Predictive control and thermal energy storage for optimizing a multi-energy district boiler

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Abstract: as part of the OptiEnR research project, the present paper deals with optimizing the multi-energy district boiler of La Rochelle (France) adding to the plant a controlled thermal storage tank. This plant supplies domestic hot water and heats residential and public buildings, using renewable and fossil resources. Due to the complexity of the district boiler as a whole and the strong interactions between the sub-systems, previous works focused first on a modular approach used for the modeling of the plant. Next, a methodology based on both a multi-resolution analysis and the use of artificial neural networks was proposed to forecast the outdoor temperature and the thermal power consumption of the hot water distribution network. The present paper deals first with the modeling of a stratified thermal storage tank. Next, a basic and easy-to-implement controller was developed. Finally, using the global model of the district boiler, a model predictive controller generated optimal command sequences dealing with the flow of the water passing through the storage tank and the wood boiler set-point temperature. As a result, the consumption of fossil fuels, CO_2 emissions and functioning cost were significantly reduced. Energy is stored during low-demand periods and used when demand is high, instead of engaging the gas-fuel oil boiler.

Keywords: multi-energy district boiler, energy resources management, fossil fuels, CO_2 emissions, model predictive control, thermal energy storage.

1. Introduction

Managing energy demand, promoting renewable energy and finding ways to save energy are worldwide concerns as well as innovative solutions to fight the global energy crisis (mainly caused by both the rarefaction of fossil fuels and an excessive energy consumption: many experts believe that by 2015 the supply of oil and natural gas will be unable to keep up with demand [1]). Renewable energy is one of the ways to limit both GreenHouse Gases (GHG) emissions and the impact of climate change on environment and health. That is why the European Council's ambitious objectives of saving 20% of the energy consumption compared to projections for 2020, of reducing of at least 20% the GHG emissions compared to the 1990 level and, finally, of raising the share of renewable energy sources in its final energy consumption from around 8.5% in 2005 to 20% in 2020 then to 50% in 2040 plays a central role in the EU energy policy [2]. As part of the OptiEnR research project, the present paper, the last of a series of three [3,4], deals with optimizing the performance of a district boiler. The just-mentioned project began in late 2008 and finished in late 2010. It involved researchers from the PROMES laboratory of the University of Perpignan Via Domitia (south of France) and engineers from two French companies, Cofely GDF-Suez [5] and Weiss France [6]. Cofely GDF-Suez is currently the leading European brand for environmental and energy efficiency services while Weiss France designs, manufactures and installs automatic boiler rooms for all types of wood, biomass, wastes and fluids. The district boiler will be described later in the present paper (section 3) and is situated at La Rochelle (west coast of France). It is managed by Cofely GDF-Suez, supplies domestic hot water and heats residential and public buildings, using mainly wood and sometimes fuel or gas if necessary. As mentioned, the OptiEnR project focused on improving the performance of the plant (first optimizing the parameters of the boilers' control systems), using a controller to manage a to-be-implemented thermal storage tank (while adding new pumps). Its main objective was to minimize the use of fossil energy, storing renewable energy during low-demand periods and using it when peak-demand is high. The project consisted of the following successive tasks (Figure 1): the first

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task was to forecast outdoor temperature and thermal power consumption (of the hot water distribution network) [3]; the second task focused on modeling the district boiler [4]; the third task dealt with studying the feasibility of adding to the plant of La Rochelle a thermal storage unit and finding the most adequate storage material; the fourth task was to model the thermal storage while the fifth task focused on optimizing the boiler performance using a basic or a Model-based Predictive Controller (MPC) [7-8], the global model of the plant and forecasted sequences dealing with the above-mentioned parameters [9]. The present paper deals with the last three tasks of the project. The basic controller we proposed is an easy-to-implement controller. It does not require significant computational resource and, as a consequence, can be used easily on-line. The results we obtained demonstrate that using such a control structure one can manage efficiently a thermal storage tank. Moreover, it highlights the pertinence of the proposed approach to improve the performance of a multi-energy district boiler (in particular when plants are poorly sized). Finally, using both the models of the tank and the district boiler of La Rochelle as well as forecasted sequences about the just-mentioned parameters, a model predictive controller allowed optimizing the flow of water passing through the tank and the wood boiler functioning. Of course, control performance is better when using the model predictive controller than when using the basic controller. However, computation time is significantly increased. The key results we obtained highlight that fossil energy consumption and CO_2 emissions are reduced. Energy is stored during low-demand periods and used when demand is high, instead of engaging the gas-fuel oil boiler.

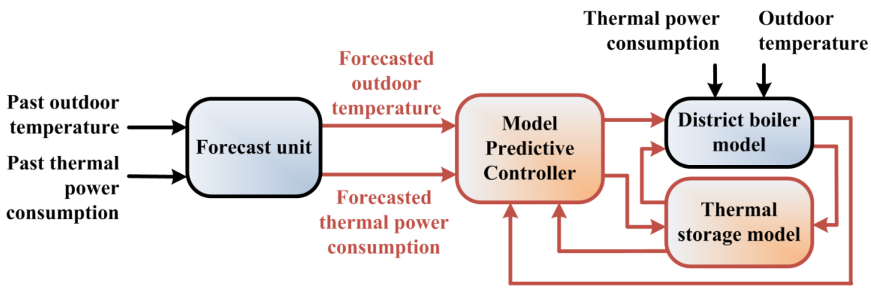

Figure 1. The OptiEnR project. In red, the proposed controlled thermal storage tank.

2. Model Predictive Control (MPC) related to energy use and management

In the present section, we highlight some interesting works about model predictive control related to energy use and management. A model predictive controller is a model-based and discrete controller that allows an optimal command sequence to be calculated. To elaborate such a sequence, one needs a model (a linear model may be used for simplicity) and a working point of the system to be controlled [10]. Originally developed to meet the specialized control needs of power plants and petroleum refineries, MPC technology can now be found in a wide variety of application areas including chemicals and energy management applications. The ability of such a controller to operate without expert intervention for long periods of time is one of the main reasons why it is getting popular. One can also note that through MPC is not inherently more or less robust than classical feedback, it can be adjusted more easily for robustness [11]. Mayne and Schroeder [12] showed that it has good properties of stability. They presented methods for constructing robust non-linear controllers for linear systems with state and control constraints. As a key point, one can highlight that model predictive controllers can be used to control non linear systems [13], hybrid systems [14-15] as well as fast systems [16]. Kambhampati et al. [13] demonstrated that, under conditions which can be fulfilled by most industrial plants, the closed-loop system is robustly stable in the presence of plant uncertainties and input-output constraints. They showed that there is no requirement for the plant to be open-loop stable and that their analysis is valid for general forms of non-linear system representation including constraint-free problems. In 2009, Lazar and Heemels presented a model predictive control scheme that achieved input-to-state stabilization for constrained discontinuous nonlinear and hybrid systems [14].

Taking a look at the latest and significant industrial applications related to energy resources management and MPC technology, one can highlight some interesting works. In 2006, Blasco et al. [17] proposed an alternative to greenhouse climatic control using MPC methods. As the proposed prediction model was non-linear and not easy to adjust, genetic algorithms were used to solve the optimization problem. In 2010, Morosan et al. [18] presented a predictive control structure for thermal regulation in buildings. The method they proposed takes advantage of the intermittently operating mode of almost all types of buildings. The same year (i.e. 2010), Paris et al. [19] used PID and MPC controllers for managing resources in multi-energy buildings. The control scheme they proposed can be implemented in buildings even if a control system based on a classical PID controller is already in use.

