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Development and application of a Predictive Controller to a mini district heating network fed by a biomass boiler

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Abstract

Energy saving is actually recognized as one of the most significant ways to reduce primary energy consumption and pollutant emissions. Due to the remarkable importance of heating systems and heat distribution grids, Siram by Veolia and the University of Parma have developed an optimal control system for District Heating Networks. Usually building control systems are designed to manage plants relying on past experience: the optimal control system described in the paper defines plant management strategy on the basis of the future behavior of the systems and the external environment. The proposed control system has been applied to the heating system and the distribution network of a school complex in Podenzano (Emilia-Romagna region). The district heating supplies heat to three different buildings (primary school, secondary school and sports hall). The heating plant is composed of three generators (two fed by natural gas and one by wooden biomass), a Thermal Energy Storage, two main distribution manifolds (supply and return) and three secondary circuits, which distribute heat to the buildings. In the first part of the paper the control algorithm is described, split into plant simulation models and the optimization algorithm. In the second part, the real application and the new communication architecture applied on site are outlined and, finally, the obtained results are reported highlighting the management strategies of generators and pumps. The optimal control strategy application gave important results in terms of energy saving, in particular the energy supplied to the buildings dropped significantly, this is the result of knowing the building behavior in advance.

Keywords: Smart Grid; District Heating Networks; Model predictive control.

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1. Introduction

For many years, the European Union has been funding a large number of research and innovation projects (e.g. within the Horizon 2020 Framework Programme) aimed at the development of smart management and optimal control strategies for district heating and cooling systems. For instance, the projects OPTi [1] and INDIGO [2] integrated advanced modeling and predictive controllers for heating and cooling distribution respectively in two hospital sites. A platform of innovative tools including Model Predictive Control to improve energy efficiency in buildings was created within the TOPAS project and its real demonstration in public and commercial buildings recently started [3]. Other work actions plan to validate the proposed solutions and quantify energy saving in relevant and scalable applications, from building scale [4] to district [5] and municipality scale [6]. This work aims to develop and to test a Model Predictive Control for the heating system and distribution network of a school complex in the North of Italy. Smart district heating opens the doors to the world of interconnection, which is full of opportunities, one of the most appealing is the interaction with a smart electric network.

Nomenclature			
A_b	area [m^2]	P	power [kW]
c_b	building heat capacity [kJ/K]	t	time [s]
c_biom	biomass cost [€/kWh]	T_air	forced ventilation air temperature [°C]
c_gas	gas cost [€/kWh]	T_b	building internal temperature [°C]
$c_\mathrm{p,air}$	specific heat [kJ/(kgK)]	T_e	external temperature [°C]
f_c	fuel cost [€]	U_b	heat transfer coeff. [kJ/(m^{2}K)]
$f_\mathrm{c,biomb}$	primary energy of biomass boiler [kWh]	z_new	dimensionless height [-]
$f_\mathrm{c,gasb}$	primary energy of gas boiler [kWh]	z_old	height starting [-]
m_forced	forced ventilation mass flow rate [kg/s]	$z_\mathrm{discharge}$	height decrease [-]
m_leak	natural ventilation mass flow rate [kg/s]	z_charge	height increase [-]

2. Model Predictive Control

The plant control algorithm is based on the Model Predictive Control (MPC) approach. This control technique usually involves three main components: the real plant, the plant model (that simulates real plant behavior) and the optimization algorithm. The first step of the algorithm is collecting the building internal temperature data from sensors and initializing the plant model with proper starting conditions. Then it recalls the plant mathematical model that simulates the plant behavior in the following time intervals searching for the optimal control strategy. Finally, it sends control signals to the real plant. The MPC iterates the procedure and sends control signals under a fixed time schedule.

