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Development of a Mixed-Integer Nonlinear Model Predictive Controller for a Virtual 5th Generation District Heating and Cooling Network

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Abstract

This paper proposes a novel two-step method for the mixed-integer non-linear model predictive control of fifth generation district heating and cooling networks. The method is applied as a proof of concept to a small, virtual district consisting of four residential buildings and one office building and it is compared to a basic integer selection control approach. The novel controller uses detailed physics-based models, developed in Modelica, for both building envelopes, thermal systems, and hydraulic components and aims to minimise the overall energy use of the district, while guaranteeing thermal comfort inside the buildings. An 8-month open-loop simulation is carried out to investigate and analyze the control behaviour. Results show that the proposed two-step method significantly outperforms the basic integer-selection control approach: it exploits the available system flexibility to minimize the energy use, and achieves good thermal comfort in the buildings.

Introduction

Fifth-generation district heating and cooling (5GDHC) networks, in which water at near-ground temperature is distributed to decentralized water-source heat pumps and chillers, have emerged as a promising solution to reduce carbon dioxide emissions in the building sector (Buffa et al. 2019). These 5GDHC networks, also known as ambient or (ultra)low-temperature district heating and cooling networks, are characterized by the non-explicit relation between the network temperature and the customer-side temperatures and by the ability to simultaneously provide heating and cooling to different buildings in the network (Lindhe et al. 2022). The key advantages of these networks are their ability to facilitate direct energy exchange among buildings operating in different modes and the high operational efficiency of the decentralized heat pumps and chillers.

However, it is not yet clear how to optimally control these districts where many distributed heat and cold sources are combined, and thus influence each other's performance. Bünning et al. developed an optimal control concept using agent-based control together with temperature set point optimisation to compare different network concepts for 5GDHC networks (Bünning et al. 2018). Wirtz et al. proposed a mixed-integer linear program (MILP) for the short-term optimisation of the network temperature (Wirtz et al. 2021), while Vivian et al. used a MILP schedule optimisation in a look-ahead structure to minimise the overall operational cost (Vivian et al. 2017). Taylor et al. developed a Model Predictive Control (MPC) strategy to optimize the energy flows in a multi-energy district with 5GDHC to achieve low operational costs (Taylor et al. 2021). MPC is an advanced control methodology characterized by the use of a dynamic mathematical model of the system, coupled with predictions of disturbances such as weather and occupancy behaviour, to determine the optimal control inputs over a finite prediction horizon. These optimal control inputs are calculated by solving a constrained optimal control problem each time step. The above-mentioned control strategies overlook the individual building dynamics and, consequently, fail to integrate and exploit the inherent flexibility within the buildings. Furthermore, the majority of advanced control strategies do not take into account nonlinearities present in the system and only optimize energy flows within these 5GDHC networks, overlooking mass flow rates, pressure losses, and temperatures inside the building. As a result, they require an additional postprocessing step to translate these optimal energy flows into actual control inputs to real-life components such as pumps and valves, resulting in suboptimal solutions.

This paper develops a nonlinear Model Predictive Control (MPC) strategy for 5GDHC networks that takes into account important nonlinearities present in these systems (e.g. cubic relation between mass flow rate and pumping power or the temperature-dependent

Coefficient-of-Performance (COP) of heat pumps and chillers) and directly determines optimal control signals that can be applied in real systems without the need of a post-processing step. Detailed physics-based (white-box) models, developed in Modelica (an object-oriented, equation-based, acausal, multi-domain modeling language), are used for both building envelopes and hydraulic components so that a high-fidelity controller model is achieved and the flexibility present in the buildings is taken into account as well. Moreover, for each building, a binary variable that determines whether the building is in heating or cooling mode is incorporated in the formulation of the optimisation problem, resulting in a mixed-integer nonlinear program (MINLP) MPC.

A novel two-step method to solve this MINLP problem is proposed and a comparison of this method with a very basic integer-selection control approach is made. In the two-step control method, the first step uses a simplified (but still non-linear) controller model without individual building hydraulics to optimize the heat flow rates to and from each building over the prediction horizon of the MPC. The values of the optimal heat flow rates of each building are then used to fix the integer values in a second NLP-based optimisation that uses the complete detailed controller model with all hydraulics. In the basic integer-selection control approach, on the other hand, the integer values are based on a simple rule, after which the NLP-based optimisation with the complete detailed controller model is carried out. TACO (Toolchain for Automated Control and Optimisation), an in-house developed Modelica-based toolchain for non-linear white-box MPC, is used to develop and solve the NLP-based optimal control problems and run open-loop MPC simulations (Jorissen, Boydens, and Helsen 2019). These open-loop MPC simulations are carried out for an 8 month-period (January to August) to investigate and analyze the control behaviour of both control approaches. The resulting energy use and thermal discomfort of both control approaches are then compared.