3. The district boiler of La Rochelle

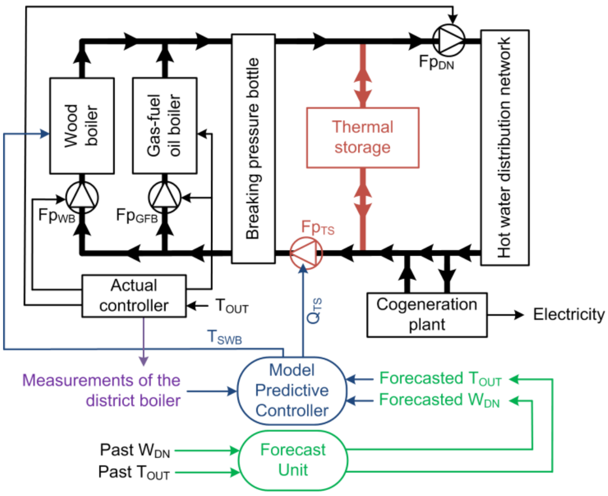

Figure 2. Synopsis of the district boiler of La Rochelle (including the proposed modifications).

The district boiler of La Rochelle (Figure 2) is composed of a breaking pressure bottle, a cogeneration plant and two thermal boilers. The first one, a 4.5 MW wood boiler, uses renewable energy. The second one, a 7 MW gas-fuel oil boiler, uses fossil energy. Both boilers have smokes and air-to-water heat exchangers. They supply hot water to the collecting hydraulic circuit according to a temperature set-point which is defined from outdoor temperature. During the cold season (from October to May), the wood boiler is continuously running while its heating power is adapted to the demand. The gas-fuel oil boiler functions during very cold periods only, when the wood boiler fails to respond to the demand. The primary hydraulic circuit (3000 m^3), or "distribution network", supplies hot water to heat residential and public buildings, for a total of 2700 accommodations. Domestic hot water is also produced, for a total of 3500 accommodations. The cogeneration plant, connected to the "return" part of the primary hydraulic circuit, produces electricity using gas and warms up the cold water before it goes back to the collecting hydraulic circuit. The breaking pressure bottle pulls apart the two hydraulic circuits, because of the difference between their respective flows.

The coverage rates of the three heat generators are 50% (wood boiler), 15 to 20% (gas-fuel oil boiler) and 30 to 35% (cogeneration plant), respectively. To minimize the gas-fuel oil boiler coverage rate, we proposed to add a thermal storage unit to the plant (Figure 2) with the aim of storing hot water when the demand is low and using it when the demand cannot be met by the wood boiler. This is a classical solution to optimize the functioning of boilers used to heat buildings [20-22]. Thus, the gas-fuel oil boiler will be only used when both the hot water demand is very high and the thermal storage unit is empty. The flow of the water passing through this unit (Q_{TS}) will be adjusted thanks to the control of the thermal storage feed pump (Fp_{TS}). With the aim of optimizing the use of this thermal storage unit and reducing the fossil boiler coverage rate, a model predictive controller will define over the next 4 hours and 30 minutes the optimal sequence of Q_{TS} and the wood boiler set-point temperature (T_{SWB}), taking into consideration some parameters measured at the district boiler as well as both the forecasted outdoor temperature (T_{out}) and thermal power consumption (of the distribution network) (W_{DN}). The wood (Fp_{WB}) and gas-fuel oil (Fp_{GFB}) boilers feed pumps are controlled using a standard on/off controller. Fp_{DN} is the distribution network feed pump (Figure 2). In the next section, we summarize briefly the way the first two tasks were accomplished.

4. Previous works: synthesis

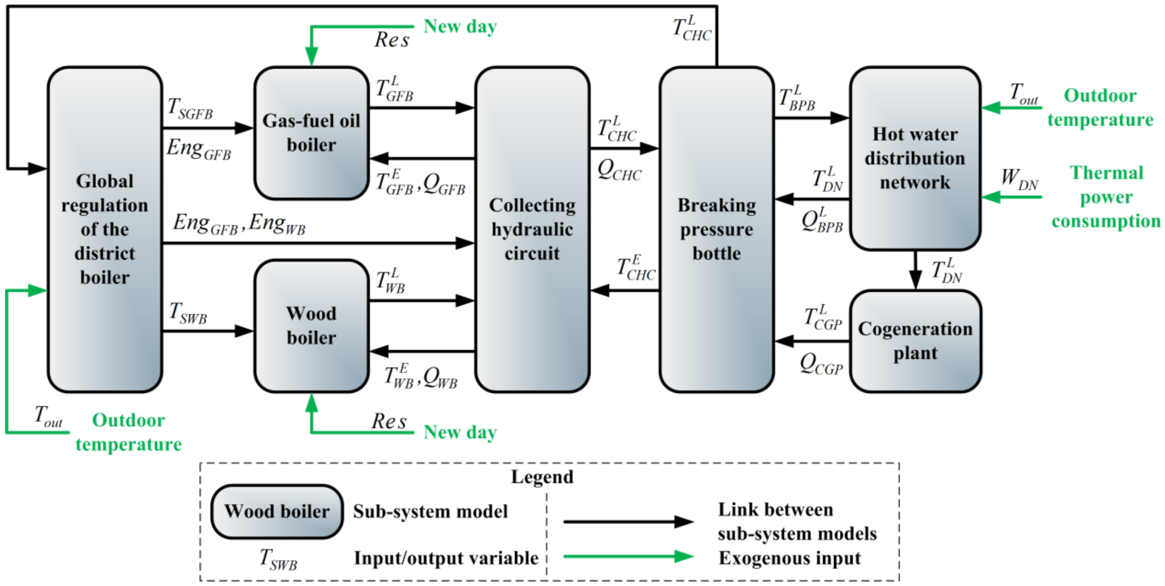

Figure 3. Modular approach proposed to model the district boiler of La Rochelle [4].

As mentioned previously, the first task of the OptiEnR project focused on forecasting both the outdoor temperature and the thermal power consumed by the hot water distribution network. The proposed short-term forecast method was based on the concept of time series [23] and used a wavelet-based multi-resolution analysis and artificial neural networks [3]. The discrete wavelet transform [24] allowed decomposing sequences of past data in subsequences according to different frequency domains, while preserving their temporal characteristics. From these coefficients, artificial neural networks were used to estimate future subsequences of 4 hours and 30 minutes (this forecasting horizon was defined as a compromise between energy storage considerations and computation time). Future values of the two above-mentioned variables were then obtained by simply summing up the estimated coefficients. One can highlight that substituting the prediction task of an original time series of high variability by the estimation of its wavelet coefficients on different levels of lower variability was the main idea of the method. In addition, the sequences of past data were completed, for each of their components, by both the minute of the day and the day of the year to place the developed forecast model in time. The results we obtained validate the proposed methodology and highlight both the impact of working with wavelet-decomposed sequences as well as the generalization capability of multi-layer neural networks [3]. Moreover, and because of both the complexity of the district boiler as a whole and the strong interactions between the sub-systems, a modular approach [4] was proposed to model the plant (the second task of the project). According to what information is available, a combination of white, grey and black boxes was used. In some cases, additional parameters were proposed and identified to answer for the lack of information. Finally, when the sub-models accuracy was as good as possible, these models were combined to obtain the district boiler model (Figure 3). The results we obtained show that the proposed global model is able to describe correctly the behaviour of the district boiler [4].

5. Thermal energy storage

This section is dedicated to the modelling of a thermal energy storage unit, used to optimize the district boiler functioning. First, some hypotheses about the material used, the characteristics of the tank as well as the way it can be implemented (i.e. the required hydraulic modification of the plant of La Rochelle) were discussed with our industrial partner (Cofely GDF-Suez) and local operators. The section of the paper also deals with the model of the thermal storage unit we developed and ends with the way one can combine this model and the district boiler model.

