REPORT

HEAT HIGHWAY

Task 3.3: control algorithm for interregional heat transmission networks

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Inhalt

1 INTRODUCTION

The use of industrial waste heat is essential for the decarbonisation of heat supply. While the electricity transmission grid connects many generation, storage and consumption units, current options for waste heat injection and interregional exchange are limited.

The project “Heat Highway” is therefore investigating interregional heat transmission networks (HTN), which combines four areas: industrial waste heat and other sustainable sources, district heating networks, industrial process heat sinks and storage. These HTNs connect consumption centers and industrial sites, by travelling through areas with other heat sources and sinks.

The project HeatHighway is coordinated by the Energy Institute at the Johannes Kepler University, Linz; and funded by the Climate and Energy Fund of the Federal Government of Austria and the Austrian State of Upper Austria in the framework of the model region “NEFI, New Energy For Industry”. More information on the project can be found at:

- Project-overview (English)
- Project-overview (German)
- Project website (English)
- Project website (German)

As part of the Heat Highway project, technical challenges for the realization of such interregional heat transmission networks were addressed.

This report discusses the development and validation of different control algorithms and operational strategies, including consideration of available flexibility options.

Therefore,

1. different control strategies were analysed via a literature review and discussion with experts and
2. for a concrete case study (the HeatHighway in Linz), a suitable control strategy was investigated.

This report focusses on the first part, details for the second part can by found in the annex. The following sections are distinguished by their application area:

1. Section 2 describes the concrete technical strategies, like heat load forecasting, temperature management on the demand or supply side, whereas
2. Section 0 described overall control strategies which operate more or entirely as tools for achieving the actual control strategies of the system, as described in the first section.

2 TECHNICAL CONTROL STRATEGIES FOR KEY COMPONENTY

2.1 Basic control strategies for DH networks

According to [1] there are six basic control strategies which operate simultaneously in a traditional DH network. These are usually implemented in the form of classical control such as rule based or PID. A graphical depiction is shown in Figure 1. (A to E are implemented at the production and pumping station level, whereas the control strategy F is implemented at the user substation level.)

A. **Supply temperature control**: The goal of this control is to modulate the thermal power at the heat generation plant to reach a fixed supply temperature set-point. The latter is generally determined by means of a heating curve as a function of the external ambient temperature, and it needs to be high enough to satisfy the temperature level required for all the customer-sited heat emission systems. In most cases this is done by varying the mass flow rate of the pump, which moves the heated water over the heat exchanger in such a way, to keep the temperature of the water after the heat exchanger on the network side constant. Higher mass flow rate leads to more heat exchanged. The maximum mass flow rate is determined by the maximum heat produced by the energy generation site. In this simple example, as long as the mass flow rate of the pump can be adjusted as fast or faster than the change of the generated heat, no further control is needed and the temperature of the water, which gets fed into the network, remains stable, provided the generated heat is in the nominal range.

B. **Minimum supply temperature control**: This control is important, especially in summer, when the DH system operates to supply only the domestic hot water (DHW) load. During the night, for instance, a bypass between the supply- and return pipelines at the end of the network allows maintaining a small recirculation in order that the supply temperature always satisfies the comfort level for the users.

C. **Minimum differential pressure control**: It is essential to maintain a minimum differential pressure between the supply and the return pipelines at the farthest substation from the network pumping station. In this way it is assured that the pressure head is enough to supply all the substations in the between.

D. **Maximum pressure control**: The pumps are controlled to avoid over-pressure at the supply line that could damage the network.

E. **Minimum pressure control**: The minimum pressure of the network that occurs at the suction of the pumps is controlled to avoid cavitation and damage of components.

F. **Heat demand and flow control**: These control strategies are implemented at the user substation level. For instance, a climatic control can be implemented to set the supply temperature on the substation’s secondary side. A modulating valve is then used to achieve this set-point by controlling the flow rate on the substation’s primary side.

