# Model Predictive Control as a System Integrator in a Heat Pump-Driven District Heating Network

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**Though often seen as distinct ways to decarbonise the (residential) heating sector, heat pumps and district heating can complement each other. Their integration is crucial for decarbonizing current and future district heating networks. However, as these integrated systems tend to become very complex, today's rule-based controllers might lead to suboptimal operation and low system efficiencies. This article shows the potential of model predictive control to increase the efficiency of a heat pump-driven district heating network at equal or better thermal comfort.**

## Introduction

If the European Union wants to achieve its ambitious climate goals by 2050, the decarbonization of the residential heating sector is a top priority. This goal can be achieved on the one hand by renovating the building envelopes, resulting in lower heat use. On the other hand, heat generation also needs to be done more efficiently and in a carbon-neutral way, thus preferably by using renewable energy sources and/or residual heat.

In areas with a relatively low heat demand density, decarbonization can be achieved by installing heat pumps (HPs). In the urban areas, on the other hand, district heating (DH) networks will play a significant role in the reduction of greenhouse gas emissions. Both methods can also complement each other: heat generated by one or multiple (collective) HPs can be transported via a DH network to multiple buildings and, if needed, upgraded locally to a higher temperature using a booster HP (BHP). An example of such an innovative system can be found in Bruges, Belgium.

Almshouses De Schipjes (Figure 1) is a social housing neighbourhood of twelve buildings in Bruges's historic city centre. The neighbourhood was built at the start of the 20$^{th}$ century and classified as heritage in 2009. In 2014, the Flemish Agency for Innovation and Entrepreneurship funded a demonstration project to deeply renovate De Schipjes with a focus on the energetic and ecological aspects. Despite the limitations set by the neighbourhood's classification as heritage, a fully-renewables-based heat supply to the buildings was achieved by the combination of a central ground-source HP (GSHP), a low-temperature DH network (so-called fourth generation DH network) and decentral BHPs.

An important aspect of such a complex thermal system is the operation: if the different components are not functioning in an efficient and collaborative manner, this might result in a significant decrease in system performance. This article shows, based on the results of a simulation study, how a model predictive controller (MPC) can act as a system integrator for the different components in the thermal system to increase global system performance. The presence of the GSHP dictates the optimal control actions taken by the MPC. The content of this article is based on the following research publications: [1,2].

## Thermal network of De Schipjes

A simplified hydronic scheme of the thermal network of De Schipjes is shown in Figure 2. Heat is generated centrally by a GSHP and solar thermal collectors (STCs), each connected to a water tank (WT) of 950 litres. The area of the STCs is, however, limited to preserve the neighbourhood's classification as heritage. The temperature of WT2 is operated around 50°C and transported to the twelve buildings, where heat is extracted through the buildings' substation, consisting of a heat exchanger and a control valve (V2).

*Figure 1: Almshouses De Schipjes.*

Space heating (SH) in the buildings is provided by low-temperature radiators in every room and a floor heating system on the ground floor level. Since a supply temperature of 50°C in the DH system is insufficient to produce domestic hot water (DHW), a BHP feeds a small DHW tank with water at 60°C in each house.

The currently used rule-based controller (RBC) can be summarised as follows: the GSHP and BHPs are controlled in an on/off manner using a hysteresis curve. For SH within the buildings, a heating curve has been implemented. The indoor temperature setpoints are set at 21°C during the day and at 17°C at night, including a reheating period of one hour in the morning. Some variations of the RBC's control rules, in an attempt to improve the RBC's performance, are described in an article published by Jansen et al. [3]

## Model predictive control

The SySi (Thermal Systems Simulation) research group, led by Professor Lieve Helsen, has over a decade of experience with MPC. The working principle of MPC is shown in Figure 3 for the operation of a building's HVAC system. To control the setpoints of the HVAC system in an optimal way, the MPC uses four crucial building blocks.

Firstly, the MPC contains a mathematical model of the real-life system called the controller model. The MPC needs to understand the effect of a specific control action on the system's operation. For example, increasing the supply temperature to the heating system will result in an increase in heating power. In addition to the controller model describing the behaviour of the system, the MPC also needs predictions. The building is subject to disturbances such as weather and occupancy behaviour,