5.1. Hypotheses

Adding to the district boiler an energy storage unit allows, when demand is high, using the excess of energy produced by the wood boiler during low-demand periods, instead of consuming gas and fuel oil. As a result, the coverage rate of the fossil energy used can be significantly reduced thanks to a better exploitation of the available renewable resources. Many options about the materials one can use to store energy were considered but due to technical reasons, their cost, the constraints related to their integration into the district boiler, their toxicity, their flammability or their relative low power, phase change materials were not used. So, we decided for a hot water tank. Some hypotheses about its shape, size and position were made. We proposed a vertical cylindrical tank whose diameter is equal to its height with the aim of minimizing its surface and, as a consequence, thermal losses. For the same reason, we supposed the tank, whose thermal insulation is insured by 10 cm of polypropylene, to be buried in the ground, where ambient temperature (T_{amb}) is about 10°C. The inlet fluid temperature (T_{in}) affects the first layers of water in the tank only, because of a grid used to protect its thermal stratification.

5.2. Modelling of the thermal storage unit

In 1999, Alizadeh investigated experimentally and numerically the thermal behaviour of a horizontal storage tank. As mentioned in his paper [25], thermally stratified storage tanks have been widely used in solar domestic hot water heating systems. In such systems, the hot water remains separated from the cold water by means of buoyancy forces rather than physical barriers. Stratified storage tanks are cost effective in both construction and operational phases and are more reliable than those employing physical barriers for producing and maintaining stratification [26]. Four sets of experiment have been carried out where cold water is injected into the bottom of the tank with three different initial thermal fields. As a result, Alizadeh proposed two simple one-dimensional numerical models, i.e. the "turbulent" and the "displacement mixing" models, for predicting the transient behaviour of vertical temperature distribution inside the tank. The displacement mixing models are defined according to two different conditions in which both the fluid thermal conductivity and heat losses to the ambient are considered or neglected. As a key result, Alizadeh obtained reasonable agreement between predicted and experimental data over the top two-thirds of the tank. The discrepancies observed in the bottom of the tank were attributed to the introduced mixing which is not properly considered in the model. The model of the vertical hot water tank we developed is based on the above displacement mixing model. Both the volume and the section of the layers are constant. This model has three inputs: the temperature of the water entering (at the top or the bottom) the tank (T_{in}), a Boolean variable ($Mode_{TS}$) characterizing the storage unit working mode and, finally, the absolute value of the flow of the water passing through this unit (Q_{TS}), from the top to the bottom or from the bottom to the top. If $Mode_{TS} = 1$ (energy storage mode), the tank is fed from its upper part. If $Mode_{TS} = 0$ (energy release mode), the tank is fed from its lower part. The volume of a fluid layer (V) is given by equation (1), with V_{tot} the tank volume and n its number of layers:

$$V = \frac{V_{tot}}{n} \tag{1}$$

The volume of water entering the tank during a time interval is given by equation (2), with Q_{TS} the flow of the water passing through the unit and T_S the sampling time:

$$\Delta V = \frac{Q_{TS} \cdot T_S}{3600} \tag{2}$$

Equations (3) and (4) define two parameters related to thermal losses (i^{th} layer of fluid), α_i and β_i, with V the volume of a fluid layer, P the cylinder cross-section, U_L the tank overall heat transfer coefficient (calculated with equation (5)), Cp_{water} and ρ_{water} the specific heat capacity and the density of water, respectively, Δz_i the height of the i^{th} layer of fluid and T_S the sampling time:

$$\alpha_i = V + \beta_i \tag{3}$$

$$\beta_i = \left[U_L \cdot \frac{P}{(Cp_{water} \cdot \rho_{water})} \right] \cdot T_S \cdot \Delta z_i \tag{4}$$

The tank overall heat transfer coefficient (U_L) is defined by equation (5), with h_{air} and h_{water} the respective convection heat transfer coefficients of air and water, respectively, k_{pp} the thermal conductivity of polypropylene (as mentioned in section 5.1, polypropylene is used as insulating material) and Δx the thickness of the polypropylene layer:

$$U_L = \frac{1}{\dfrac{1}{h_{air}} + \dfrac{\Delta x}{k_{pp}} + \dfrac{1}{h_{water}}} \tag{5}$$

Equations (6), (7), (8) and (9) depict the model proposed for energy storage (the tank is fed from its upper part with hot water) and release (the tank is fed from its lower part with cold water), with e the number of layers directly affected by the inlet fluid temperature (only for these layers, the inlet fluid and the fluid already inside the tank intermix), T_i the temperature of the i^{th} layer of fluid and k the time index (the other variables have already been defined):

- Energy storage mode ($Mode_{TS} = 1$), $\forall i \in [\![1,n]\!]$:

$$For\ i > n - e,\ T_i(k+1) = \frac{\left(V - \left(\dfrac{\Delta V}{e}\right)\right) \cdot T_i(k) + \left(\dfrac{\Delta V}{e}\right) \cdot T_{in}(k) + \beta_i \cdot T_{amb}(k)}{\alpha_i} \tag{6}$$

$$For\ i \leq n - e,\ T_i(k+1) = \frac{(V - \Delta V) \cdot T_i(k) + \Delta V \cdot T_{i+1}(k) + \beta_i \cdot T_{amb}(k)}{\alpha_i} \tag{7}$$

- Energy release ($Mode_{TS} = 0$), $\forall i \in [\![1,n]\!]$:

$$For\ i \leq e,\ T_i(k+1) = \frac{\left(V - \left(\dfrac{\Delta V}{e}\right)\right) \cdot T_i(k) + \left(\dfrac{\Delta V}{e}\right) \cdot T_{in}(k) + \beta_i \cdot T_{amb}(k)}{\alpha_i} \tag{8}$$

$$For\ i > e,\ T_i(k+1) = \frac{(V - \Delta V) \cdot T_i(k) + \Delta V \cdot T_{i-1}(k) + \beta_i \cdot T_{amb}(k)}{\alpha_i} \tag{9}$$

After modeling with equations (6) to (9) the way the fluid temperature is evolving inside the tank, one needs to calculate the temperature of the water leaving this tank, using the flow of the water passing through the storage unit as well as the fluid temperature for the top (in energy storage mode) or the bottom (in energy release mode) layers. If the volume of water leaving the tank during a time interval is lower than the volume of a layer, the temperature of the leaving water will be equal to the temperature of the top ($T_{TS}^{bot} = T_1$) or the bottom ($T_{TS}^{top} = T_n$) layer, in energy storage and release mode, respectively. Table 1 summarizes the main parameters of the proposed storage model.

5.3. Hydraulic modification of the plant of La Rochelle

The characteristics of the thermal storage unit being defined, one may think about the way the tank would be integrated into the district boiler of La Rochelle. That is why we proposed a hydraulic modification of the plant, as shown in red on Figure 2. We decided to place the tank between the breaking pressure bottle and the hot water distribution network, before the feed pump of the distribution network and after the cogeneration plant. A new pump (Fp_{TS}) is used to control the flow of the water passing through the tank. When the wood boiler works alone, one can store or release energy. To store energy, the flow of the pump Fp_{TS} has to be higher than the flow of the pump Fp_{DN} (the distribution network feed pump). The difference between these two flows is the flow of the water passing through the storage unit. Conversely, to release energy, the flow of the pump Fp_{TS} has to be lower than the flow of the pump Fp_{DN}. Again, the difference between these two flows is the flow of the water passing through the storage unit (Figure 2). With this approach, the difference in flows between the collecting and the primary hydraulic circuits is compensated by the recycling process carried out inside the breaking pressure bottle (section 3). So, one can easily control the flow of the water passing through the storage tank (from the top to the bottom or from the bottom to the top) [4] thanks to the pump Fp_{TS}.

Table 1. Parameters of the storage tank model.