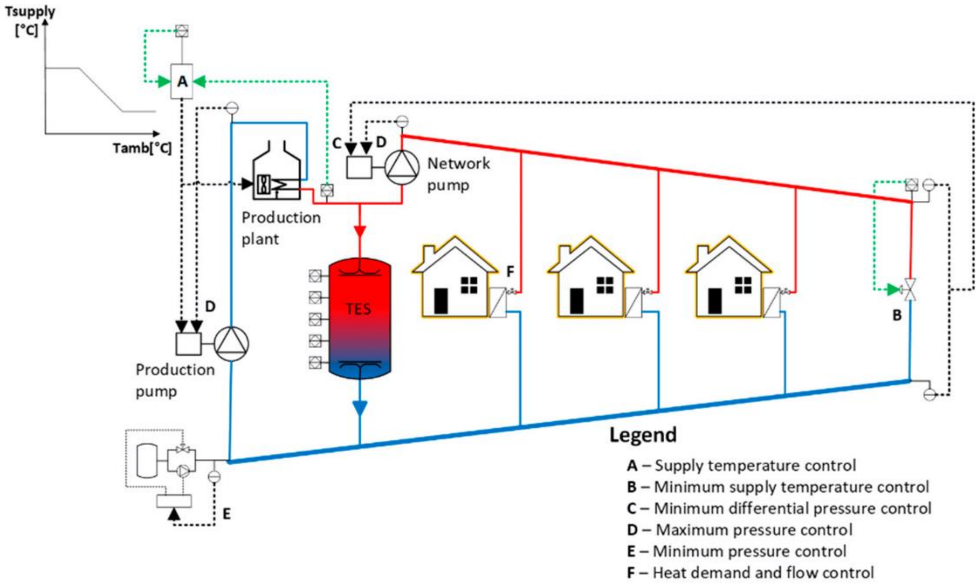

Figure 1: Basic control strategies in traditional district heating (DH) systems [1].

2.2 Temperature management in HTNs

Maintaining the temperature of flow and return is vital to the consistent operation of a HTN. Substations may be required to maintain temperature and pressure over the long distances. In the case of a Heat Highway, where various users feed into and take from a central “highway”, it can be the case that different heating or cooling sources provide and or use varying temperatures and cannot directly feed into the network. It can be the case that the temperature provided by these sites is not high enough to heat the flow line (As it is often the case with industry waste heat for example). In such a case some sort of post heating is required. The post heating can occur in one of two main ways. Either

- heating before the infeed of the heat into the flow line of the HTN. This post heating can be achieved via heat pumps (HPs) or a conventional post heating system (electric or gas-based boiler). Where this post heating occurs is dependent on the specific network but would normally be done at a bigger power plant, which already provides a sizable portion of the thermal energy in the HTN.
- adding a lower temperature line (i.e. pipe) to the network, which transports lower temperature water which gets heated to the flow temperature at a different point in the network.

The second option is particularly useful, if a higher number of industrial waste heat is fed into the system, which are similar in temperature, either to the flow temperature our around a lower temperature, where a second mid-temperature line could be added to have a post heating solution at one or a few centralized points in the system. This system can get quite complex quite quickly, especially, when the waste heat is not produced in a predictable fashion.

In long distance heat transfer networks (LDHTN), this is even more relevant, because of the potentially higher number of substations to maintain the necessary temperatures. The very important question of where to place additional post heating substations in the specific case is difficult to answer and relies heavily on the existing topology and size of the system.

Expanding on the previously mentioned addition of temperature lines, besides the necessary flow and return lines, here the general idea would be, that in some circumstances – especially if there is a lot of lower temperature industrial waste heat concentrated in an area – the addition of a separate pipe transporting the lower heat to a centralized post heating spot would start to be more economically viable. Especially if the alternative would be to post heat every instance of a low temperature heat source to the flow temperature and increase the losses of the transportation to the different heat sinks in the network. This would increase the additional energy (in most cases electrical and in the worst cases fossil fuels) used substantially.

2.3 Thermal Energy Storage

Thermal energy storage (TES) systems based on short-term tanks provide several advantages in traditional DH networks. They help to equalize the load of the heat production plants, while heat demand by consumers is fluctuating, and can cover the peak demand by avoiding that peak generation units with high operational costs switch on. Moreover, TES systems allow the system to operate when the heat demand is below the technical minimum of the heat production plant and increase the flexibility of combined heat and power (CHP) systems by permitting electricity generation during off-peak hours of the heat load without wasting the heat produced. If a TES is directly connected to the DH network such as in Figure 1, the control measures are trivial [1].

centralised vs decentralised:

The centralised storage has less heat loss due to the lower surface to volume ratio. In most cases it is also cheaper to build.

But, in urbanised areas there is less free space available for a large, centralised storage.