Two main concepts for 5GDHC networks exist (Sommer et al. 2020; Buffa et al. 2019). The first network concept is the bidirectional energy flow, directional fluid flow network concept, where each building has the autonomy to select its operating mode (heating or cooling). However, a centralized pumping station ensures a directional fluid flow throughout the network. The second network concept is the bidirectional energy flow, non-directional fluid flow network concept where decentralised pumps in each substation determine the fluid flow direction in the network. Again each building has the autonomy to choose its operating mode.

In this paper, the two-step method and basic integer-selection control approach are both applied to a small virtual bidirectional energy flow, non-directional fluid flow 5GDHC network that consists of 4 residential buildings, 1 office building, and a central balancing unit.

System and model description

In this section, the system considered and the corresponding detailed controller model are discussed. A simplified schematic overview of the overall system is shown in Figure 1. The complete white-box controller model is developed with Modelica, using component and building models of the IDEAS library (Jorissen et al. 2018). However, since TACO requires all model equations to be continuous and twice differentiable, the models for pumps, valves, and heat pumps are taken from an in-house developed component library suitable for optimisation (with TACO). Figure 2 shows the resulting outer model layer. For all buildings, linear two-zone white-box models are used, which in residential buildings correspond to a day zone and a night zone, and in the office building to a north zone and a south zone. The most important building parameters are listed in Table 1. These buildings were chosen to create a typical Belgian district with a high variety in building types and the models were generated using the method of De Jaeger et al. (De Jaeger, Lago, and Saelens 2018). There is a central balancing unit consisting of a large buffer tank of 20 m^3, a large modulating (air-source) chiller (AS CHI), and a large modulating (air-source) heat pump (AS HP). The heat pump and chiller are required to keep the buffer tank temperature and thus also the network temperature above a minimum allowed temperature (set at 3 $°C$) and below a maximum allowed temperature(set at 16 $°C$ to allow free-cooling with a heat exchanger). The buildings and the central balancing unit are connected by district heating pipes, which are modelled as one volume per pipe with steady-state heat losses to the ground.

Energy transfer stations

The buildings have an underfloor heating and cooling system in each zone (FH1 and FH2), regulated by two-way valves (VAL1 and VAL2), and connected to an energy transfer station (ETS) that is the same in all buildings. This energy transfer station, whose simplified hydraulic scheme is shown in Figure 3, consists of (i) a free-cooling heat exchanger (HEX1) through which the

Table 1: Summary of the building specifications (De Jaeger, Lago, and Saelens 2018).

		Floor area $[m^2]$	Air volume $[m^3]$	UA-value building $[W/K]$	$\dot{Q}$ design $[kW]$	n50 $[1/h]$	Window area $[m^2]$	glazing type -	U-value glazing $[W/(m^2K)]$
house 1	day zone	40.6			2.8	8.0	7.9	double	1.4
	night zone	40.6			2.8	8.0	7.9	double	1.4
	total	81.2	269	89.3	5.6		15.8		
house 2	day zone	171.5			28.3	8.0	34.3	single	5.8
	night zone	135.1			32.3	8.0	27.0	single	5.8
	total	306.6	1093	1820.1	60.6		61.3		
house 3	day zone	167.0			10.3	8.0	20.1	double	1.4
	night zone	167.0			10.4	8.0	20.1	double	1.4
	total	334.0	1027	391.7	20.7		40.2		
house 4	day zone	87.5			11.2	8.0	13.0	double	2.9
	night zone	65.1			10.5	8.0	4.7	double	2.9
	total	152.6	517	549.7	21.7		17.7		
office	north zone	100.0			4.4	3.0	20.0	double	1.4
	south zone	100.0			4.4	3.0	20.0	double	1.4
	total	200.0	600	173.1	8.8		40.0		