Parameter	Value	Unit	Parameter	Value	Unit
V_{tot}	2000 (default)	m^3	k_{pp}	0.1	$W.m^{-1}.K^{-1}$
n	20	-	h_{air}	50	$W.m^{-2}.K^{-1}$
e	2	-	h_{water}	5000	$W.m^{-2}.K^{-1}$
Δx	0.1	m	Cp_{water} (75°C)	75504	$J.mol^{-1}.K^{-1}$
U_L	1.2	$W.m^{-2}.K^{-1}$	ρ_{water} (75°C)	54.46	$mol.m^{-3}$

5.4. Combination of the district boiler and the storage unit models

To reflect the impact of the thermal storage unit on the district boiler, some subsidiary models were developed, as shown by Figure 4. Indeed, some flows between the breaking pressure bottle and the thermal storage tank changed while some temperatures were affected by the tank functioning (sections 5.4.1 to 5.4.4).

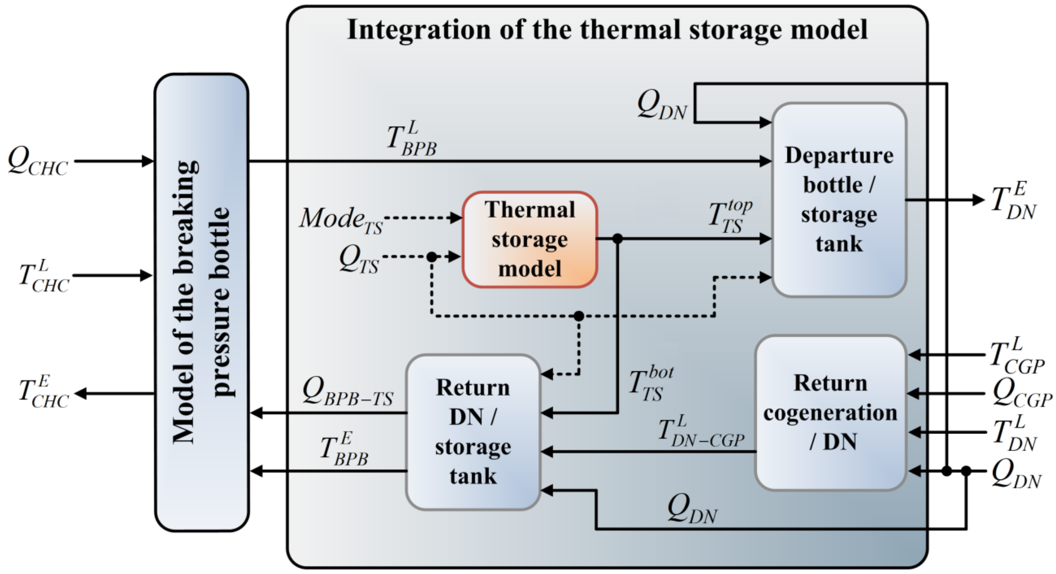

Figure 4. Subsidiary models developed to combine the plant and the thermal storage models.

5.4.1. Temperature of the water entering the distribution network

Without thermal storage tank, the temperature of the water entering the distribution network (T^E_{DN}) is equal to the temperature of the water leaving the breaking pressure bottle (T^L_{BPB}) [4]. However, implementing the tank modifies partially the calculation of T^E_{DN}. In storage mode, a part of the water leaving the breaking pressure bottle enters the distribution network while another part enters the tank. In this case, the calculation of T^E_{DN} remains unchanged (i.e. $T^E_{DN} = T^L_{BPB}$). In release mode, the water leaving the tank at the top is mixed with the water leaving the breaking pressure bottle. As a consequence, T^E_{DN} can be expressed as a power balance between T^L_{BPB} and T^{top}_{TS} (the temperature of the water leaving the thermal storage tank at the top), weighted by their respective flows (Q_{DN} and Q_{TS}). With $Mode_{TS}$ the Boolean variable characterizing the storage unit working mode (section 5.2) and Q_{TS} the flow of the water passing through the tank, equation (10) depicts the temperature of the water entering the distribution network:

$$T_{DN}^{E} = \frac{T_{BPB}^{L} \cdot (Q_{DN} - Q_{TS} \cdot (1 - Mode_{TS})) + T_{TS}^{top} \cdot Q_{TS} \cdot (1 - Mode_{TS})}{Q_{DN}} \tag{10}$$

5.4.2. Temperature of the mix of water back from the distribution network and leaving the cogeneration plant

Without thermal storage unit, the temperature of the mix of water back from the distribution network and leaving the cogeneration plant (T_{DN-CGP}^{L}) is equal to the temperature of the water entering the breaking pressure bottle (T_{BPB}^{E}) [4]. As for T_{DN}^{E} (section 5.4.1), implementing the tank modifies the calculation of T_{DN-CGP}^{L}. As a consequence, T_{DN-CGP}^{L} can be expressed as a power balance between the temperatures of both the water back from the distribution network (T_{DN}^{L}) and the water leaving the cogeneration plant (T_{CGP}^{L}), weighted by their respective flows ($Q_{DN} - Q_{CGP}$ and Q_{CGP}) (equation (11)):

$$T_{DN-CGP}^{L} = \frac{T_{DN}^{L} \cdot (Q_{DN} - Q_{CGP}) + T_{CGP}^{L} \cdot Q_{CGP}}{Q_{DN}} \tag{11}$$

5.4.3. Flow of the water between the breaking pressure bottle and the thermal storage tank

In storage mode, the flow of the water between the breaking pressure bottle and the thermal storage tank ($Q_{BPB\text{-}TS}$) is given by the sum of the respective flows of the water passing through the distribution network (Q_{DN}) and the water passing through the tank (Q_{TS}). In release mode, $Q_{BPB\text{-}TS}$ is given by the difference between Q_{DN} and Q_{TS} (equation (12)):

$$Q_{BPB-TS} = Q_{DN} + (2 \cdot Mode_{TS} - 1) \cdot | Q_{TS} | \tag{12}$$

5.4.4. Temperature of the water entering the breaking pressure bottle

Without thermal storage unit, the temperature of the water entering the breaking pressure bottle (T_{BPB}^{E}) is equal to the temperature of the mix of water coming back from both the distribution network and the cogeneration plant (T_{DN-CGP}^{L}). With the tank, the impact of the storage process ($Mode_{TS} = 1$) has to be taken into consideration. Indeed, the cold water leaving the tank at the bottom (its temperature is T_{TS}^{bot}) is mixed with the water coming back from both the distribution network and the cogeneration plant. Consequently, T_{BPB}^{E} can be expressed as the mean of T_{DN-CGP}^{L} and T_{TS}^{bot}, weighted by their respective flows (Q_{DN} and Q_{TS}) (equation (13)):

$$T_{BPB}^{E} = \frac{T_{DN-CGP}^{L} \cdot Q_{DN} + (T_{TS}^{bot} \cdot Q_{TS}) \cdot Mode_{TS}}{Q_{DN} + | Q_{TS} | \cdot Mode_{TS}} \tag{13}$$

6. Criteria for optimizing the district boiler performance

The present section of the paper deals with the criteria we defined to optimize the plant performance using control schemes. These criteria are based on the energy and environmental characteristics of the combustibles used to produce heat by burning [27,28].