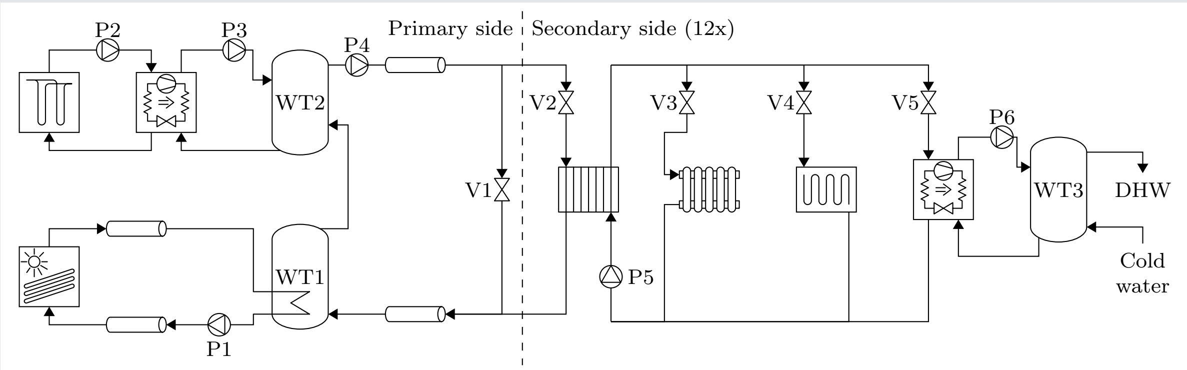


*Figure 2: Simplified hydronic scheme of the thermal network of De Schipjes.*

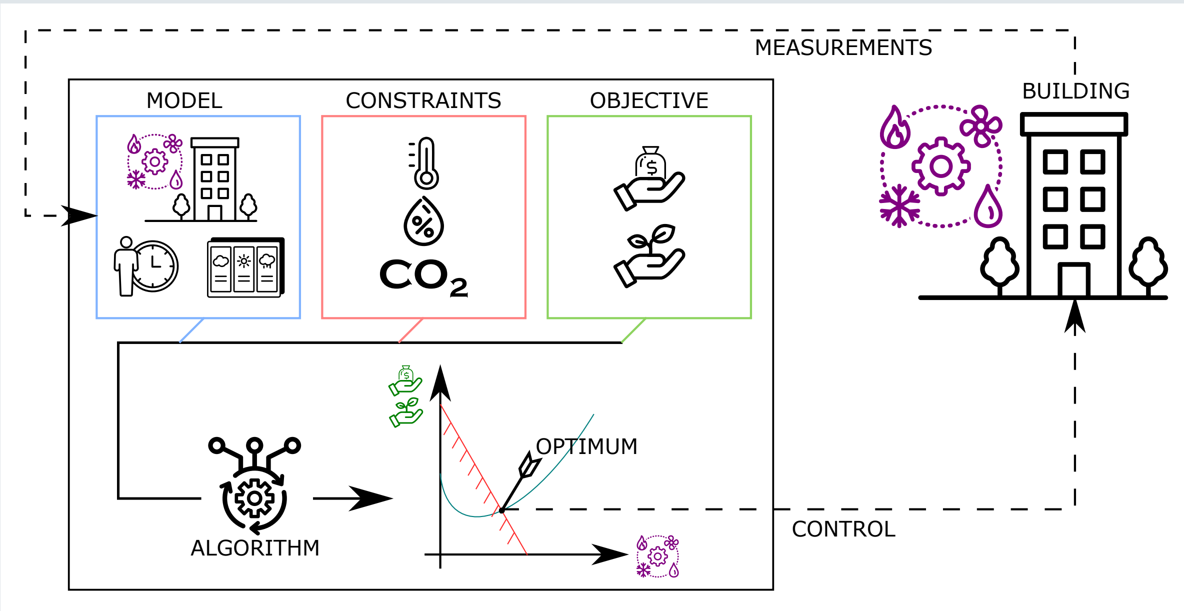


*Figure 3: MPC working principle (figure used with permission of D. Picard & F. Jorissen, Builtwins BV).*

which influence the temperature and air quality inside the building. This information needs to be provided to our MPC. The fact that the MPC uses both a model and predictions to determine optimal control actions also explains the name of this controller.

Secondly, the MPC must consider specific constraints that have been imposed, such as a minimum and/ or maximum indoor temperature, to ensure thermal comfort. Thirdly, the MPC has a cost function that is optimised, for example, to minimise operational costs or maximise the share of renewable energy. The information in these three building blocks – 'the model with predictions,' 'constraints,' and 'cost function' – is then used as input for an optimisation algorithm, which determines the optimal control actions for the building.

However, this scheme does not yet fully describe how an MPC operates. Another important aspect is that when determining the optimal control setpoints, their impact on the system's behaviour in the future is also considered, known as the prediction horizon (feedforward action). This strategy allows us to anticipate future events, for example, a significant change in the outdoor temperature or setpoint in the building. The optimal control actions are, therefore, determined for the entire prediction horizon. Still, only the first inputs of the first control interval are applied to the real-life system, after which the available sensors send their measurements to the MPC to update the controller model (feedback action). The optimisation is repeated for a new prediction horizon that is shifted with a one-time step.

## Simulation study for De Schipjes

To compare the performance of this MPC approach for De Schipjes to the existing RBC, a simulation study was conducted. For this purpose, a detailed simulation model of the real-life DH system was developed in Modelica. Simulations were carried out with the current RBC and an MPC that minimises the electrical energy use of the entire DH system, comprising the electrical energy use of the central GSHP, decentral BHPs, and all circulation pumps while ensuring thermal comfort in the buildings.

Two simulations of three days were performed: one in winter (February 9-12) and one in spring (April 22-25). Table 1 shows the most important performance indicators: the electrical energy use of the overall system, the thermal discomfort in the buildings, the COP of the GSHP, and the average COP of all BHPs.