2.1. Plant Model Components

The plant model includes mathematical models of buildings that are based on the energy conservation equation. As explained in [7], this equation can be written as follows:

$$\frac{\Delta T_\mathrm{b}}{\Delta t} = -a(T_\mathrm{b} - T_\mathrm{e}) + \mathrm{b} \cdot P - c(T_\mathrm{b} - T_\mathrm{e}) - d(T_\mathrm{b} - T_\mathrm{air}) \quad (1)$$

$$a = \frac{U_\mathrm{b} A_\mathrm{b}}{c_\mathrm{b}};\ b = \frac{1}{c_\mathrm{b}};\ c = \frac{m_\mathrm{leak} c_\mathrm{p,air}}{c_\mathrm{b}};\ d = \frac{m_\mathrm{forced} c_\mathrm{p,air}}{c_\mathrm{b}} \quad (2)$$

where *a* regards heat exchange through walls, *b* represents the building thermal inertia related to introduced heat power *P*, *c* and *d* take into account the natural and forced ventilation contributions, respectively. Natural gas and biomass boilers are modelled through algebraic equations that relate conversion efficiency to load factor (Fig. 1).

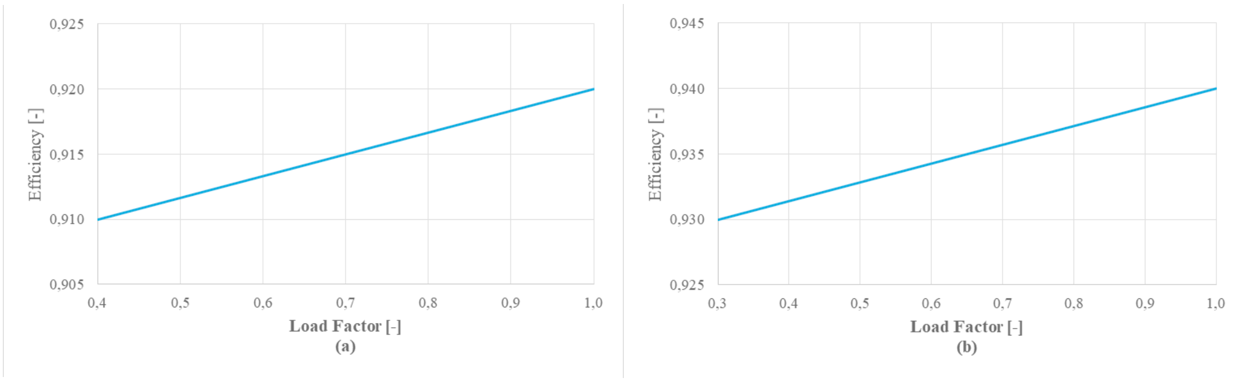

Fig. 1. Load-efficiency curves of heat generators: a) natural gas boiler performance, b) biomass boiler performance

The network is also fitted with a Thermal Energy Storage tank (TES) that can be mathematically described by the thermocline position (i.e. a thin, yet definite layer in a fluid body that divides two zones with different temperatures), which depends on the inlet and outlet flow mass balance within the thermal energy storage tank. This assumption allows the definition of the TES "state of charge" and its management in an optimal way. The mathematical model is derived from the literature [8,9] and is based on the main equation:

$$z_{\text{new}} = z_{\text{old}} + z_{\text{discharge}} - z_{\text{charge}} \tag{3}$$

The thermocline can move within the storage from the bottom (z=1.0) to the top (z=0.0) depending on the warm inlet (z_{charge}) and the warm outlet ($z_{\text{discharge}}$) mass flow rates and its position is updated at each calculation time-step.

2.2. Optimization algorithm

The optimization algorithm employed in this application is based on the Dynamic Programming approach and it has been adapted from the one developed by Sundström and Guzzella [10]. The optimization algorithm returns the definite optimal point to minimize the overall fuel cost. The objective function, where the fuel consumption of each boiler is multiplied by the corresponding specific cost, has been assumed as follows

$$f_{\text{c}} = c_{\text{biom}} f_{\text{c,biomb}} + c_{\text{gas}} f_{\text{c,gasb1}} + c_{\text{gas}} f_{\text{c,gasb2}} \tag{4}$$

2.3. Control algorithm

The control algorithm (Fig. 2) is divided into four optimization problems, because finding the optimal solution with a single problem (i.e. with four state parameters) could take several hours, which is not suitable for control purposes.