The decentralised storage can be further split into substation level storage and building level storage.

1. Substation storage: Because the storage is located in the substation location, the power doesn't need to be transported from source to substation location during network peak demand. Therefore, the transport pipe sizes can be designed with smaller diameters for substation level storage, but the distribution pipe sizes remain the same. Moreover, the source power can be reduced, similar to the centralized storage. However, as mentioned before, the distributed storage is more costly for the same total storage size when compared to centralized storage.
2. Building level storage: Here, storage tanks are placed at every building. In many cases it is difficult to find the place for such a storage, but the heat can be stored and used directly by the building and less heat needs to be transported there during peak demand times. Therefore, both the transport and distribution network pipe size can be designed with smaller diameters. Furthermore, like the substation storage, the source power will also be reduced.

Especially in LDHTN a thermal energy storage is an essential addition to the system. Decentralized storages along a LDHTN, can help decouple the heat production units from the demand side, and also provide fast response times, when the demand increases.

2.4 Hydraulic Switch

A hydraulic Switch is basically a subset of a thermal storage. It can be used in cases where different serial components in a HTN have different ramp up/down times, applying some decoupling to maintain consistent temperatures over various load changing behaviour. For example, one heat generation unit varies to fast for HPs or other control mechanisms to follow in time. In such a case a hydraulic switch and an additional pump may be used to help compensate for this difference in response times. In this case the two sides of the system are decoupled via the hydraulic switch, which acts as a storage-bypass with two temperature levels and a boundary between them, which can vary in position. Each pump follows the two sides of the system with their respective ramp up/down times. While there is a load change, the mass flow rates will differ, and this difference is compensated by the stored water from the hydraulic switch at the respective temperatures and the position of the boundary will change accordingly.

The minimum ideal volume of the switch V_{switch} can be calculated with a simple integration over difference in the respective mass flow rates:

$$V_{switch} \geq 2 \int_{t_{start}}^{t_{end}} \left(\dot{m}_1(t) - \dot{m}_2(t)\right) dt \,,$$

where t_{start} and t_{end} are the start time and end times respectively of the maximum load switch, $\dot{m}_1(t)$ and $\dot{m}_2(t)$ are the two differently changing mass flow rates as a function of the time t, where $\dot{m}_1(t) \geq \dot{m}_2(t)\ \forall\ t \in [t_{start}, t_{end}]$, which means that $\dot{m}_1(t)$ changes slower than $\dot{m}_2(t)$, if both start at 100% the nominal mass flow rate $\dot{m}_{max}$ and end at some minimum mass flow rate $\dot{m}_{min}$. The factor two is needed because one half of the switch is filled with hot and the other with cold water and it is assumed, that the switch maintains equal volume of both hot and cold water.

Assuming this change in mass flow rate happens linearly, then this expression simplifies to

$$V_{swich} \geq (\Delta t_1 - \Delta t_2)(\dot{m}_{max} - \dot{m}_{min}) \, ,$$

where Δt_1 and Δt_2 are the time the respective pump needs, to change from $\dot{m}_{max}$ and $\dot{m}_{min}$ or vice versa.

If the fill level of the hydraulic switch is adjusted dynamically in relation to the current mass flow rate, a better switching behaviour can be achieved, and the minimum ideal volume of the switch can be cut in half:

$$\tilde{V}_{swich} \geq \frac{(\Delta t_1 - \Delta t_2)(\dot{m}_{max} - \dot{m}_{min})}{2} \, .$$

This is because to the upper and lower boundary of the mass flow rate limit the respective maximum switching direction. For example, if both pumps already are pumping the maximum mass flow rate, there cannot be a switch in the direction of more mass flow. So, there is only one direction the switch can be filled, in this case and the fill level can be adjusted to one side of the switch, so that the maximum volume can be used for the switching process. Same for the minimum mass flow rate.

2.5 Heat Pumps

When using heat pumps (HPs), there are numerous ways of controlling and implementing them. In cases with low-, mid-, return- and flow temperature lines, a number of HPs are used in series, to lift the return temperature to the flow temperature along the condenser-side of the HPs and cool the mid temperature to the low temperature along the evaporator-side.

The operation of the HPs in this system is with constant mass flow rate over the evaporator and the condenser. The variation of the mass flow rate is done via a pump at the beginning or end of the serial cascade and bypasses over the individual HPs (see Figure 2). This is done so that the mass flow rate over the heat exchanger remains constant.