6.1. Global consumption cost

The first criterion we defined is the "global consumption cost" J_1, expressed in € (equation (14)). It is based on the respective consumptions of wood (related to the number of tappet strokes per five minutes), gas and fuel oil as well as on the unitary cost of these combustibles ($UC_{wood} = 1.8648$ €.$\text{N}_{\text{tappet}}^{-1}$, $UC_{gas} = 0.378$ m^{-3} and $UC_{FOD} = 0.40$ €.l^{-1}):

$$J_1 = UC_{wood} \times N_{tappet} + UC_{gas} \times V_{gas} + UC_{FOD} \times V_{FOD} \tag{14}$$

6.2. Temperature set-point error

The second criterion we defined (J_2) is related to the temperature of the water entering the distribution network. If this temperature (T_{DN}^{E}) is lower than the set-point (T_{SDN}) chosen by the operators of the district boiler of La Rochelle, the correct heating of the district buildings will be problematic. Moreover, the storage of hot water when the energy demand is low requires a temperature for the water leaving the breaking pressure bottle and, as a consequence, entering the distribution network, higher than T_{SDN}. That is why we defined J_2 (expressed in °C) as the mean temperature set-point error, taking only into consideration $T_{DN}^{E}(k) < T_{SDN}(k)$, with k the time index (equation (15)):

$$J_2 = \frac{1}{2 \cdot N} \sum_{k=1}^{N} (| T_{SDN}(k) - T_{DN}^{E}(k) | - (T_{DN}^{E}(k) - T_{SDN}(k))) \tag{15}$$

So, if $T_{SDN}(k) > T_{DN}^{E}(k), | T_{SDN}(k) - T_{DN}^{E}(k) | = T_{SDN}(k) - T_{DN}^{E}(k)$ and $J_2(k) = T_{SDN}(k) - T_{DN}^{E}(k) \geq 0$. By contrast, if $T_{SDN}(k) \leq T_{DN}^{E}(k), | T_{SDN}(k) - T_{DN}^{E}(k) | = T_{DN}^{E}(k) - T_{SDN}(k)$ and $J_2\ (k) = 0$.

6.3. Primary energy consumption

The third criterion we defined (J_3) deals with the energy efficiency of the district boiler of La Rochelle (equation (16)). It is expressed in kWh and based on the respective consumptions of wood (again related to the number of tappet strokes per five minutes), gas and fuel oil as well as on the unitary low heating value of these combustibles ($UE_{wood} = 133.2$ kWh.$\mathrm{N}_{\mathrm{tappet}}^{-1}$, $UE_{gas} = 10.5$ kWh.m^{-3} and $UE_{FOD} = 9.76$ kWh.l^{-1}):

$$J_3 = UE_{wood} \times N_{tappet} + UE_{gas} \times V_{gas} + UE_{FOD} \times V_{FOD} \tag{16}$$

6.4. Fossil energy coverage rate

Because of the rarefaction of fossil fuels, leading to a significant increase of production costs, one of the main objectives of the OptiEnR project is to reduce the fossil energy consumption. That is why we defined a criterion (J_4) dealing with the fossil energy coverage rate (%), expressed as the ratio between the fossil energy (gas and fuel oil) and the total energy consumed (equation (17)):

$$J_4 = \frac{UE_{gas} \times V_{gas} + UE_{FOD} \times V_{FOD}}{UE_{wood} \times N_{tappet} + UE_{gas} \times V_{gas} + UE_{FOD} \times V_{FOD}} \tag{17}$$

6.5. CO_2 emissions

CO_2 is emitted naturally through both the carbon cycle and human activity, like the burning of fossil fuels. The release of GHG and aerosols resulting from human activity are changing the amount of radiation coming into and leaving the atmosphere, likely contributing to climate change. That is why the fifth criterion we defined (J_5) focuses on CO_2 emissions (equation (18)). So, the CO_2 emissions of the plant of La Rochelle can be expressed, in kgCO_2, as the sum of the respective parts of the combustibles used. It is based on the consumptions of wood (again related to the number of tappet strokes per five minutes), gas and fuel oil as well as on the unitary CO_2 emissions of these combustibles ($ULCA_{wood} = 1.7316$ kgCO_2.$\mathrm{N}_{\mathrm{tappet}}^{-1}$, $ULCA_{gas} = 2.28384$ kgCO_2.m^{-3} and $ULCA_{FOD} = 2.928$ kgCO_2.l^{-1}):

$$J_5 = ULCA_{wood} \times N_{tappet} + ULCA_{gas} \times V_{gas} + ULCA_{FOD} \times V_{FOD} \tag{18}$$

6.6. Combined criterion

Finally, we defined a "combined" criterion (J_6) allowing taking into account all the just mentioned considerations (%), related to the consumption cost (J_1), the temperature set-point error (J_2), the primary energy consumption (J_3), the fossil energy coverage rate (J_4) and the CO_2 emissions (J_5). These criteria being expressed with different units of measurements, we decided to norm them on the basis of their respective values without process of energy storage (equation (19)):

$$J_6 = \frac{1}{5} \times \sum_{n=1}^{5} 100 \times \frac{J_n(\textit{with energy storage})}{J_n(\textit{without energy storage})} \tag{19}$$

7. Design of a basic controller

First, a basic controller has been designed. It does not require significant computational resource and regulates on-line the flow of the water passing through the thermal storage tank (Q_{TS}), from the respective temperatures of the water leaving the breaking pressure bottle (T_{BPB}^{L}), the water entering the distribution network (T_{DN}^{E}) and the water at the top of the tank (T_{TS}^{top}).

7.1. Energy storage mode

7.1.1. Hypothesis and conditions

Energy can be stored if the temperature of the water leaving the breaking pressure bottle (T_{BPB}^{L}) is higher than the distribution network set-point temperature (T_{SDN}) (condition 1). Moreover, the gas-fuel oil boiler does not operate ($Eng_{GFB} = 0$) (condition 2) (equation (20)). Otherwise, energy storage would be the result of fossil fuels (gas and fuel oil) combustion, leading to an increase of fossil fuel consumption. Of course, one can store energy only when the district boiler production is too large. In this case, a part of the hot water leaving the breaking pressure bottle enters the storage tank at the top. As a consequence, the flow of the water entering the distribution network (Q_{DN}) is equal to the difference between the flow of the water leaving the breaking pressure bottle (Q_{BPB}^{L}) and the flow of the water entering the tank (Q_{TS}). Because Q_{DN} is fixed by the distribution network feed pump (Figure 2), Q_{BPB}^{L} is the flow we adapted. We fixed a maximal value for Q_{TS} (Q_{TS}^{max}) (equation (20)) slightly lower than Q_{DN} to preserve a positive flow for the water leaving the breaking pressure bottle:

$$(Eng_{GFB} = 0) \wedge (T_{BPB}^{L} > T_{SDN}) \Rightarrow 0 \geq Q_{TS} \geq -Q_{DN} + 5 = Q_{TS}^{max} \tag{20}$$

7.1.2. Feeding of the storage tank

It seems wise to store hot water if the temperature of the water leaving the breaking pressure bottle (T_{BPB}^{L}) is higher or equal to the temperature of the water at the top of the tank (T_{TS}^{top}). In this case, equation (21) expresses the flow of the water entering the tank (Q_{TS}), with K_{in} a parameter to be optimized:

$$T_{TS}^{top} \leq T_{BPB}^{L} \Rightarrow Q_{TS} = K_{in} \cdot Q_{TS}^{max} \cdot \frac{T_{BPB}^{L} - T_{SDN}}{T_{DN}^{E}} \tag{21}$$

