DISTRHEAT

Digital intelligent and scalable control for renewables in heating networks

Deliverable D6.1

Technical synthesis and multi-scale strategy for DHC systems

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Executive summary

The project dealt with two case studies in different countries:

1. A small-scale district heating and cooling network with a multi-energy thermal power station, which supplied the Cona Hospital, located near Ferrara in northern Italy.
2. A large-scale district heating network in the city of Västerås, in central Sweden.

The project activities consisted in developing and demonstrating smart control strategies for optimally managing these networks. Even if the two case studies were different in size and composition, the approaches showed similarities in the following aspects:

- A gray-box or physics-informed load model for the distribution side of the network is created, in order to use specific data but maintain the generality of the physical phenomena.
- The average temperature is used to represent the load model.
- >A multi-agent hierarchical control architecture is adopted to tackle the entire system
- Model Predictive Control is the selected control method.
- The proposed controller is verified in Model-in-the-Loop and Herdware-in-the-Loop environments, before being implemented in the real test site.

Nevetheless the approaches highlighted two potential limitation in their replication:

- In service-sector networks (Italian test site), different management strategies can be applied by the system operator as long as the comfort service is assured, while in residential buildings (Swedish test site) this may depend on the specific customer.
- The actual adoption of the control solutions may depend on the share of district heating in the heat end use of the specific country of installation.

The experiences in the project permitted to learn these lessons and key elements for implementation of smart controller:

- The importance of keeping the physical information of the load and network
- The possibility to avoid custom-made solutions, which are difficult to replicate
- The controller demonstration on a digital twin or emulator of the network, in order to foster its uptake and extension.

To overcome the identified limitations and exploit the lessons learnt, the final output of the project is a scalable approach. This consists of dividing a generic network into different parts for which a dataset is available and representing each part as an aggregated consumer with an equivalent model. This model is included within the Model Predictive Control strategies (demonstrated within the project) for controlling the entire system in a smart way.

Since this procedure does not depend on the size or configuration of the system, it opens up the possibility to manage generic energy networks (i.e. a city, a neighborhood or a multi-story building) in a fractal way.

1. Introduction

This report is the deliverable D6.1. of work package WP6 of the DISTRHEAT project, led by University of Parma. The work package "WP6 – Technical synthesis for a scalable approach", aims to collect the lessons-learnt from the two case studies of the project.
The first case study regards the implementation and testing of a smart control strategy in a small-scale district heating and cooling network (DHC) located in Italy (i.e. the multi-source energy network supplying the hospital of Cona, near the city of Ferrara). These activities were carried out within WP2 and WP3 and are described in Deliverables D2.1, D2.2, D2.3 (development and modeling) and D3.1, D3.2, D3.3 and D3.4 (implementation and testing).
The second case study aimed to demonstrate a smart control strategy in a large-scale district heating network supplied by a waste-to-energy cogeneration plant located in Sweden (i.e. the city of Västerås). These activities were carried out within WP4 and WP5 and are described in Deliverables D4.1 and D4.2.

The approaches of these two development phases were coordinated and evaluated at the beginning and during the project (Figure 1). The methods and results were analyzed and the similarities and limitations were investigated. Finally, it was possible to draw a technical synthesis of the project results, and to propose a unified methodology for the smart management and control of generic district heating and cooling networks.

Figure 1. Technical synthesis between the two case studies of the project.

The output of this Deliverable and of the DISTRHEAT project is this technical synthesis that can be exploited by researchers and practitioners in the field of district heating management.

2. Comparison between case studies

2.1. Results in brief

2.1.1. Small-scale DHC

The activities regarding the development, implementation and testing of the smart controller in the Italian case study are here summarized:

- **Selection and characteristics of the test site (D2.1 and D3.1)**. The test site is the Sant'Anna Hospital of Cona, located close to the city of Ferrara, in the north-east of Italy (Emilia-Romagna region). The system comprises (i) the thermal power station and (ii) a small-scale district heating and cooling network. The thermal power station can be divided into the following sub-systems: a trigeneration plant which comprises a cogenerator and an absorption chiller, four natural gas boilers, four electric chillers, three steam generators, and the connection with the power grid. Based on the analysis of the site selected as small DHC case study and on the investigation of the thermal power station composition, the requirements for the following activities of the WP were drawn. For each energy conversion unit in the thermal power station, the following details are required: (i) its numerosity, (ii) the nominal input power, (iii) the minimum input power and, (iv) the nominal efficiency. Moreover, it is recommended to collect the minimum efficiency, ramp up and ramp down limits, start-up cost, idle cost, minimum up-time and down-time. Regarding the whole site, it is necessary to have the forecast of the following disturbances: thermal power demand, cooling power demand, electrical power demand, steam demand, outdoor temperature, cost of electricity sold to the grid, cost of electricity bought from the grid and cost of fuel.
- **Development of the small-scale DHC model, also called digital twin (D2.2)**. A digital twin of the small-scale DHC (Cona Hospital) is built by combining together the components from an in-house library of models for integrated energy systems. Each block represents a physical component that can be found in multi-energy networks, covering various domains, i.e. heat, electrical energy, fuels. The control logic implemented in the digital twin represents the traditional way in which the energy system of the real-world hospital is operated. All relevant variables of the system (e.g. mass flow rates, temperatures, pressures, powers) can be monitored to produce datasets of system operation, in order to determine the complete energy and environmental performance in given operating conditions and allow to verify if the technical requirements of the distribution systems are maintained.
- **Development of a Model Predictive Control algorithm for controlling the small-scale DHC with a double time scale (D2.3).** The novel control algorithm is based on Model Predictive Control (MPC). It aims to combine the benefits of short-term optimization (i.e. with short control horizon and high detail) and long-term optimization (i.e. with long control horizon and low time resolution) within a unique architecture, that is able to (i) fulfill end-user demand of all energy vectors, (ii) couple two different time scales, and (iii) be applied in a real-time MPC. This is achieved through a multi-agent hierarchical architecture with three different modules: one for the distribution of hot and cold water to the end-users (which includes a gray-box dynamic model of the buildings), one for the real-time control of the thermal power station (solved with a Mixed Integer Linear Programming model) and one for the long-term planning of the system (solved with a Linear Programming model). These modules communicate and interact continuously and are periodically updated with their specific time schedule (i.e. every

15 minutes for the distribution and short-term module, every day for the long-module). The software implementation of the algorithm is done both in MATLAB® and in Python.

- **Verification of the MPC algorithm in a Model-in-the-Loop simulation environment**. The control code is used to control the digital twin of the system for an entire operating year. In brief, a 99% reduction in dissipation from the cogeneration plant, an increase in utilization of the absorption chiller, a 10% reduction in operating cost and a lower dependency from the power grid were achieved, with respect to the traditional way to manage the system. The complete results are reported in (Saletti, Morini and Gambarotta, 2022).
- **Installation of the monitoring equipment in the real test site and definition of the baseline of operation (D3.2)**. The baseline has the primary objective of determining the standard operations of the energy plant, independently of changes of the external environment (outdoor temperature, variation of heated volume, etc.). Hence, a method based on linear regression analysis is used to define it.
- **Implementation of the new MPC algorithm within the real test site (D3.3).** The hardware installation and configuration was carried out by Siram Veolia with the help of the local system integrator, which is responsible for any modification on the pre-existing Building Management System (BMS) side. After the installation of the hardware (i.e. a dedicated touch screen computer with a resilient power supply), the communication software was configured and real-time communication between the MPC and BMS was validated. Finally, Siram Veolia and the University of Parma configured the MPC and defined a debugging procedure in order to adjust and correct MPC parameters during operations. The solution has been correctly demonstrated in the real operational environment.
- **Evaluation of the new controller performance (D3.4).** This was done by comparing traditional operation and MPC operation to the defined baseline, which is needed to eliminate the effect of variable external disturbances. While the consumption of natural gas has slightly increased, a significant reduction in electricity consumption and economic cost where obtained. The application of the MPC showed a clear positive impact on the plant's economic performance, acting both in the production and in the consumption side

2.1.2. Large-scale DHC

The activities regarding the development, implementation and testing of the smart controller in the Swedish case study are here summarized:

- **Development of a physical model of the large-scale district heating network (D4.1)**. The digital twin of the DHC of Västerås, Sweden, is created by starting from the characterization of energy requirements, topology, length, and time delays. The model includes all components as well as the heat losses from the pipelines (Zimmerman et al. 2019). The validation of the model is carried out with respect to measured data from all the main pumping stations of the network.
- **Development of a physics-informed data driven model of the load of a DHC (D4.2).** The model development approach combines the benefits of white-box and black-box models, as it accounts for the physical phenomena together with the availability of real data from the system. The calibrated model has been verified against measured data coming from three different buildings in Västerås, Sweden. The model has demonstrated adaptivity rendering it as a “plug-and-play” solution for real-time prediction without significant pre-tuning requirements. Error quantifications for the

model have demonstrated acceptable accuracy and robustness. It aims at large-scale utilization within smart control algorithms.

- **Hardware-in-the-Loop demonstration of an MPC controller based on the physics-informed load model**. The algorithm was installed within the XC05 micro-controller provided by First Control, and the signal interfacing and installation within a building was carried out. The solution will be demonstrated in real operational environment during the heating season 2022-2023. This activity will be reported in D5.1.

2.2. Similarities

The similarities of the two case studies are as follows:

- **Modeling approach**. Even if small-scale and large-scale DHC differ in terms of the characteristics number of buildings connected to the network (tens of buildings in small-scale DHC, thousands of buildings in large-scale DHC), in both case studies it was chosen to use a load model based on data and physical information, namely gray-box model (Figure 2). In this way, the deriving consumer model maintains the knowledge of the underlying physical phenomena and avoids the issues of machine learning models (e.g. lack of significant datasets or bad model prediction in operating points not covered by the training dataset). At the same time, such a model is not too complex and can be implemented within a control solution.

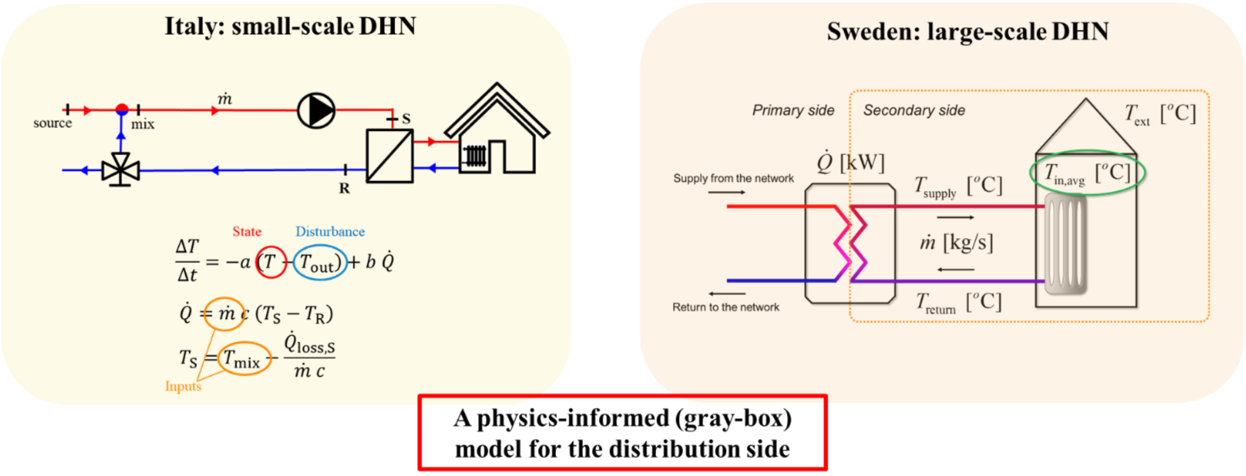

Figure 2. Similarities between the two case studies: modeling approach.

- **Considering an average temperature for the load model**. This is fundamental to avoid complex and detailed building models which makes the computation heavy without adding significant improvements to the control performance.

- **Control architecture**. In both case studies, it was chosen to divide the control problem (characterized by high dimensionality) into different parts, each realized by a dedicated agent or module. The deriving architecture is multi-agent and hierarchical, meaning that the different control modules communicate with each other and send relevant information (Figure 3). In this way, each sub-problem has a lower computational cost and can be solved within the time-steps specific of real-time control in thermal systems. More specifically, both architecture include dedicated modules for the heat distribution to the end-users as well as dedicated modules for the production side.