A HP in this system has three degrees of freedom:

1. compressor power: In simple terms, the power of the compressor can be adjusted to move more heat between condenser and evaporator and therefore provide a higher heating/cooling power.
2. mass flow rate over evaporator: Same as the temperature control via mass flow rate. Here the heat from the water flowing over the heat exchanger is moved into the HP refrigerant cycle and up to a higher temperature via compression and the heat is deposited on the condenser side. Depending on the mass flow rate over the evaporator, more or less heat can be deposited. Higher mass flow rate means more heat is deposited. This can be done only up to a certain point and is in part limited by the power of the compressor and dependent on the type of HP.
3. mass flow rate over the condenser: Same as with the evaporator. Higher mass flow rate leads to more heat transferred from refrigerant to the water flowing over the heat exchanger of the condenser.

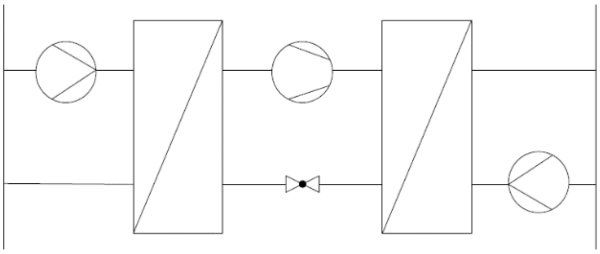

Figure 2: Heat pump setup, with a pump at the evaporator, another pump at the condenser and two bypasses over the respective in- and outputs.

When implementing HPs, a cooling line may also be an option. By heating up the mid temperature line, for example, the return could be used as a heat source and could be cooled further.

This cooling line could also be provided to industry, to help cool down different processed, which would normally cool via air, rives or ground, which can be a problem in some regions, where river temperatures are already too high for example.

2.6 Demand-Side Management

The demand is normally uncontrollable from a heat network operators' points of view, and its quantity varies during the day and along the season. To flatten the load curve, system operators usually implement demand-side management (DSM) strategies that consist of a portfolio of practices aimed at modifying the demand side of an energy system by promoting information programs, energy efficiency, energy saving but also with the implementation of demand response (DR) programs.

A critical issue in DH networks is the presence of peak requests, particularly in the morning. Here, DR can play a vital role on the demand side to shave these peaks and potentially avoid large investments in centralized TES systems.

Peak-shaving and load management are two main applications of DR that add flexibility to an energy system by making the demand more elastic. In general, DR strategies are classified into **price-based** and **incentive-based** programs:

- To **price-based programs** belongs all the solution that aims at influencing end-user choices with time-dependent tariffs such as real-time pricing (RTP) or common time-of-use (TOU) tariffs.
- Differently, **incentive-based programs** are based on contractual agreements with grid operators or utility companies and foresee a reward to the customer for the reduction in their load upon request or with the direct remote control of some equipment.

Using DR, a genetic optimization algorithm has been adopted to select the binary values for thermal peak shaving and a resulting reduction of the global load. To shave the peak of DH substations, a simplified approach of DSM was used, which increased heat exchanger efficiency and reduce peak load. To exploit the thermal mass of buildings for a DH network the temperature set point in the buildings was varied according to a mixed-integer linear programming (MILP), which led to a significant reduction in on–off switching of the peak units (more details on MILP in section 3.3, Linear Programming and Mixed-Integer Linear Programming). Sector-coupling between electrical and thermal grids is also possible by exploiting the presence of HPs and TES systems at the customer sited-station level and allowing their participation in more common electrical DR programs [1].

3 METHODS FOR CONTROL FOR THE OVERALL SYSTEM

Challenges such as weather uncertainty, user behaviour and customer-sited substation operation need smart control strategies at centralized and decentralized levels, which need to be applied on top of basic control strategies.

The implementation of advanced control strategies in DH systems is challenging, since they are affected by time-varying nonlinear dynamics, time-varying set-points and disturbances. Advanced control strategies applied in DH can be classified as hard, soft and hybrid control.

3.1 Fault Detection and Diagnosis

For the whole system to operate as efficiently as possible, faults need to be kept to a minimum.

Several factors, such as compensation actions triggered by control algorithms or lack of proper maintenance practice, can make these faults remain undetected. One typical operating problem in district heating systems is the heat carrier loss through water leakage. Other operating problems are higher temperature levels due to high return temperatures caused by typical malfunctions such as set-point errors in substations and customer heating systems or short-circuit flows in the thermal grid.