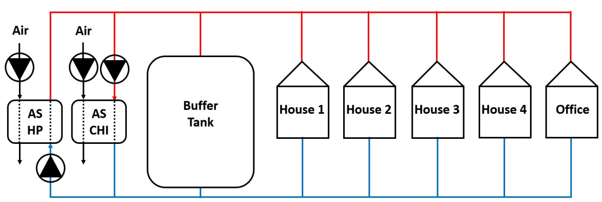

Figure 1: Simplified hydraulic scheme of the considered 5GDHC system

flow is regulated by a two-way valve (VAL3), (ii) a modulating water-to-water heat pump for heating (WSHP), (iii) two on-off circulation pumps (P1 and P2) on the primary side of the energy transfer station, respectively, providing fluid flow through the free-cooling heat exchanger (P1) and heat pump (P2), (iv) a modulating circulation pump (P3) on the secondary side providing fluid flow through the underfloor heating system, (v) a three-way valve (VAL4) to switch between heating and cooling mode on the secondary side of the energy transfer station, (vi) a heat exchanger (HEX2) on the condenser side of the heat pump to decouple the heat pump flow and emission system flow, and (vii) an on-off circulation pump (P4) that circulates the fluid flow in the condenser loop.

For these components, the following modelling approaches are used: all pumps are modelled as pumps with a prescribed pressure head, all valves are modelled with a linear opening characteristic, the free-cooling heat exchanger (HEX1) and the decoupling heat exchanger (HEX2) are modelled as fixed effectiveness heat exchangers with an effectiveness of respectively 0.8 and 1, and the Coefficient of Performance of the heat pumps in the energy transfer stations ($COP_{HP,ETS}$) is calculated by Eq 1.

$$COP_{HP,ETS} = 4.47 - 0.096(T_{con,out} - 40.9) + 0.043(T_{eva,out} - 9.7) \quad (1)$$

where $T_{con,out} [^\circ C]$ and $T_{eva,out} [^\circ C]$ are respectively the condenser and evaporator outlet temperatures. The part-load ratio dependency of the COP is not explicitly taken into account.

The $\dot{Q}_{design}$ values of the zones are used to determine the required size of the heat pump and to calculate the nominal mass flow rates in the energy transfer station. On the secondary side of the energy transfer station, a temperature difference of 5 K is assumed in the underfloor heating system, and on the primary side (DHC network side) of the energy transfer station, a temperature difference of 3 K in the heat pump evaporator and 4 K in the free cooling heat exchanger are assumed.

In heating mode, pump P1 is turned off, pumps P2 and P4 are turned on, and the three-way valve (VAL4) sends the fluid flow through the heat exchanger HEX2. In cooling mode, pump P1 is turned on, pumps P2 and P4 are turned off, and the three-way valve sends the fluid flow through the free-cooling heat exchanger (HEX1).