7.1.3. No feeding possibilities

If the temperature of the water leaving the breaking pressure bottle (T_{BPB}^{L}) is lower than the temperature of the water at the top of the tank (T_{TS}^{top}), its feeding has to be stopped. Indeed, mixing the hot water one can find at the top of the tank with coldest water coming from the breaking pressure bottle would damage the stratification of the tank. That is why, in this case, the flow of the water entering the tank will be zero (equation (22)):

$$T_{BPB}^{L} < T_{TS}^{top} \Rightarrow Q_{TS} = 0 \tag{22}$$

7.2. Energy release mode

7.2.1. Hypothesis and conditions

Energy can be released if the temperature of the water leaving the breaking pressure bottle (T_{BPB}^{L}) is lower than the distribution network set-point temperature (T_{SDN}). In this case, energy is needed to increase the temperature of the water entering the distribution network (T^E_{DN}). So, hot water can leave the storage tank at the top and be mixed with the water leaving the breaking pressure bottle while the cold water coming back from the network can enter the tank at the bottom. The flow of the water passing through the storage tank (Q_{TS}) does not be higher than the distribution network flow (Q_{DN}) to avoid an inversion of the updraft and downdraft flows (Q^{up}_{BPB} and Q^{down}_{BPB}) inside the breaking pressure bottle (equation (23)). As a result, T^E_{DN} is equal to the mean of the temperatures of the water leaving the breaking pressure bottle (T^L_{BPB}) and the water leaving the storage tank (T^{top}_{TS}), weighted by their respective flows (equation (24)):

$$T^L_{BPB} < T_{SDN} \Rightarrow 0 \leq Q_{TS} \leq Q_{DN} - 5 = Q^{max}_{DN} \tag{23}$$

$$T^E_{DN} = \frac{T^L_{BPB} \cdot (Q_{DN} - Q_{TS}) + T^{top}_{TS} \cdot Q_{TS}}{Q_{DN}} \tag{24}$$

7.2.2. Optimal use of the energy released from the tank

If the temperature of the water at the top of the tank (T^{top}_{TS}) is higher than the distribution network set-point temperature (T_{SDN}), one can calculate what should be the flow of the water passing through the storage tank (Q_{TS}) (equation (25)) to obtain for the water entering the distribution network (T^E_{DN}) a temperature equal to T_{SDN} (equation (26)):

$$T^{top}_{TS} > T_{SDN} \Rightarrow Q_{TS} = -Q_{DN} \cdot \frac{T_{SDN} - T^L_{BPB}}{T^{top}_{TS} - T^L_{BPB}} \tag{25}$$

$$T^E_{DN} = T_{SDN} \tag{26}$$

7.2.3. Limited use of the energy released from the tank

Energy can also be released if the temperature of the water at the top of the tank (T^{top}_{TS}) is higher than the temperature of the water leaving the breaking pressure bottle (T^L_{BPB}) but lower than the distribution network set-point temperature (T_{SDN}). In this case, one can find a value for the flow of the water passing through the storage unit (Q_{TS}) leading to $T^E_{DN} = T_{SDN}$. However the energy released from the tank increases T^E_{DN} and delays (avoids) the gas-fuel oil boiler engaging (equation (27)). K_{out} is a parameter to be optimized:

$$T^L_{BPB} < T^{top}_{TS} < T_{SDN} \Rightarrow Q_{TS} = -K_{out} \cdot Q^{max}_{TS} \tag{27}$$

7.2.4. No release possibilities

If the temperature of the water at the top of the tank (T^{top}_{TS}) is lower than the temperature of the water leaving the breaking pressure bottle (T^L_{BPB}), it is unwise to use the storage tank. Indeed, this would decrease T^E_{DN} and accelerate the gas-fuel oil boiler engaging. In this case, the flow of the water passing through the tank (Q_{TS}) is fixed to zero (equation (28)):

$$T^{top}_{TS} < T^L_{BPB} < T_{SDN} \Rightarrow Q_{TS} = 0 \tag{28}$$

7.3. Wood boiler set-point temperature

The current district boiler operation is not adequate for an optimal use of a thermal storage tank. Indeed, the power to be supplied to the distribution network varies with time. As a result, the wood boiler set-point temperature (T_{SWB}) also varies. When the hot water demand is low (when outdoor temperature is high), T_{SWB} is low, what does not enable energy storage. Moreover, the basic controller we proposed as a first approach is not able to take into account the future hot water demand. As a consequence, we proposed as a solution to find an appropriate and constant value for the wood boiler set-point temperature, allowing storing energy during low demand periods and releasing it when demand is high (equation (29)):

$$T_{SWB} = constant \tag{29}$$

8. Design of a model predictive controller

The model predictive controller we designed uses the global model of the district boiler (i.e. including the model of the thermal storage unit) (sections 4 and 5) as well as forecasted sequences dealing with outdoor temperature (T_{out}) and thermal power consumption (W_{DN}) (section 4) [3,4]. This controller defines, according to the storage unit working mode ($Mode_{TS}$), the flow of the water passing through the tank (Q_{TS}) and the wood boiler set-point temperature (T_{SWB}) (Figure 2). Of course, computation time is significantly increased when using such a control approach instead of the basic controller.

8.1. Controller configuration

We simulated the behaviour of the plant of La Rochelle and tested the proposed model predictive controller for a given period of 45 consecutive days. One of the parameters to be considered when one wants to implement such a controller is the forecasting horizon (H_f). H_f deals with simulation time and, as a consequence, with the minimization of the chosen objective function (section 6). As previously mentioned (section 4), it is set to 4 hours and 30 minutes. Let us remember that this forecasting horizon was defined in agreement with operators from Cofely GDF-Suez as a compromise between energy storage considerations and computation time. This leads to a total of 54 points, using a sampling time of 5 minutes. Another significant parameter when implementing such a controller is the control horizon (H_c) whose length (set to 3 hours, due to forecast accuracy deterioration over time) is lower or equal to H_f. As a result, command values can vary in time for the first 36 points of the sequence and cannot for the last 18 points. As a key point, one can note that new command sequences can only be applied in real time if the optimization phase is shorter than a time interval. That is why, with the aim of reducing computation time (in simulation and because of *in situ* limited computer resources), we limited the number of evaluations of the chosen objective function to 100. One can also note that command sequences were upsampled by a factor of 6. As a consequence, the numerical optimizer used will only calculate a command value every 30 minutes (for a total of 9 values, according to the above mentioned forecasting horizon of 4 hours and 30 minutes). With such a sampling time, one can avoid high frequency variations in the command sequence without impacting negatively the control performance as well as the way energy can be stored and released. Interpolation gives intermediate command values. Moreover, we decided to apply to the considered system the first 6 components of an optimal command sequence, instead of applying the first component only. The number of optimization phases is so reduced by a factor of 6. So, optimization has been done every 30 minutes instead of every 5 minutes. This also reduced computation time. It was finally of about 3 days to simulate the behavior of the plant of La Rochelle during the 45 consecutive days we considered.

8.2. Optimization problem

Equations (30) and (31) depict the optimization problem related to the district boiler control. Command sequences dealing with both the flow of the water passing through the storage tank (Q_{TS}) and the wood boiler set-point temperature (T_{SWB}) are so optimized thanks to the minimization of the chosen criteria, which is, as decided by industrial partner Cofely GDF-Suez, the global consumption cost J_1 (defined in section 6.1). Of course one can choose another of the proposed criteria as objective function, depending on the way the district boiler is managed. f and c are the prediction and control horizon indexes, respectively, and k is the time index (equation (30)):

$$\min_{\begin{pmatrix} Q_{TS}(k/k),\ldots,Q_{TS}(k+c-1/k) \\ T_{SWB}(k/k),\ldots,T_{SWB}(k+c-1/k) \end{pmatrix}} J_1 \tag{30}$$

$$\begin{cases} \textit{Global model of the district boiler with predicted input sequences} \\ 0 \le Q_{TS}(k+i\,/\,k) \le Q_{DN} - 10,\ \forall i \in [\![0, f-1]\!] \\ (Eng_{GFB}(k+i\,/\,k)=1) \vee (T_{BPB}^{L}(k+i\,/\,k)) \le T_{TS}^{top}(k+i\,/\,k) \Rightarrow Q_{TS}(k+i\,/\,k) \le 0,\ \forall i \in [\![0, f-1]\!] \\ 90°C \le T_{SWB} \le 97°C,\ \forall i \in [\![0, f-1]\!] \\ \Delta Q_{TS}(k+h) = 0 \textit{ and } \Delta T_{SWB}(k+h) = 0,\ \forall h \in [\![c, f-1]\!] \\ (f,c) = (54,36) \end{cases} \quad (31)$$

Equation (31) deals with the path constraints we defined. In particular, one can highlight that the tank cannot store hot water when the gas-fuel oil boiler works ($Eng_{GFB} = 1$) while thermal stratification must always be ensured. That is why we need a temperature of the water leaving the breaking pressure bottle (T_{BPB}^{L}) higher than the temperature of the water at the top of the tank (T_{TS}^{top}) to store energy.