There is a huge range of different fault detection (FD) techniques.

- “Externally based” or hardware methods, such as visual inspection, infrared image processing or cable methods are not usually suitable to be included in an automatic FD system.
- So called “internally based” methods FD methods may be model-based or based purely on process history data. The model-based methods depend on knowledge of the basic physical processes and principles governing those system(s) being the target of the analysis. Qualitative model-based approaches including rule-based fault detection. They rely on the data from the system in operation. These include statistical regression models, artificial neural networks (ANN), etc.

In general terms, algorithms used in fault detection and diagnosis (FDD) can be divided into **physical model-based methods** and **data-driven methods**. Both can be used to compare the real and the predicted value of one or several variables and deploy an action when this difference reaches a certain threshold. The action to perform can vary from a simple alarm to a complex control action to minimize safety and performance problems, and it can be applied at the component level but also at the facility level [1].

The main pros (+) and cons (−) for **physical model-based methods** are [1]:

- (+) They are made up of simple and usually well-known algorithms based on physical laws and equations.
- (+) Once the models are calibrated, online data can be used directly to predict some indicators and compare them with the real situation without the need for training the model periodically.
- (−) The integration of physical models from different components to create a complete facility model may suppose an important effort to be assumed by developers and testers.

The main pros (+) and cons (−) for **data-driven methods** are [1]:

- (+) Can be useful to represent complex real phenomena that are not easy to explain with equations based on physics.
- (+) Can be very accurate in the prediction of the behaviour of a system.
- (−) The models have to be trained using usually different datasets for the different states of the system, one for a regular state and one for each possible failure state or even combination of several failures at the same time.
- (−) It is necessary to have a huge amount of experimental data that in most of the cases are not available, with the consequence to resort to using small not representative experimental datasets or data coming from simulations or physical models.

Some of the approaches for algorithms used for FD based on ML techniques such as ANNs are not useful, since models trained with laboratory data or data coming from simulations do not achieve a good enough performance when working with online data.

But, these kind of FDD applications show a very promising growth and may be a good option to solve complex FDD problems in the near future [1].

3.1.1 Leakage Detection

Leakage Detection is one of the state-of-the-art FD approaches and algorithms that are mainly applied in DH systems. Failures on district heating pipes are often caused by water leaks due to corrosion, mechanical impacts and insufficient or deteriorated performance of the thermal insulation solutions. However, some degree of leakage is impossible to be avoided during extended operation since pipeline performance degrades over time. Therefore, an anticipated diagnosis of leakage occurrence is highly necessary to improve efficiency, reduce operating costs and protect the environment [1].

As mentioned before, methods found in literature are usually divided as **internally-** or **software-based** and **externally-** or **hardware-based**.

- **software-based**: A physical model-based algorithm may include a dynamic monitoring module (DMM) and a static testing module (STM). The DMM can detect larger leakages analysing pressure waves through amplitude propagation and attenuation models. The STM, based on the pressure loss model, can detect micro-leakages, thus being able to act as an effective compensation for the DMM.
- **hardware-based**: One example consists of training a decision-tree-based ensemble ML algorithm using data generated by a simplified physical model and using it to detect leakage in pipes through the collected data from pressure and flow sensors present in a DH network and substations. This requires a number of pressure sensors to be available in the system.

Two interesting proprietary “hardware-based” solutions deserve mentioning (see [1]). One of them has been developed by the smart meter brand Kamstrup and consists of a leakage detection system based on the analysis of the signal coming from ultrasonic flowmeter installed in substations.

The other one is based on the well-known impedance method using sensing cables. When a leak takes place, the cable gets saturated with fluid, thus altering its impedance.

The advantages include high accuracy in determining leak location and easy configuration and maintenance. In contrast, the installation has very high costs and wiring requirements.

In the field of image processing, infrared sensors are able to capture variations in the heat flow caused by underground fluid leaks, and then show them as hot spots in the DHC system route. This process can be accomplished on the ground, from an aerial platform or from an aircraft or drone. This way, thermography reveals sources of heat and the relative differences in temperature from one object to another. Postprocessing of IR images may be computationally expensive, and their analysis could lead to false negatives because some colour differences caused by a leakage could be almost inappreciable. To solve this, ML algorithms to improve postprocessing have also been developed [1].