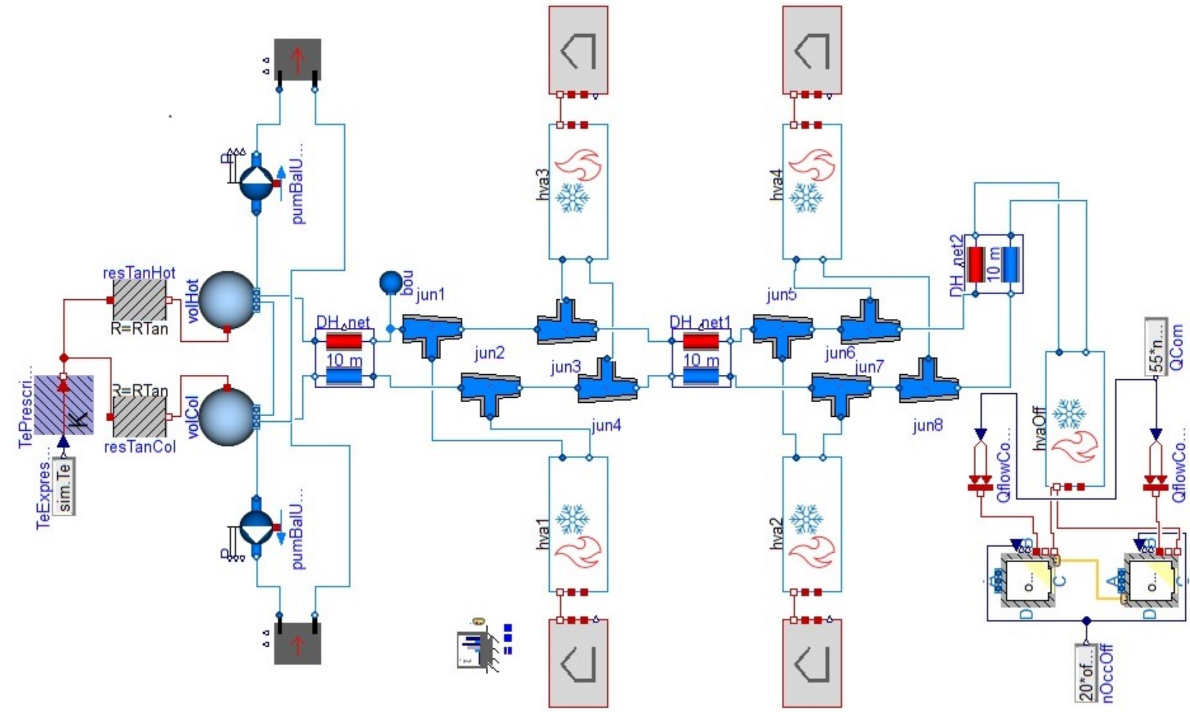

Figure 2: Modelica model of the district.

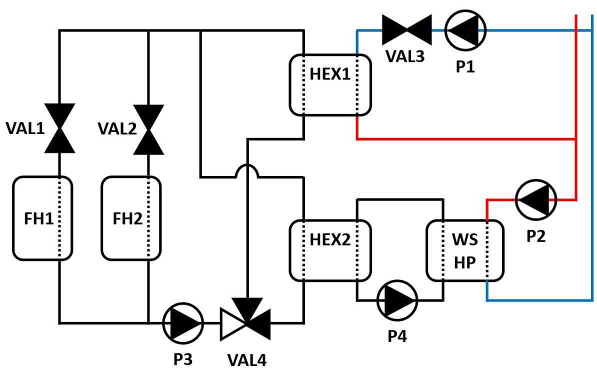

Figure 3: Simplified hydraulic scheme of the energy transfer station.

Central Balancing Unit

To take into account thermal stratification, the buffer tank is modelled as two connected mixing volumes of 10 m^3 (one volume at high temperature and one volume at low temperature). The (modulating) air-source chiller, which has a nominal cooling power of 64 kW, takes water from the high-temperature volume and injects water into the cold-temperature volume, while the (modulating) air-source heat pump, which has a nominal heating power of 60 kW, takes water from the low-temperature volume and injects water in the high-temperature volume. The COP of the heat pump ($COP_{HP,BU}$) and the EER ($EER_{chi,BU}$) of the chiller are calculated using Eq. 2 and Eq. 3, respectively. The flow direction in the buffer tank directly depends on the operation of the pumps at the primary side of the energy transfer stations of the buildings.

$$
\begin{aligned}
COP_{HP,BU} = 4.7 - 0.2(T_{con,out} - 35) \\
+ 0.1(T_{eva,out} - 6.98)
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
EER_{chi,BU} = 3.78 - 0.13(T_{con,out} - 35.56) \\
+ 0.079(T_{eva,out} - 7)
\end{aligned} \tag{3}
$$

where $T_{con,out}[^{\circ}C]$ and $T_{eva,out}[^{\circ}C]$ are respectively the condenser and evaporator outlet temperatures. The part-load ratio dependency of the COP and EER is not explicitly taken into account.

Occupancy and weather conditions

To determine thermal comfort inside the buildings, fixed occupancy schedules, and corresponding temperature limits are assumed. In the office building, it is assumed that 20 people are present per zone during standard office hours (which span from 8 a.m. to 6 p.m. on weekdays). When people are present the temperature should remain between 21 $^{\circ}C$ and 23 $^{\circ}C$, while it should remain between 15 $^{\circ}C$ and 25 $^{\circ}C$ when no people are present. A fixed internal (appliances) heat gain of 55 W per person is considered, while the metabolic heat gains are set to 45 W latent heat production per person and 73 W sensible heat production per person (ASHRAE 2009). For the residential buildings, people are assumed to be present outside office hours, and then the temperatures should remain between 21$^{\circ}C$ and 23$^{\circ}C$ in the day zone and between 18 $^{\circ}C$ and 23 $^{\circ}C$ in the night zone. When there are no people present, temperatures should remain above 15 $^{\circ}C$ and below 25 $^{\circ}C$. Internal heat gains are neglected in the residential buildings.

Weather conditions are provided through a TMY-file (Typical Meteorological Year) of the IDEAS library for the region of Uccle in Belgium.

Methodology

In this section, the two control approaches considered are discussed in more detail. As mentioned in the introduction, this paper develops a two-step method for solving a MINLP MPC and compares it with a basic approach for determining the integers. The developed method uses a simplified non-linear controller model to determine the optimal heat flow to each building and subsequently, the corresponding integer values, while the basic approach uses a simple rule to determine the integer values.