8.3. Objective function minimization

The global model of the district boiler of La Rochelle we developed (sections 4 and 5) being strongly non-linear, one cannot use solvers with local convergence only. Indeed, such solvers find the optimum of an objective function in the basin of attraction of the starting point. In contrast, solvers with global convergence are designed to search through more than one basin of attraction. That is why we used a Generalized Pattern Search (GPS) algorithm to find the global minimum of the objective function J_1.

GPS algorithms are a class of direct search algorithms, originally introduced and analyzed in [29] for unconstrained minimization problems, and then extended by Lewis and Torczon to problems with bound [30] and general linear constraints [31]. A summary of the work related to GPS algorithms can be found in [32].

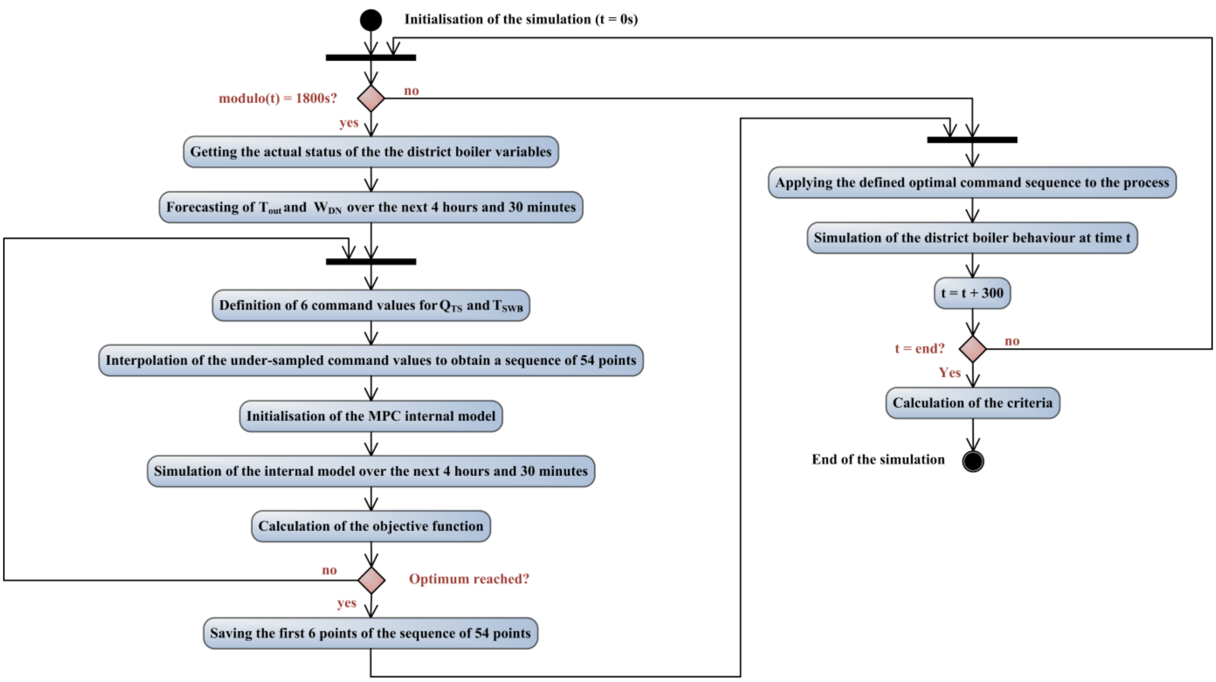

Figure 5. Working of the proposed model predictive controller.

8.4. Working of the controller

Finally, Figure 5 describes the iterative working of the proposed model predictive controller, based on the global model of the district boiler and forecasted sequences dealing with outdoor temperature (T_{out}) and thermal power consumption (W_{DN}).

9. Control results

This section of the paper deals with the simulation results (for a duration of 45 days) we obtained using the global model of the district boiler of La Rochelle (i.e. including the model of the thermal storage tank) and one of the two proposed controllers.

First, considering the basic controller (section 7), we focused on the impact of the two gains K_{in} (equation (21)) and K_{out} (equation (27)) used to calculate the flow of the water passing through the tank, in energy storage or release mode, on the district boiler performance. We also considered the impact of both the wood boiler set-point temperature (T_{SWB}) and the storage volume (V_{tot}). So, simulation campaigns were carried out using the following values for the four just-mentioned parameters: K_{in} = {0.2; 0.4; 0.6; 0.8; 1}, K_{out} = {0.2; 0.4; 0.6; 0.8; 1}, T_{SWB} (°C) = {92; 93; 94; 95; 96; 97} as well as V_{tot} (m^3) = {1000; 1500; 2000; 2500; 3000; 3500; 4000}. For each of the controller configurations we tested, the respective consumptions of wood, gas and fuel oil as well as the six proposed criteria J_1, J_2, J_3, J_4, J_5 and J_6 were evaluated. The study we carried out deals first with the impact of T_{SWB} and V_{tot} while next we were interested in the impact of K_{in} and K_{out}. In addition, and as previously mentioned in section 8, the predictive controller we designed uses J_1 (the global consumption cost) as objective function. Let us remember that we set the forecasting (H_F) and the control (H_C) horizons to 4h30 and 3h, respectively. We studied the impact of V_{tot} (the storage volume) on both the respective consumptions of wood, gas and fuel oil and the performance criteria we defined in section 6. Simulation period (45 consecutive days) remains unchanged.

Table 2. Remarkable configurations.

Parameter/Criterion		*Configuration*						
Name	*Unit*	*Reference*	BC_1	BC_2	BC_3	BC_4	BC_5	*MPC*
V_{tot}	m^3	0	3500	3000	4000	1000	4000	1500
T_{SWB}	°C	-	92	97	97	97	97	-
K_{in}	-	-	0.2	1	0.2	0.6	1	-
K_{out}	-	-	0.4	0.6	0.6	0.2	0.8	-
N_{tappet}	-	24635	25486	28208	27262	27555	28418	21203
V_{Gas}	m^3	38001	59901	15815	20376	17070	15796	17533
V_{FOD}	L	3287	13676	3027	2445	3089	2993	2244
J_1	k€	61.62	75.64	59.79	59.52	59.07	60.16	47.07
J_2	°C	0.56	1.002	0.096	0.227	0.191	0.072	0.252
J_3	MWh	3712	4157	3953	3869	3880	3980	3030
J_4	%	11.6	18.34	4.95	6.15	5.40	4.90	6.80
J_5	tCO_2	139.1	221.0	93.8	100.9	95.8	94.1	83.3
J_6	%	100	146.1	66.2	73.4	69.9	65.5	64.3

