Controller tuning of district heating networks using experiment design techniques

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The various governmental policies aimed at reducing the dependence on fossil fuels for space heating and the reduction in its associated emission of greenhouse gases such as CO_2 demands innovative measures. District heating systems (DHSs) using residual industrial waste heats could provide such an efficient method for house and space heating. In such systems, heat is produced and/or thermally upgraded in a central plant and then distributed to the final consumers through a pipeline network. In this work the main objective is to tune a non-linear model predictive controller which is for assuring to satisfy the heat demands of the heat consumers in the system as soon as possible. A well-known method in field of experiment design is applied to tune the model predictive controller to reach the best performance. In environmental aspects it means that the heat-demand of the consumers is mainly fulfilled by using waste heat and completing the lack of heat from a secondary heat producer beside reach the control goal in the fastest way.

1. Introduction

Today the majority of the buildings in western Europe are heated with individual boilers that are fed either with city gas or with oil. It is only in some cases, when the recycling of heat generated by the combustion of city waste allows it for instance, that a district heating network is implemented to use this heat. The main advantages of district heating systems are:

1. Fewer sources of emission in densely populated areas.
2. Less individual boilers, thus increasing the available space in the buildings that can be used for other purposes.
3. A professional and on-going operating and maintenance of the centralized heating technology.

Several variations exist for district heating networks: in Benonysson et al. (1995) the district heating network includes several consumers located in different areas, but there is no energy storage and just one production unit. In Zhao (1998), a storage tank is added to the network. In Ravn and Rygaard (1994), a storage tank is also considered, but there is no thermal energy supply network. So the variety of the district heating networks are numerous.

The models of a district heating network in the literature either can be a physical description of the heat and mass transfer in the network like Sandou et al. (2005) and Tveit et al (2009) or they are based on a statistical description of the transfer function from the supply point to the critical point considered. The proposed forecast methodology in Søgaard (1993) is to set an ensemble of ARMAX (Auto-Regressive Moving Average with Exogenous input) models with different fixed time delays, and to switch between models depending on some estimated current time. In Nielsen and Madsen (2006) the grey-box approach for modeling combines physical knowledge with data-based, statistical modeling; physical knowledge provides the main structure and statistical modeling provides details on structure and the actual coefficients/ estimates. This is advantageous since the physical knowledge reduces the model-space which must be searched, whereby the validity of the statistical methods is better preserved.
In order to meet the consumers requirements the suppliers have to pay significant attention to find the optimal control strategies that have some restrictions e.g. assure the minimum inlet temperature of consumers this way satisfying their heat demand. The aim of the control strategies to meet these restrictions and at the same time minimizing the operational costs of the heat supplier or the effects of operation on the environment like in Molyneaux (2010). The model predictive control methods are highly applicable for meet these demands since the formulation of the objective function can assure the possibility to take every aspect into consideration.
Managing a district heating network implies to assign values to integer and continuous variables. Integer variables represent mostly the status of production units. As a result, the optimization of the production and energy supply planning appears to be a huge, mixed and non linear optimization issue in Manesh et al. (2009). Consequently, most studies use a simplified model, leaving aside some of the district heating network aspects. This modeling approach allows the use of one of the classical optimization methods listed in Subir and Kothari (1998), but the solution can be strongly suboptimal when applied to the whole district heating network.
The aim of this work is to reduce the transition time in a non-linear model predictive controlled DHS presented by Dobos et al. (2009) by tuning the parameters of the non-linear MPC. To reach this goal the simplex method is applied which is a well-known method in field of experiment design and appropriate for handling mixed-integer optimization problems which is occurred by the integer values of prediction and control horizon.
The paper is organized as follows: in the following section the topology of the applied district heating network will be introduced. In the third section the applied MPC solution is introduced and then the tuning method and the control results will be examined.