Optimal control problem

The two investigated approaches only differ in the way the integer values are determined, so once these integer values are set, both approaches solve the same optimal control problem, formulated by Eq. 4. The time step is 1 hour and a fixed prediction horizon Δt_{pr} of 3 days is used.

$$\min_{\mathbf{o}(t)} \int_{t_i}^{t_i+\Delta t_{pr}} \left(J_{el}(t) + w\left(a^2+b^2\right) + \sum_{n=1}^{N_z} w\left(h_n^2 + c_n^2\right) \right) \mathrm{d}t \tag{4a}$$

$$\text{s.t.} \quad \frac{\mathrm{d}\mathbf{x}(t)}{\mathrm{d}t} = \mathbf{F}\left(\mathbf{x}(t), \mathbf{z}(t), \mathbf{o}(t), t\right) \tag{4b}$$

$$0 = \mathbf{H}\left(\mathbf{x}(t), \mathbf{z}(t), \mathbf{o}(t), t\right) \tag{4c}$$

$$\mathbf{x}(t_0) = \mathbf{x}_0 \tag{4d}$$

$$T_{min,n}(t) - T_{z,n}(t) \leq h_n \quad n = 1...N_z \tag{4e}$$

$$T_{z,n}(t) - T_{max,n}(t) \leq c_n \quad n = 1...N_z \tag{4f}$$

$$T_{tank,min}(t) - T_{cold,tank}(t) \leq a \tag{4g}$$

$$T_{hot,tank}(t) - T_{tank,max}(t) \leq b \tag{4h}$$

$$h_n, c_n \geq 0 \quad n = 1...N_z \tag{4i}$$

$$a, b \geq 0 \tag{4j}$$

Here, $\mathbf{x}(t)$ is the vector of state variables, $\mathbf{o}(t)$ is the vector of optimisation variables, $\mathbf{z}(t)$ is the vector of remaining algebraic variables, $T_{z,n}$ is the temperature in the nth zone, $T_{min,n}$ and $T_{max,n}$ are respectively the minimum and maximum allowable temperature in the nth zone, $T_{tank,hot}$ is the temperature of the high-temperature mixing volume, $T_{tank,cold}$ is the temperature of the low-temperature mixing volume, $T_{tank,min}$ and $T_{tank,min}$ are respectively the minimum and maximum allowable temperature in the buffer tank, and N_z is the total number of zones. The functions $\mathbf{F}$ and $\mathbf{H}$ are the governing equations. The optimal control variables considered ($\mathbf{o}(t)$) are the modulation of all heat pumps and the central chiller, the prescribed pressure head of the underfloor heating/cooling circulation pumps (P3), and the opening of the two-way valves inside the buildings (VAL1, VAL2, and VAL3). The main objective of this optimal control problem is minimising the electricity use of all heat pumps and the central chiller while also minimising thermal discomfort inside the buildings. The minimisation of the electricity use occurs through the variable J_{el}, which is described by Eq. 5.

$$J_{el}(t) = P_{HP,BU}(t) + P_{chi,BU}(t) + \sum_{n=1}^{N_b} \left(P_{HP,ETS,n}(t)\right) \tag{5}$$

where $P_{HP,BU}$ and $P_{chi,BU}$ are the power uses of the central air-source heat pump and central air-source chiller, respectively. $P_{HP,ETS,n}$ is the power use of the heat pump in the ETS of the n-th building and N_b is the total number of buildings. The thermal comfort within the buildings is maximised by implementing soft constraints introduced by the slack variables h_n and c_n. Slack variables a and b are introduced to maintain the tank temperature between its specified temperature limits. All temperature penalisations are scaled with respect to electricity use with a weighting factor w, which has a value of 10000. This value is chosen as it results in good thermal comfort, while still having a well-conditioned optimisation problem that results in a sufficiently small convergence time. TACO directly infers all equations and variables from the Modelica controller model. Subsequently, these equations are manipulated using computer algebra, discretised using a non-equidistant time grid, and solved by a derivative-based NLP solver (Jorissen, Boydens, and Helsen 2019).