The first, second and third calculations are made to find the optimal control strategy for the valve position and inlet temperature in the plant secondary circuits for the following two days using forecasted external temperature. Afterward, the last calculation optimizes the boilers and the TES control parameters in order to minimize the thermal power plant fuel cost.

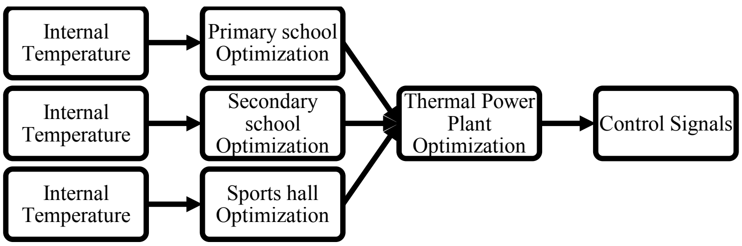

Fig. 2. Control algorithm flowchart

3. Application

The proposed MPC algorithm is then tested on a real plant. For this purpose, a small district heating system aimed at providing heat to three school buildings with different uses (primary school, secondary school and sports hall) is considered (Fig. 3). The district heating is powered by three heat conversion systems (two natural gas boilers and one biomass boiler), a TES, two main distribution manifolds (supply and return) and three secondary circuits, which supply the buildings with hot water.

In the pre-existing configuration, the internal temperature of the building was controlled through a climatic curve as a function of the external temperature and with time-scheduled pump activation. The energy conversion systems were controlled on the basis of an “on/off” weekly schedule and through their built-in control systems.

In the proposed configuration, the MPC-based management system can control every single component, i.e. boilers on/off, pumps on/off and valve position.

3.1. New Communication Architecture

The innovative system control based on MPC requires a new communication architecture (Fig. 4). In the pre-existing configuration set-points and time-schedules were set in the Building Management System (BMS) software and were implemented in the Programmable Logic Controllers (PLCs) through a proprietary communication protocol.

Since it was not possible to implement the MPC algorithm in the BMS software, the communication architecture had to be changed and a new workstation, with the new control algorithm, now has the task of managing the plant (the BMS software is used for backup). An Open Platform Communication (OPC) client and server are used to communicate with the existing proprietary communication protocol. For example, during the calculation, the control algorithm takes the building internal temperature from the PLCs through the OPC structure, where the OPC server collects the information from the proprietary communication protocol. Subsequently, the control algorithm estimates new set-points for the control parameters and sends this information to the PLC through the same process explained here above and the cycle is repeated indefinitely.