2. Modeling and control approach of a district heating network

2.1 The applied topology and modeling approach

In the following section the topology of the examined district heating network is presented. The model of this network is developed with using the method of Sandou et al. (2005) so applying the physical description of the heat and mass transfer in the network. Structural approach is used to obtain a convenient global model: considering

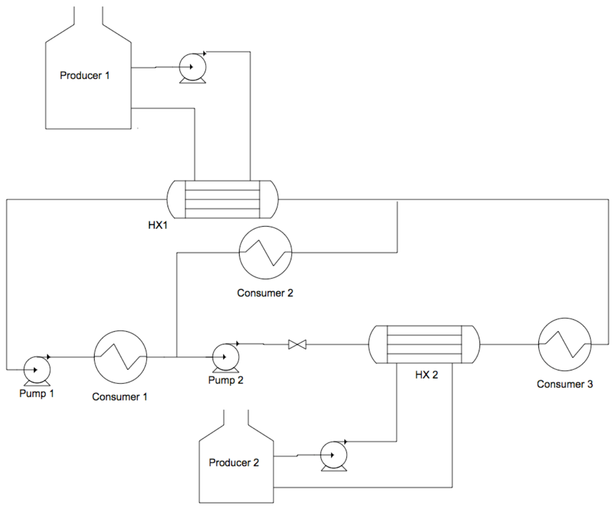

Figure 1: Topology of the examined district heating network

complexity of the system, local models of the components of the network are established and then brought together. Detailed modeling description of the topology below can be found in Dobos et al. (2009).

The topology presented in Fig. 1. was chosen to represent the main characteristics of a district heating network. As it can be seen the network contains two heat production units, three consumers, two pumps and a valve. The production unit, called Producer 1, is the base load boiler, which can represent a waste incineration plant. The other production unit, called Producer 2, is the peak load boiler station, which has to satisfy the increased heat demand in the network, especially in case of the Consumer 3. HX1 and HX2 heat exchangers are for transfer the produced heat from the primary circles to the secondary circle that is practically for distributing the heat for the consumers.

2.2 Control system synthesis

In control system synthesis of district heating networks it is usually to define integer (e.g. status of production units) and continuous variables for control purposes. However solving a non-linear mixed integer optimization might have the ability to provide a control signal that may provide better performance than solving a simple non-linear optimization problem. In this paper a simple non linear SQP method with soft constraints will be introduced to avoid the complexity of mixed integer non linear programming. Detailed control description of the current district heating network could be found in Dobos et al. (2009). To take the different weights of the control variables into consideration the classical MPC objective function is augmented with the absolute value of the control variables:

$$\min_{\Delta u_o(k+j)} \sum_{i=1}^{N_i} \beta_i \sum_{j=1}^{p} (w_i(k+j) - y_i(k+j))^2 + \sum_{o=1}^{N_o} \alpha_o \sum_{j=1}^{p} u_o^{\,2}(k+j) + \lambda_o \sum_{j=1}^{c} \Delta u_o^{\,2}(k+j-1) \qquad (1)$$

where N_i is the number of inputs, N_o it the number of outputs, w_i is the i^{th} setpoint signal, y_i is the controlled i^{th} controlled variable u_o and Δu_o is the absolute value and the change of the i^{th} control variable, *p, c,* α, β, γ are the tuning parameters of the MPC. To fulfill the heat requirements of the consumers, to make the possibility of controllability the control variables of the system is needed to be defined. In the case of the depicted district heating network in Figure 1 the possible control variables are the invested heat in Production unit 1 and 2, pump duty of P1 and P2 pumps and the valve opening. Since the P1 pump is chosen to compensate the pressure drop of the heat exchangers and pipelines, the P1 pump does not take part in satisfying the heat demand of consumers, so it was considered to be controlled by a local regulator.

The pressure drop in the direction of the Consumer 2 and in the direction of the Consumer 3 must be the same. To reach this goal two control variables can be used: the valve opening and the pump duty of the P2 pump. These control variables are for determining the split ratio on the splitter and through this control the flow in the two directions to be able to transfer enough heat to the consumers.

The aim of the controller to fulfill the heat demand of consumers. The performance of the controller is highly depends on its tuning parameters so it is crucial project in reduction of transition time.

2.3 Applied methodology for controller tuning

A well-known simplex methodology was employed for optimization of the tuning parameters of model predictive controller which is widely applied in field of experiment design. The application way of simplex method stands the following steps:

I. In case of *N* pieces of variables, *N+1* pieces of experiments are necessary to be carried out to create the initial simplex.
II. Evaluation of values of peaks of the simplex. In case of minimizing the value of the objective function the peak with the highest value of objective function shall be mirrored to the n dimensional hyperplane determined by the other n peaks. In case of maximizing the objective function the peak with the lowest value shall be mirrored. With mirroring the appropriate peak the parameters of the new experiment is yielded.
III. The obtained parameters shall be substituted it to the mirrored peak.
IV. Carrying out the experiment with the new parameters
V. Evaluation the new simplex and continue the mirroring until the value of the objective function reach the desired value.