Two-step MINLP-based MPC method

As stated above, the developed two-step control method determines the integer values by solving an optimal control problem with a simplified controller model to determine the optimal heat flows to and from each building. This simplified controller model is derived from the detailed model by removing all hydraulics of the energy transfer stations and the heating and cooling network and by modelling the central buffer tank as a single mixing volume. A consequence of removing these hydraulics is that pumping energy is completely neglected in the simplified controller model. It is thus implicitly assumed that the pumping energy does not influence the choice of operational mode. Furthermore, the effect of the network and building operation on the buffer tank temperature is taken into account by adding (net cooling demand in the buildings) or by extracting (net heating demand in the buildings) the sum of all building heat flow rates to the buffer tank. The models of the buildings, the central chiller, and the central heat pump remain unchanged. The formulation of the optimal control problem is equivalent to that in Eq. 4. The governing equations ($\mathbf{F}$ and $\mathbf{H}$) and states ($\mathbf{x}(t)$) are again automatically inferred from the controller model, while the optimisation variables are the modulation of the central heat pump and chiller, the heat flow rate to each building, and a distribution factor for each building to distribute the heat flow of the building between the zones. As there is no dynamic model for the heat pumps in the energy transfer stations, their electricity use is approximated by using a fixed COP-value of 7.

If the optimal heat flow rate to a building is positive (heat is added to the building), the corresponding integer value is set to 1 (corresponding to the heating mode in the detailed model), and if the optimal heat flow rate to a building is negative (heat is extracted from the building), the corresponding integer variable is set to 0 (corresponding to the cooling mode in the detailed model).

Basic integer-selection MPC approach

In the basic integer-selection control approach, a very simple basic rule based on the average outdoor temperature is used to determine the operating mode of each building. Each time step, the average of the current outdoor temperature, the outdoor temperature of the previous three time steps, and the predicted outdoor temperature of the next three time steps is calculated. For the office building, the threshold for this average outdoor temperature to go from heating to cooling mode is set at 12.5 $^{\circ}C$, while for residential buildings, this threshold is set at 15.5 $^{\circ}C$. The values of these thresholds are based on full-year simulations, and the difference in threshold between the office and the residential buildings is justified by the large amount of internal heat gains and the presence of large windows in the office building.

Results

In this section, the results of two 8-month open-loop simulations are used to analyze and investigate the control behaviour of the two control approaches. The total computational times required for the simulations were 12.18 hours with the basic-integer control approach and 30.15 hours with the two-step MINLP-based approach. Table 2 gives an overview of the simulation results and shows the electricity use of the heat pumps and the chiller, the average COP of all heat pumps, the average EER of the central chiller, and the thermal discomfort in each building. The total electricity uses are 34.96 MWh for the two-step MINLP control method and 33.99MWh for the integer-selection control approach. This suggests that the integer-selection approach outperforms the two-step method. However, the total thermal discomfort[1] with the integer-selection approach (2931 Kh) is significantly higher than the discomfort with the two-step MINLP control method (491 Kh), showing that the basic rule based on an outdoor temperature threshold is insufficient to correctly assess the operating mode of the buildings. Furthermore, the average COP of all decentralised residential heat pumps is lower with the integer-selection approach. This is the result of lower tank temperatures in the winter months, which is visible in Figure 4 that shows the evolution of the average tank temperature for both control approaches. With the integer-selection approach, the outdoor temperature threshold is never achieved during the winter months, and thus no cooling can occur in those months, while with the two-step MINLP control method cooling is present, especially in the office building with many internal heat gains. As a consequence, in the integer-selection approach, the internal heat gains of the office building can not be injected in the DHC network and all heat has to be provided by the central heat pump. The MPC controller most likely allows these lower tank temperatures to increase the central heat pump's COP.

The seasonal performance factor SPF, which is calcu-

[1] Based on the the ISO7730 standard (International Organization for Standardization 2005) and the ASHRAE standard 55 (ASHRAE 2004), it was shown that in the Belgian climate, the requirement for thermal comfort can be translated to a requirement on the operative temperature. As a consequence, thermal discomfort can be expressed in Kelvin-hours (Verhelst 2012).

Table 2: Summary of results of 8-month open-loop MPC simulation (A: two-step MINLP control method, B: integer-selection control method)

Component		E_{use} $[MWh]$	Avg. COP $[-]$	Avg. EER $[-]$	Thermal discomf. $[Kh]$
house 1	A	0.51	6.19		9.87
	B	0.45	6.17		21.28
house 2	A	15.99	5.19		266.11
	B	15.86	4.78		559.39
house 3	A	2.37	6.17		33.22
	B	2.22	6.12		62.33
house 4	A	3.59	6.17		60.761
	B	3.38	5.65		175.42
office	A	7.99	6.28		121.42
	B	0.3	6.30		2112.48
balancing unit	A	12.16	8.97	5.99	
	B	11.77	9.27	6.13	

lated using Eq. 6, with the two-step MINLP control method is 3.81, while it is 3.51 with the integer-selection control approach. This again indicates the weaker performance of the integer-selection approach.