Whatever the controller used, some remarkable configurations allowing minimizing at least one of the performance criteria we defined deserve to be highlighted (Table 2). We considered as reference configuration the results (data are very closed to experimental values) we obtained in simulation without energy storage and predictive control. The first configuration of the basic controller one can highlight (BC_1) deals with a wood boiler set-point temperature (T_{SWB}) set to 92°C and a storage volume (V_{tot}) of 3500 m^3. Among the five basic configurations (BC_1, BC_2, BC_3, BC_4 and BC_5) we considered, this one leads to the lowest consumption of wood: the number of tappet strokes per five minutes (N_{tappet}) is 25486. However it is higher than the reference value (24635) of about 3.5%. As one can see when taking a look at Table 2, whatever the basic configuration used, the consumption of wood is higher than the reference value. The second configuration of the basic controller (BC_2) (T_{SWB} = 97°C and V_{tot} = 3000 m^3) allows reducing both the consumption of gas (V_{Gas}) and the CO_2 emissions (J_5) (of about 74% and 33%, respectively) compared with the reference values

(38001 m^3 and 139.1 tCO_2). Using the third basic configuration proposed (BC_3), dealing with a wood boiler set-point temperature (T_{SWB}) set to 97°C and a storage volume (V_{tot}) of 4000 m^3, the consumption of fuel oil (V_{FOD}) is reduced of about 26% compared with the reference value (3287 liters). Moreover, among the five basic configurations we considered, this one leads to the lowest value of J_3. However it is higher than the reference value (3712 MWh) of about 4.2%. The fourth basic configuration (BC_4) deals with a wood boiler set-point temperature (T_{SWB}) set to 97°C and a storage volume (V_{tot}) of 1000 m^3 only. Of course, this is the lowest storage volume used, whatever the considered configuration of the basic controller. Keeping in mind that the higher the volume, the higher the manufacturing and maintenance costs of the tank, configuration BC_4 is an interesting choice. Moreover, J_1 is reduced of about 4% compared with the reference value (61.62 k€). Among the five basic configurations we considered, using configuration BC_4 leads to the lowest value of J_1. Finally, the last configuration of the basic controller we proposed (BC_5) (T_{SWB} = 97°C and V_{tot} = 4000 m^3) allows reducing J_2, J_4 and J_6. These three criteria are reduced of about 87%, 58% and 36%, respectively, compared with the reference values (0.56 °C, 11.6% and 100%).

After proposing a basic controller which is not dependent on the future behavior of the district boiler, we designed a model predictive controller. As previously mentioned, such a controller uses the global model of the district boiler as well as forecasted sequences dealing with outdoor temperature (T_{out}) and thermal power consumption (W_{DN}). The controller defines the storage unit working mode ($Mode_{TS}$), the flow of the water passing through the tank (Q_{TS}) and the wood boiler set-point temperature (T_{SWB}). Table 2 highlights the best simulation results we obtained, with a storage volume (V_{tot}) set to 1500 m^3. As one can remark, the proposed model predictive controller minimizes the consumptions of wood (N_{tappet}) and fuel oil (V_{FOD}) as well as the criteria J_1, J_3, J_5 and J_6. Taking as a reference the best results the basic controller can provide (according to the chosen configuration), N_{tappet}, V_{FOD}, J_1, J_3, J_5 and J_6 are reduced of about 16.8% (21203 vs. 25486 with BC_1), 8.2% (2244 liters vs. 2445 liters with BC_3), 20.3% (47.07 k€ vs. 59.07 k€ with BC_4), 21.7% (3030 MWh vs. 3869 MWh with BC_3), 11.2% (83.3 tCO_2 vs. 93.8 tCO_2 with BC_2) and 1.8% (64.3% vs. 65.5% with BC_5), respectively. Only the consumption of gas (+11%) as well as the criteria J_2 and J_4 (+250% and +38.8%, respectively) are higher than when using the basic controller (configuration BC_5), but with V_{tot} set to 4000 m^3 what increases significantly the manufacturing and maintenance costs of the storage tank. In every instance, the results we obtained in simulation with the designed model predictive controller are better than the reference values: 21203 vs. 24635 for the number of tappet strokes per five minutes (-14%), 17533 m^3 vs. 38001 m^3 for the consumption of gas (-53.9%), 2244 liters vs. 3287 liters for the consumption of fuel oil (-31.7%), 47.07 k€ vs. 61.62 k€ for J_1 (-14.6%) (let us remember that the global consumption cost is the predictive controller's objective function), 0.252 °C vs. 0.56 °C for J_2 (-55%), 3030 MWh vs. 3712 MWh for J_3 (-18.4%), 6.8% vs. 11.6% for J_4 (-41.4%), 83.3 tCO_2 vs. 139.1 tCO_2 for J_5 (-40.1%) and, finally, 64.3% vs. 100% for J_6 (-35.7%). Clearly, the model predictive controller we designed allows a significant reduction in costs, fuel consumption and greenhouse gas emissions, using a storage volume of 1500 m^3. However, because of the criterion chosen as objective function (the global consumption cost J_1), the temperature set-point error (J_2) is the criterion for which the predictive controller gets the worst results. Indeed, to favour the minimization of the consumption of energy, the MPC controller is intentionally less accurate with the tracking of the distribution network set-point temperature. As a key point, one can also highlight that because of the good stratification of the modeled tank (section 5), whatever the controller used, the storage volume faintly impacts on the simulation results. The stratification of the tank being always preserved, an unnecessary increase in volume does not modify these results: hot water is stored in the upper layers of the tank only. A big storage volume (3000 or 4000 m^3) seems to be judicious only in case of long and large energy needs. Otherwise, a smaller volume (1000 or 1500 m^3) is as often as not sufficient for efficiently regulating the energy provided to the hot water distribution network.

10. Conclusion

As part of the OptiEnR research project, the present paper deals with the optimization of the multi-energy district boiler of La Rochelle (west coast of France) adding to the plant a controlled thermal storage tank. The district boiler supplies domestic hot water and heats residential and public buildings, using wood, gas and fuel oil. Due to both the complexity of the plant as a whole and the strong interactions between the sub-systems, previous works focused on its modeling via a modular approach. A combination of white, grey and black boxes was used to keep the modeling process on track. Next, a methodology dealing with a wavelet-based multi-resolution analysis and the use of artificial neural networks was proposed to forecast, over the next 4 hours and 30 minutes, the outdoor temperature (T_{out}) and the thermal power consumed by the hot water distribution network (W_{DN}). First, this paper deals with the modeling of a stratified thermal storage tank, used to optimize the plant performance. The model of the vertical hot water tank we developed is based on the turbulent mixing models proposed by Alizadeh. Both the volume and the section of the layers are constant. Next, we defined six criteria, based on the energy and environmental characteristics of the combustibles used to produce heat by burning, about energy consumption, CO_2 emissions, functioning cost and the temperature of the water entering the distribution network. Finally, we developed and tested in simulation two control schemes: a basic controller and a model predictive controller. The basic structure is easy to implement. It does not require significant computational resource and, as a consequence, can be used easily on-line. The results we obtained demonstrate that using such a control structure one can manage efficiently a thermal storage tank. Moreover, it highlights the pertinence of the proposed approach to improve the performance of a multi-energy district boiler (in particular when plants are poorly sized). Using the global model of the plant and forecasted sequences about T_{out} and W_{DN}, the model predictive controller generated optimal command sequences dealing with the flow of the water passing through the storage tank and the wood boiler set-point temperature. Whatever the controller used, the overall performance of the district boiler was improved. However, the proposed model predictive controller performed best, with a storage volume set to 1500 m^3. The fossil energy consumption, CO_2 emissions and functioning cost were clearly minimized. Energy is stored during low-demand periods and used when demand is high, instead of engaging the gas-fuel oil boiler. Future work will first focus on implementing *in situ* the developed tools. Next, the proposed optimization approach will be generalized to other district boilers (mainly focusing on poorly-sized plants) managed by Cofely GDF-Suez. These plants have been instrumented with the aim of collecting data and, if necessary, adapting the developed tools. Finally, other control structures, for example based on fuzzy inference systems or artificial neural networks, will be tested.

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