3.2 Model Predictive Control

Model Predictive Control (MPC) is an advanced control strategy widely used due to its ability to handle multivariable control problems with constraints. It requires a surrogate model of the plant that is used to simulate the behaviour of the system in a dynamic optimization problem, with the goal of minimizing a cost function in a receding horizon fashion (for more detail see [1]).

Set up correctly, the MPC can help in managing fluctuating demand and manage the large distances by predicting, when a larger load for example may appear at the demand and heat source side and act accordingly.

In comparison with a standard PID controller a MPC controller based on a dynamic programming (DP) optimization algorithm led to a decrease in natural gas consumption. By scheduling boilers, TES units and flexible loads, a MPC succeeded in reducing operating and maintenance costs in a DH power plant. It was also used to improve the thermal storage tank management in a multi-energy district boiler and reduced fossil energy consumption and CO2 emissions, while the economic profit increased. A MPC has been applied to decentralized solar thermal collectors fields connected to a DH network in the return-supply configuration, solving the problems of the previous PID controller, that was not capable of limiting severe supply temperature and flow rate cycling variations that can be a cause of fatigue problems in buried steel pipes [1].

Strengths (+) and Weaknesses (−) of MPC [1]:

- (+) Instead of corrective operations, it employs a proactive approach with anticipatory control actions.
- (+) Load forecast and stochastic disturbances can be handled.
- (+) Systems with delays and operational constraints are taken into account.
- (+) Multiple objectives can be formulated in a cost function and achieved by exploiting advanced optimization algorithms.
- (+) It can be formulated in both centralized and distributed fashion but also at the master or slave level.
- (−) Time-consuming for the implementation and model identification phase.
- (−) Non-technical users require specific background knowledge of the method.
- (−) Require significant higher expenditures, which may not be repaid by additional savings in a short period.

3.2.1 Model Predictive Control merged with other Methods

Sometimes for covering the disadvantages of MPC and obtaining the best performance and result, MPC has been merged with other methods.

To control the supply temperature in the DH network, a combination of the MPC and fuzzy direct matrix control (FDMC) was used. Findings confirm that FDMC can command the inherent nonlinearity in the acknowledgment characteristics of DH systems by considering the volume flow rate at the plant as a fuzzy variable. Additionally, the trade-off between pumping and heat loss costs can significantly impact minimizing operational costs.

A tool using MPC strategy was used to optimize operational costs by considering technical and operational constraints. Different configurations with increasing cost-saving, installation costs, renewable energy source generation and primary energy saving are presented, and results demonstrated the success of the method [1].

3.2.2 Heat Load Forecasting

In general, the demand is characterized by seasonal variations, weekly variations between workdays and weekends and daily ones. Different techniques like simple linear regression, neural networks, machine learning (ML) algorithms etc. can be employed for heat load forecasting [1]. In the case of long distance HTNs, this can be even more important, because of potentially the longer distances between heat production and heat consumption.

3.3 Linear Programming and Mixed-Integer Linear Programming

Linear programming (LP) and mixed-integer linear programming (MILP) are commonly used to determine the optimal size and scheduling for components in complex energy systems.

A MILP model was used for the design and operation of an urban energy system and is based on a flexible value web framework for representing integrated networks of resources and technologies. It can be used for different temporal and spatial scales.

A MILP was also applied to minimize the total annual cost for an industrial area with the integration of solar thermal production and showed a reduction of primary energy consumption and yearly total cost.

A MILP-based controller managed to reduce the system operational costs of a DH supplied by a large share of low-grade excess heat, with respect to a standard rule-based control [1].

Strengths (+) and weaknesses (−) of MPC with mixed-integer linear programming (MILP) [1]:

- (+) Good and exact optimal solution.
- (+) Rigorousness, flexibility and extensive modelling capability.
- (−) Time-consuming particularly for large problems.
- (−) It is known to often have weak linear programming relaxations.
- (−) Loss of original discrete structure.
- (−) Introduction of auxiliary binary variables.

3.4 Meta-Heuristic Algorithms

Adequate optimization algorithm depends on the problem formulation; likewise, how to formulate the problem depends on the optimization algorithm to use. In some cases, the execution time increases exponentially according to the problem dimensions and deterministic optimization algorithms cannot solve challenging and complicated issues. In [2] a meta-heuristic is defined as: “An iterative generation process which guides a subordinate heuristic by combining intelligently different concepts for exploring and exploiting the search space, learning strategies are used to structure information in order to find efficiently near-optimal solutions.”