$$SPF = \frac{\sum_{n=1}^{N_b} \left(Q_{FC,hex,n} + Q_{HP,con,n}\right)}{E_{HP,BU} + E_{chi,BU} + \sum_{n=1}^{N_b} \left(E_{HP,ETS,n}\right)} \quad (6)$$

Here, $Q_{FC,hex,n}$ is the total amount of heat extracted from the building in the free-cooling heat exchanger of the n-th building, $Q_{HP,con,n}$ is the total amount of heat added to the building in the heat pump condenser of the n-th building, $E_{HP,BU}$ is the total electricity use of the central heat pump, $E_{chi,BU}$ is the total electricity use of the central chiller, and $E_{HP,ETS,n}$ is the total electricity use of the heat pump in the n-th building.

Because of the poor performance of the integer-selection approach in terms of achieving thermal comfort, further analysis of the control behaviour is only done for of the two-step MINLP control method.

Firstly, Figures 5 and 6, which show the temperature evolution of the zones in house 1 and the office building in the period May 1-14, illustrate that the developed MPC controller keeps the zone temperatures well within its limits. Furthermore, some drifting of the zone temperatures can be observed, but nicely within the bounds. The results in Table 2, however, show that house 2 has a high thermal discomfort in comparison to the other buildings. This is probably the result of the low-performant building envelope (single glazing and

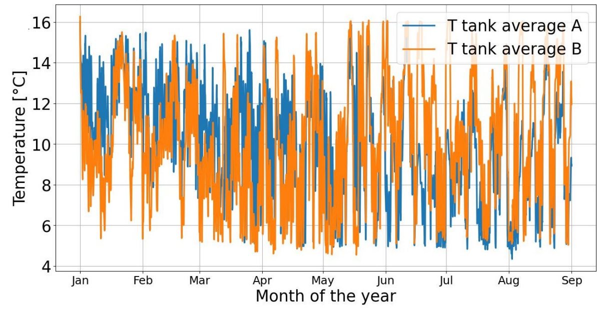

Figure 4: Average buffer tank temperature for both control approaches (A: two-step MINLP control method, B: integer-selection control method)

a high UA-value) of house 2, making the building less suitable for an underfloor heating and cooling system.

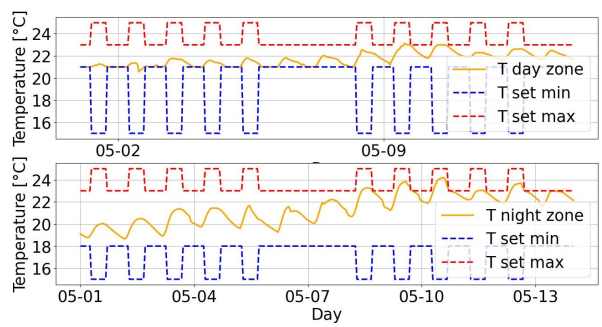

Figure 5: Evolution of the temperature in the day and night zone of house 1 (T day zone and T night zone) and their corresponding minimum and maximum values in the period Mayu 1-14.

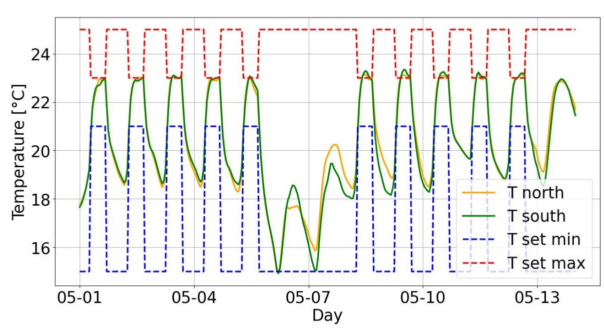

Figure 6: Evolution of the temperature in the north and south zone of the office building (T north and T south) and their corresponding minimum and maximum values in the period May 1-14.

