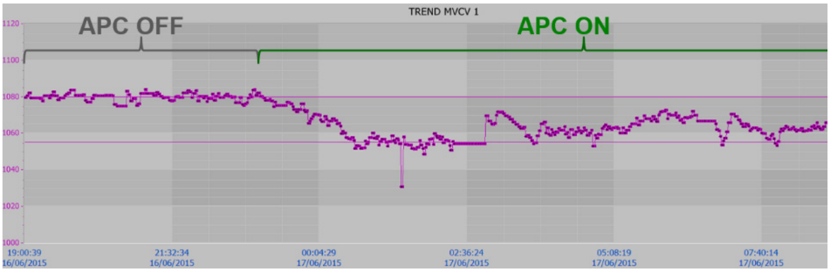

Figure 6: Billets final temperature trends and related constraints (straight lines) without (APC OFF) and with (APC ON) the designed APC system.

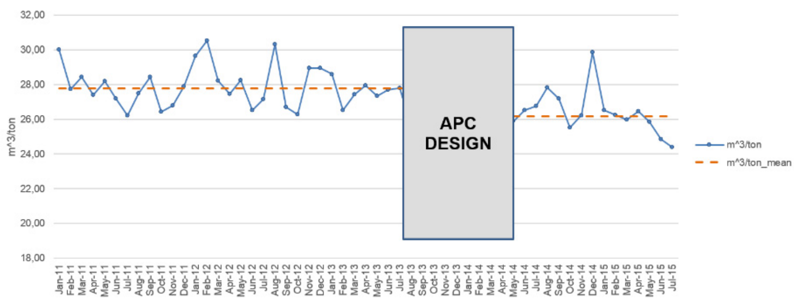

Figure 7: Fuel specific consumption trends (blue straight line) and related expected values (red dotted line) without (left) and with (right) the designed APC system.

5 Conclusions

In this work, the problem of the energy efficiency increase in a walking beam billets reheating furnace located in an Italian steel plant has been addressed. For this purpose, an Advanced Process Control system has been designed. In order to exploit accurate dynamical models of the considered process, first principles and identification based procedures have been adopted. The obtained models have been introduced in a two-layer linear Model Predictive Control system. After the installation of the designed system on the real plant, a remarkable reduction of billets final temperature has been registered. In this way, energy saving and environmental impact decreasing have been obtained.

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