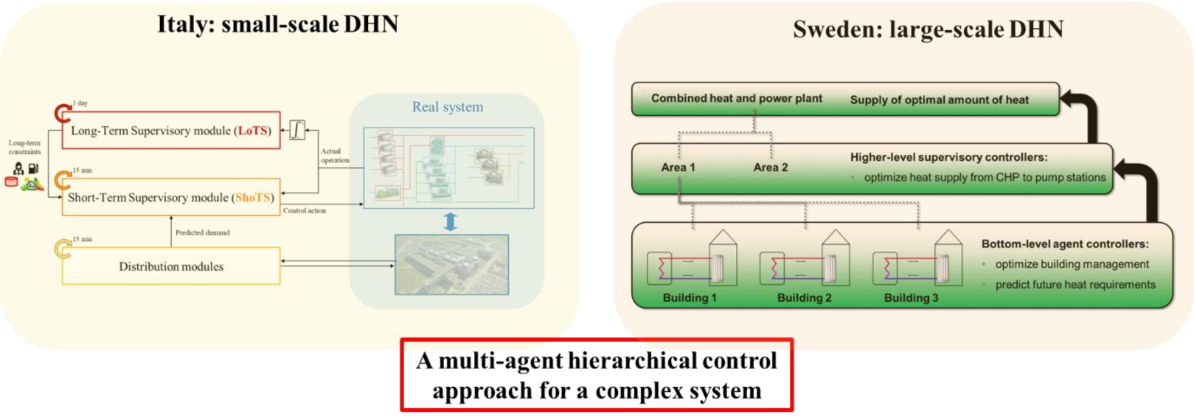

Figure 3. Similarities between the two case studies: control architecture.

- **Control method**. All modules are based on Model Predictive Control, which has been demonstrated as a promising control strategy for energy systems and networks (Saletti et al., 2020).

- **Control verification**. In both case studies, the control solution was verified in simulation environment before proceeding to the implementation within the test site. In the Italian case study, it was then implemented in the thermal power station and tested in the background. This allowed to verify its robustness and complete the debugging phase. In the Swedish case study, additional tests on a Hardware-in-the-Loop controller has been carried out. This may be required in case residential customers are involved.

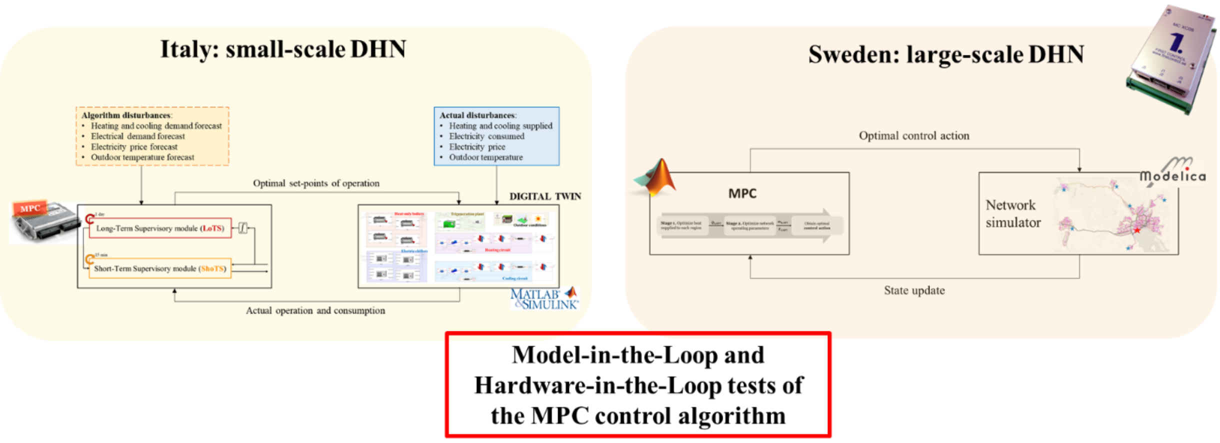

Figure 4. Similarities between the two case studies: control architecture.