Meta-heuristic optimization algorithms are usually population-based biological-inspired algorithms, with some of the most used being genetic algorithms (GA), particle swarm optimization (PSO) and ant colony optimization.

A two-level algorithm is proposed to reap the benefits of the MILP formulation for the optimal operation problem, while overcoming its main drawbacks by means of a GA at the design level.

A hierarchical optimization strategy is used, where the higher layer for binary decision is dedicated to the GA, while the MILP algorithm is used in the lower to choose the system’s optimal operation. Results show a remarkable reduction in computing time [1].

A combination of ML models and meta-heuristic algorithms can also be implemented. There, the ML models are mainly used to cope with system non-linearities, and the meta-heuristic algorithms are used to solve the constrained optimization problem.

Strengths (+) and weaknesses (−) of meta-heuristic algorithms [1]:

- (+) Straightforward coding in any programming languages.
- (+) Very quick convergence.
- (+) No need for complicated mathematical operations because they are gradient-free.
- (−) Easy to drop into local optimum.
- (−) Possible stagnation after some initial stages.
- (−) Efficiency reduction with an increase in problem dimension.

3.5 Multi-Agent System

The multi-agent system (MAS) approach benefits several critical computer applications such as communication network configuration, process control, planning or concurrent systems. MASs are formed by several agents that have a considerable number of communications with each other. In general, agents act to support the users and have different goals and motivations. An agent is defined as an autonomous entity that can be viewed as perceiving and acting upon its environment. An agent must be able to communicate with other agents. To interact successfully, agents must have the ability to cooperate, coordinate and negotiate with each other [1].

Conversely from traditional MPC, multi-agent systems (MAS) control can be considered a hierarchy-free solution where different entities interact, e.g., as in a peer-to-peer market and operate without mandatory signals from a centralized higher-level controller. They are not widely applied in the DH sector.

Nevertheless, the MAS approach was used to decreased peak loads by peak shaving. The MAS approach was used to control a compressed unit providing heating, ventilation, and domestic hot water production in a low-energy building. It improved thermal comfort with only minimally increase in cost. Combining MAS and PSO is also effective in maximizing the comfort index using minimum power consumption [1].

Strengths (+) and weaknesses (−) of the MAS approach [1]:

- (+) Based on the goals, agents can act autonomously in their environment, which could be cooperative or competitive.
- (+) Decreased need for massive data manipulation.
- (+) The other agents modify and continue the system functions if one controller loses.
- (+) According to some rules, allow the manufacturers or loads to embed programmable agents in the equipment controllers.
- (+) Agents are able to learn from their behaviours and past activities.
- (−) Communication languages, protocols and the design of agents’ ontologies should be based on common standards.
- (−) Since plenty of multi-agent platforms have been developed, selecting the most appropriate is a tricky task.
- (−) The design of an intelligent agent is challenging.

4 CASE STUDY

Based on the above investigations for a concrete case study (the HeatHighway in Linz), a suitable control strategy was investigated. The case study posed some concrete design challenges:

An array of heat pumps (low temperature and mid temperature heat pumps) is used to increase the temperature of a part of the return flow to the flow temperature. The low temperature waste heat together with the mid temperature waste heat are used as heat sources of these heat pumps.

Due to the fast response time of the low temperature waste heat and because the control system of the HPs needs a longer time to maintain stability, a hydraulic switch is needed to decouple these two systems. This hydraulic switch needs to be accurately sized, to hold enough water. To “refill” this hydraulic switch after a change of the low temperature waste heat, a fitting control mechanism needed to be devised. When in steady state, the two pumps generate, if possible, a difference in mass flow rates, which restores the temperature balance inside the hydraulic switch to the needed level.

Decoupling the control circuit of the mass flow rate of the pump on the condenser side, which provides the adequate mass flow rate to lift the return temperature to the flow temperature, from the control circuit for the compressor power of the HPs was not so easy. The various PI controls were tuned individually and the implemented together and adjusted again, to resolve the oscillations, which resulted from the similar time constants of the two control circuits.

For details, see Annex „*Regelungstechnische Untersuchung des „HeatHighway kurz“ in Linz*“

5 LITERATURE

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