Secondly, the MPC's ability to make use of the flexibility available in the system is nicely illustrated by the results shown in Figures 7 and 8. Figure 7 shows the evolution of the temperature in the high-temperature mixing volume, the net amount of heat injected in the DHC by the buildings (negative value means more heat is extracted from the network than injected), and the heat addition to the buffer tank by the central heat pump in the period March 6-11. During periods of low heat demand, the MPC does not turn off the central heat pump but keeps heating the buffer tank such that in periods of high heat demand, the supply temperature of the decentral heat pumps is higher and a higher COP is achieved. This is a nice illustration of controller anticipation in a period of mainly heating demand. This controller anticipation is also present during periods with more cooling demand, which is illustrated by Figure 8. The figure shows the evolution of the temperature in the low-temperature mixing volume, the outdoor temperature, the net amount of heat injected in the DHC by the buildings, and the heat extraction from the buffer tank by the central chiller in the period May 7-14. In this period, there is a large cooling demand throughout daytime. Figure 8 shows that the MPC controller predominantly uses the central chiller to cool the buffer tank during the night. This might seem strange as cooling demand is low during the night. However, the outdoor temperature is then also lower and, as a result, a higher EER is achieved.

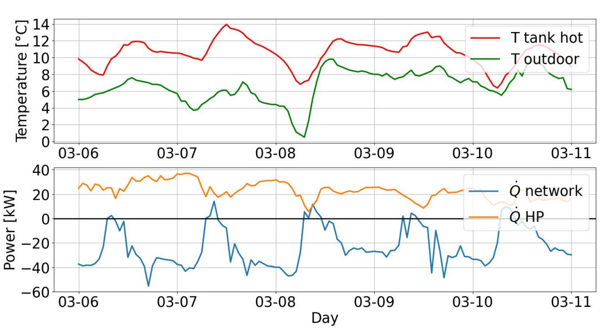

Figure 7: Evolution of the temperature in the high-temperature mixing volume (T tank hot), the outdoor temperature (T outdoor),the net heat injection in the DHC network ($\dot{Q}$ network), and the heat addition of the central heat pump to the buffer tank ($\dot{Q}$ HP) in the period March 6-11.

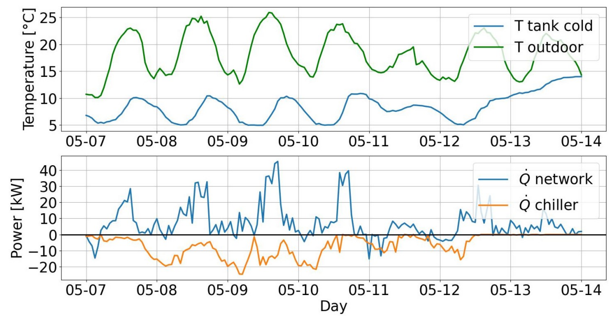

Figure 8: Evolution of the temperature in the low-temperature mixing volume (T tank cold), the outdoor temperature (T outdoor), the net amount of heat injected in the DHC by the buildings ($\dot{Q}$ network), and the heat extraction from the buffer tank by the central chiller ($\dot{Q}$ chiller) in the period May 7-14.

Further work

The above results show the potential of the developed two-step method to optimally control a 5GDHC network. However, further developments, such as including pump energy in the objective function, improving the buffer tank model, and integrating DHW (Domestic Hot Water) into the system, are still possible to enhance the overall functionality of the controller. Subsequently, expanding the application of this method to a larger district, encompassing multiple building types, is crucial for obtaining a better understanding of the method's effectiveness in diverse scenarios. Moreover, further research is needed to fully determine the added value of going to MINLP-based MPCs for the considered type of DHC networks. To identify and quantify this added value (i.e. determining the energy and cost saving potential), the proposed two-step MINLP-based MPC should be applied to a real-life use case and compared with current practice control and/or a control approach with a better rule (compared to the rule used in the proposed integer-selection approach) to select the operating mode of each building.

Conclusion

In this paper, a novel two-step method for MINLP-based MPC control, taking into account the non-linear dynamics of the hydraulic system and directly determining the control inputs to realistic systems, is developed. This method is applied to a small, virtual bidirectional energy flow, non-directional fluid flow 5GDHC network and compared with a very basic integer-selection control approach that determines the integer values based on a simple rule. For both approaches, an 8-month open-loop simulation is carried out. The results of these simulations show that the proposed simple approach is not suitable for the control of the considered system, as it results in large thermal discomfort. The proposed MINLP-based MPC shows promising potential for the optimal control of the considered 5GDHC system, as it can achieve thermal comfort while also exploiting the system flexibility to minimize energy use. Nevertheless, further research is still needed to increase the accuracy of the controller model and to quantify the added value of the optimal controller compared to current practice. Confirmation of this added value through the demonstration of cost and energy savings would underscore the imperative of incorporating building dynamics and the non-linear physics of the system into the district controller. Morover, this confirmation would show the proposed controller can increase the economic viability of 5GDHC networks, thereby fostering the potential for a broader implementation.

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