2.3. Limitations

Using the large-scale approach for a small-scale network and viceversa, however, may be subject to some limitations. Potential critical points are identified as follows:

- The Italian test site is a third-sector system. The load is subject to variation but the system operator can fully decide how to manage energy supply, as long as the comfort service established by the contract is provided. In this way, the flexibility of the network and buildings can be exploited to support network management. On the other hand, the Swedish test site is mainly composed of residential buildings, generally managed by housing associations. Hence, there is lower potential for altering the management of each individual building or apartment, as it depends on each specific customer. In this perspective, WP7 is entirely dedicated to analyzing the social acceptance of new control solutions by residential customers.

- The adoption of the proposed control solutions can be different in the two cases, since district heating networks are more widespread in Sweden (where they cover around 50% of the heat end use) then in Italy (where they cover less than 5% of the heat end use). However, in Italy the diffusion of small-scale networks dedicated to service buildings is growing, coherently with the case study selected for Italy.

3. Technical synthesis

3.1. Lessons learnt from the case studies

As detailed in the previous section, the modeling and control approaches adopted for the small-scale and large-scale DHC are basically equivalent and allowed to draw a list of recommendations and lessons-learnt from the project:

- **Maintaining the physics information** is a key element for a high performance model in district heating and cooling networks. This is particularly relevant in presence of high climate variability.
- **Avoiding custom-made solutions**, which are currently common practice in DHC management due to the large differences between systems, can be achieved by adopting a modular multi-agent approach.
- **Demonstrating a control solution** on a digital twin and then through a Hardware-in-the-Loop method can foster and speed-up the solution uptake and extension.

Table 1 provides a complete summary of the two case studies.

Table 1. Summary of features of the control solutions

Feature	**Small-scale DHC**	**Large-scale DHC**
Location	Nothern Italy	Central Sweden
Type of system	Hospital	City district
Type of customer	Service sector	Residential
Load model	Gray-box	Physics-informed
Datasets for model training	A few days	A few days
Model temperature	Average building temperature	Average building temperature
Control architecture	Multi-agent hierarchical	Multi-agent hierarchical
Control method	Model Predictive Control	Model Predictive Control
Thermal power station management	Double-time scale control with short-term and long-term objectives	Possibility to control network supply temperature
Control verification	Model-in-the-Loop	Model-in-the-Loop and Hardware-in-the-Loop
Real-time implementation	Achieved	Scheduled for 2022-2023 heating season

3.2. Scalable approach

The output of this activity is the definition of a scalable approach that allows for the extended implementation of smart controllers based on Model Predictive Control to district heating networks, regardless of their layout and size.

Indeed, as suggested from the case studies, it is possible to apply the following procedure:

- Divide the generic network into different parts, each supplied by a substation heat exchanger or pumping station, for which data on the hear supplied are available;
- Each part is represented as an aggregated region or aggregated consumer (Figure 5).

- A model of the aggregated region is built as in (Saletti et al., 2022). This model is suitable for both small-scale and large-scale networks, as it may represent a single building or an aggregated set of buildings supplied by a substation, respectively. An equivalent (i.e. average) temperature is considered for representing the energy content of each aggregated region.
- The model is trained by means of the available datasets.
- The model is included within a Model Predictive Control module for controlling the distribution side of the network.
- The demonstrated multi-agent hierarchical structure is exploited for controlling the entire network as well as the energy conversion units. Innovative network management strategies such as peak shaving (Saletti et al., 2021) can also be tested, thanks to the model structure (i.e. it includes information on the heat capacity of the aggregated region).