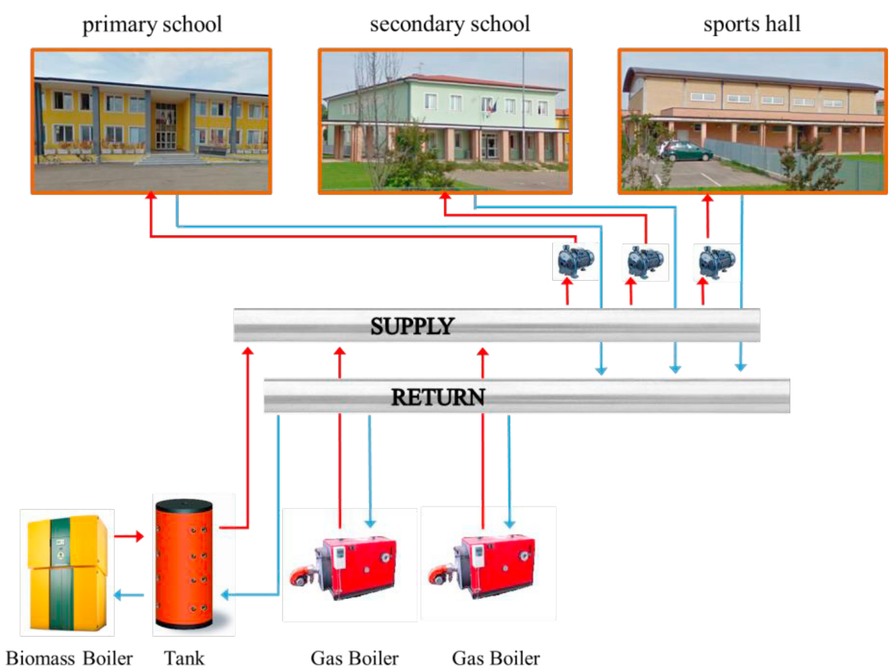

Fig. 3. Schematic representation of the considered plant

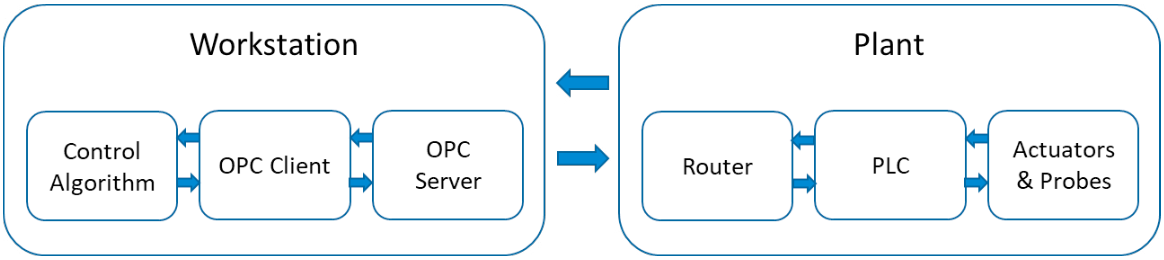

Fig. 4. Communication architecture

4. Results

The MPC algorithm functionality in the considered plant was tested for a whole winter season. Figures 5 and 6 show the results of a two-day measurement: traditional control strategies are represented with dashed lines, while the MPC strategy is represented with a full line. Interesting results were obtained when dealing with the energy conversion system management (Fig. 5), where the biomass boiler is switched on in the first part of the day, and natural gas boilers are switched on later to maintain the building internal temperature (because start-up is faster for natural gas boilers than biomass boilers).

The improved control strategy highlighted how it is better to use the biomass boiler in the morning during the start-up phase, while it is more appropriate to use gas boilers during the day in order to maintain the building internal temperature.

A further significant consideration regards pump activation. In the pre-existing configuration, pump activation was defined on the basis of specified timetables, while in the proposed strategy, pump activation is decided by considering the building thermal requirements. Switching the pumps on and off (Fig. 6) allows the required set point of the building internal temperature to be fulfilled with further electric energy saving, which has not been evaluated in this study.

A further goal of the work was to perform an endurance test. In real applications, it is very important to guarantee reliability and security in the long term. In the first test developed during the heating season, failures of the proposed control system were detected only due to interruptions in the Internet connections.