The values in the first two columns show that during the winter period, MPC provides significantly better thermal comfort compared to RBC using a similar amount of electrical energy (+0.4%). In the spring period, on the other hand, MPC and RBC reach the same level of thermal comfort, but the former uses 31% less electrical energy.
To better understand these results, we zoom in on some more detailed simulation results. Figure 4 shows the indoor temperature evolution in one of the buildings. During the winter period, the reheating period of one hour, included in the RBC rules, appears to be insufficient, leading to significant thermal discomfort in the morning. However, during the spring period, one hour is more than sufficient, explaining the minimal thermal discomfort in that period.

In order to reach thermal comfort in the winter period, the MPC makes use of its ability to anticipate (feedforward action): the MPC knows that it should be 21°C from 7 a.m. onwards, and since the physics of the building are partially captured in the controller model, the MPC knows when to start reheating the building. However, this is not efficient from an energy point of view, because the heat losses of the building are now higher at night due to the higher indoor temperatures. So, how can this 'remarkable' control behaviour be explained? For that, it’s necessary to look at the main heat source of the system: the GSHP.

| | **Electrical energy use [kWh]** | **Thermal discomfort [Kelvin-hour/day /building]** | **COP GSHP [-]** | **COP BHPs [-]** |
|---|---|---|---|---|
| **Winter (9-12 February)** | | | | |
| **RBC** | 506 | 3.81 | 3.93 | 4.19 |
| **MPC** | 508 | 0.25 | 4.27 | 3.99 |
| **Spring (22-25 April)** | | | | |
| **RBC** | 110 | 0.03 | 4.06 | 4.10 |
| **MPC** | 75 | 0.03 | 4.67 | 3.13 |

***Table 1: Performance indicators in the winter period and spring period for RBC and MPC.***

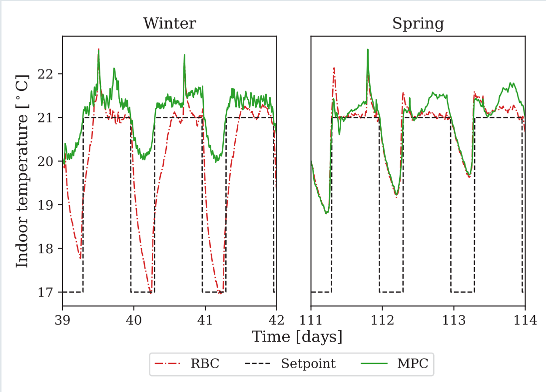


*Figure 4: Indoor temperature in one of the buildings in the winter period and spring period for RBC and MPC.*

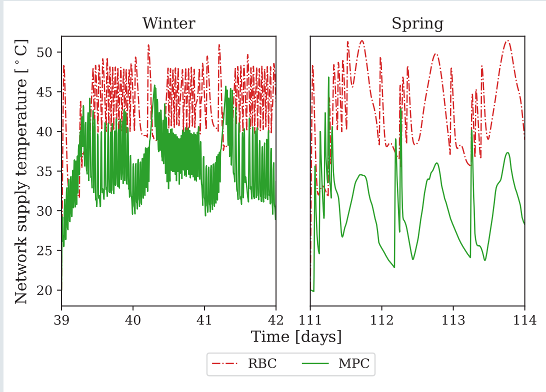


*Figure 5: Network supply temperature in the winter period and spring period for RBC and MPC.*

The COP of this HP depends on the temperature that needs to be generated on the condenser side, which is the DH network supply temperature for the thermal system of De Schipjes. The lower this temperature, the higher the COP will be. Figure 5 shows that the MPC aims for a significantly lower DH network supply temperature compared to the RBC. This results in a higher COP for the GSHP, as indicated by the values in column 3 of Table 1, and therefore explains the lower electrical energy use for the MPC compared to the RBC. On top of that, the lower network temperatures also lower the heat losses of the DH network pipes compared to the RBC.

However, the lower network temperature also lowers the heat emission power of the radiators and floor heating system. The only way the MPC can ensure thermal comfort in the morning is by sufficiently heating the buildings at night. Another drawback of the lower network supply temperature is a decrease in the BHPs' COP (column 4 of Table 1) due to the lower evaporator inlet temperature. However, the lower electrical energy use for MPC shows that the higher COP of the GSHP dominates the lower COP of the BHPs and higher heat losses in the buildings, both in the winter period (in which the DHW demand is about 8% of the total heat use) and in the spring period (in which the DHW demand is about 45% of the total heat use).

## Conclusions

Based on the results, we can conclude that MPC outperforms RBC in terms of electrical energy use and/or thermal comfort. Three important reasons for this are:

1. *Heating the buildings at night, thereby using the flexibility provided by the thermal inertia of the building envelopes.*
2 *Reducing the network temperatures to increase the COP of the GSHP.*
3. *Using predictions to anticipate future events.*

For the DH system of De Schipjes, characterised by a central GSHP and decentral BHPs for DHW production, the COP of the GSHP appears to be dominant in the MPCs operation strategy.

In general, the use of an MPC, acting as the system integrator for the different parts of the thermal system, can lead to a significant increase in the overall system performance in multiple aspects: energy efficiency, cost, share of renewable and residual energy sources, GHG emissions.

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For references see p. 30
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