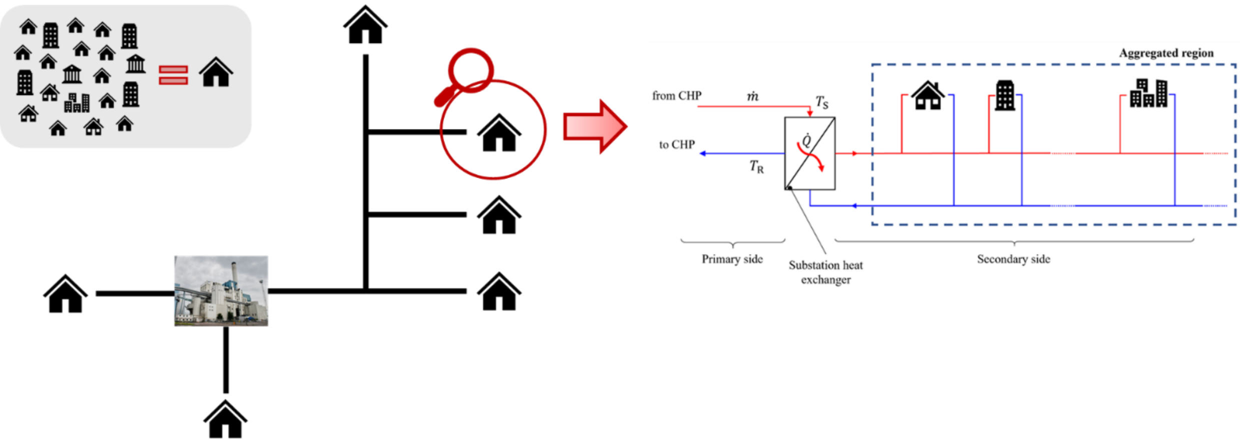

Figure 5. Scalable approach: considering a network part as an aggregated consumer.

To sum up, it can be noted that this procedure does not depend on the size or configuration of the system. Thus, it opens up the possibility to treat generic energy networks (i.e. a city, a neighborhood or a multi-story building) in a fractal way, as schematized in Figure 6.

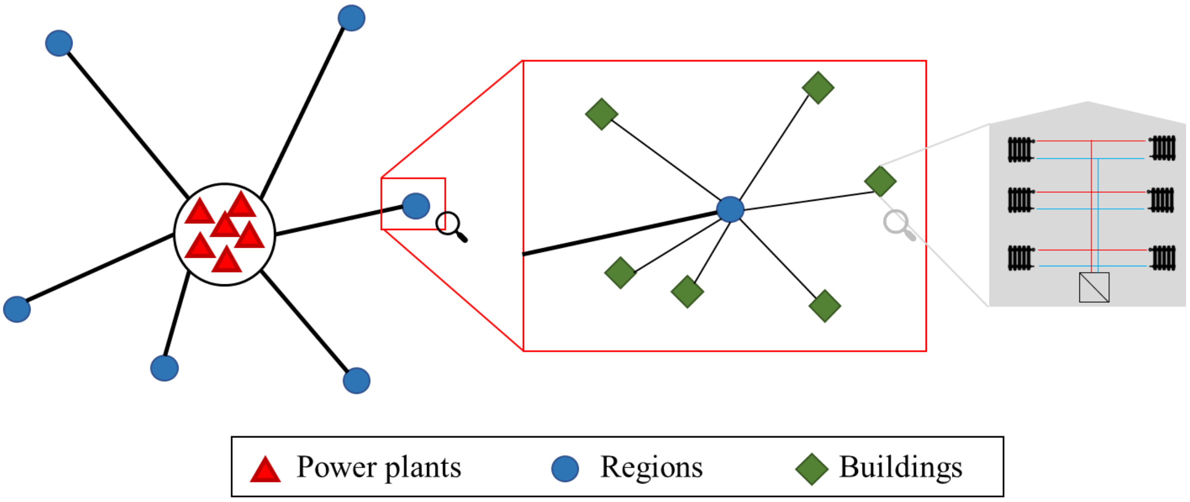

Figure 6. Scalable approach: a fractal architecture for tackling all different types of distribution networks.

4. Conclusions

In this report, the activities of the WP6 are reported. The results and details from the Italian and Swedish case studies are collected and summarized. The similarities are analyzed, in particular regarding the load model, control architecture, control method (i.e. Model Predictive Control) and control verification. The limitations of the proposed approaches are also reported, in particular the final consumer and potential for adoption in the countries related to the case study.

Finally, the lessons-learnt and a technical synthesis of the demonstrated solutions are presented. They can be relevant to researchers, system operators and policy makers.

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