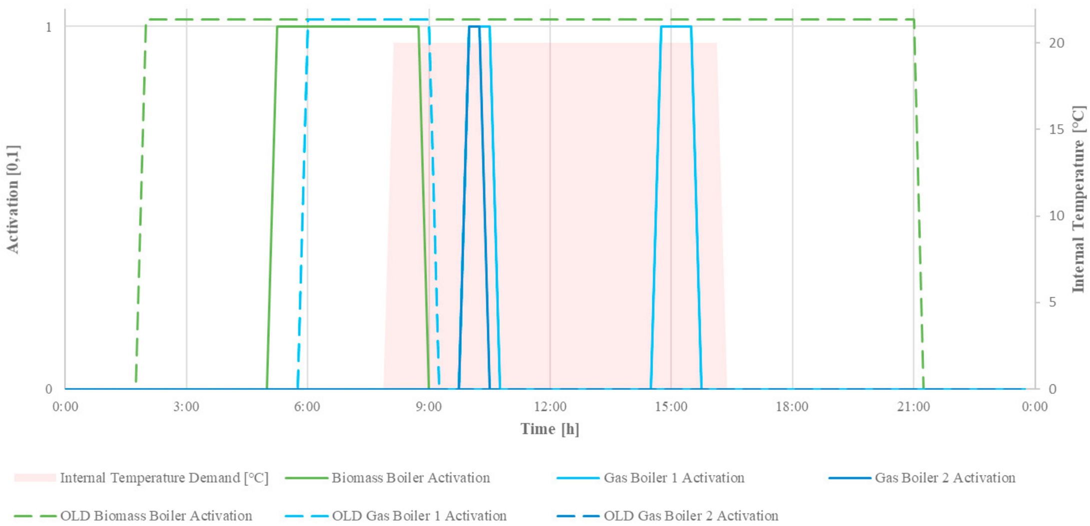

Fig. 5. Boiler management strategies

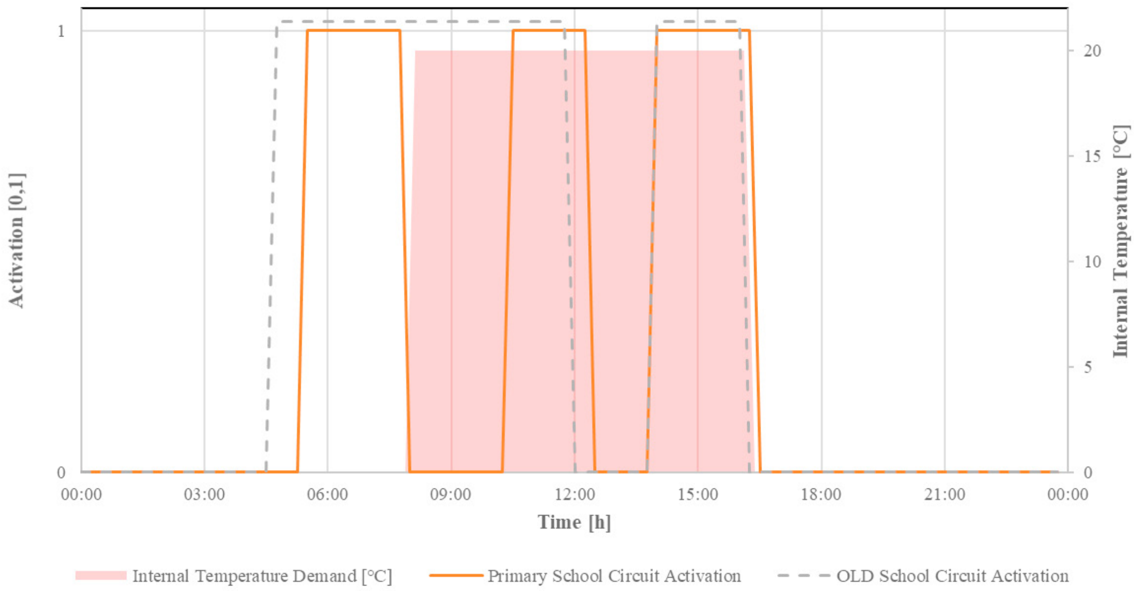

Fig. 6. Pump management strategies

5. Conclusion

In this article, an enhanced MPC-based control system has been proposed and applied to the heating system and distribution network of a school complex in the North of Italy. The MPC-based algorithm is divided into three main components: the real plant, the plant model, and the optimization algorithm. After the endurance test, very interesting results were achieved allowing for the improvement of the standard management criteria for thermal power plants. For example, in the case of the biomass boiler, which was supposed to reach lower specific fuel consumption if operated at nominal power for long periods of time, the presented application showed that its better use is limited to the morning period. In the future, this control approach will allow a significant reduction in energy consumption and environmental impact.

Thanks to this first application, plant control strategies and plant automatic control systems can be significantly improved in the years to come.

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