The equation for the procedure of mirroring can be written:

$$n_{new,i} = \frac{1+\lambda}{N} \cdot \sum_{i=1}^{N} n_i - (\lambda + \frac{1+\lambda}{N}) \cdot n_{worst,i} \quad (2)$$

Where N is the number of experiments, n_i is the i^{th} parameter and λ is a weight that can determine the direction and length of mirroring.

3. Application example

In the case study the main goal is to minimize the transition time between two different levels of heat demand of consumers as much as possible by tuning the MPC. The tuning parameters are the values of the prediction and control horizon and the values of α and λ in Eq. (1) which parameters are collected in n in Eq. (2). To minimize the transition time with the method presented in the previous section the linear cost function presented in Eq. (3) is applied.

$$\sum_{i=1}^{N_o} E_i = P_i^{on-demand} \cdot Q_i^{on-demand} + P_i^{off-demand} \cdot Q_i^{off-demand} \quad (3)$$

where N_o is the number of consumers, $P_i^{on/off-demand}$ is the income when the consumed heat in the i^{th} consumer is inside/ outside the specification limits and $Q_i^{on/off-demand}$ shows that the consumed heat is inside/ outside the determined limits (*values are 0-1*).

To express the development in the reduction of time-consumption of transitions, the performance of the controller with initial and tuned parameters have been compared, see Fig. 2.

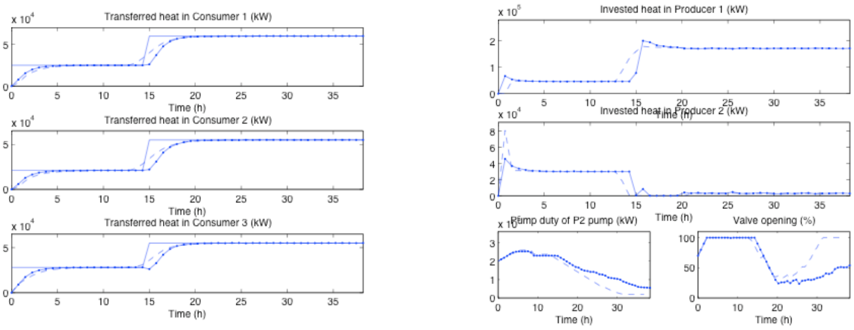

Figure 2: Comparison of the transitions with initial parameters (dashed line) and with the experimentally determined parameters (dotted line)

As Fig. 2. shows, the time demand of the transition is significantly shortened. Although a badly tuned MPC is also capable of performing the transition, the optimization of tuning parameters is necessary, because in the optimized case the system fulfill the requirements more than 65 % of the examined time horizon in contrast to the initial guess where this ratio is under 58 %.

To increase the performance of the controller the simplex method was applied with the cost function formulated in Eq. (3). In this case 11 experimental steps have to be carried out, since 7 steps are necessary to determine the initial simplex and four more to improve the control performance as Fig. 3. Shows (values are normalized).

Finally the efficiency of the proposed method could be stated. Since the simplex method is easily implementable it might be a simple way to handle model predictive controller tuning on-line.

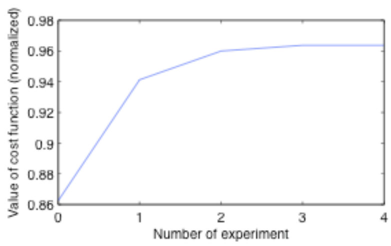

Figure 3: Change in the values of the cost function during the experiments

4. Conclusion

Chapter 2 In this study an optimal control solution of a district heating network by non linear model predictive control was introduced. An optimization approach incorporating the simplex method for controller tuning were applied for optimization of transition of in a district heating network in case of fulfilling the consumers requirement as soon as possible. The proposed method involving a reduced number of experimental runs to localize the optimal value of tuning parameters of a model predictive controller.

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