A Digital Twin for the "District LAB" Test Facility: Background, Ideas and current Activities. An Overview.

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Abstract

District heating systems are an important element for the success of the heat transition and the associated and necessary decarbonisation of the urban heat supply. Although the expansion and transformation of district heating grids towards decentralised supply solutions based on renewable energies or waste heat is accompanied by some advantages, there are also obstacles, especially economic ones. Digitalisation measures appear to be a promising way of counteracting these. The aim of the doctoral thesis presented in this paper is to develop a solution and to test these empirically at the experimental facility "District LAB". The methods planned to achieve these goals are primarily the creation of a simulation model that contains all the essential thermo-hydraulic components and control structures of the test facility, as well as the transfer of this model into a digital twin that has access to its hardware. Furthermore, a solution regarding the predictive optimisation of the operation strategy is to be developed and subsequently tested. In the following, the planned methods and work steps are presented in detail and the first results of theoretical investigations are shown.

Introduction

Current scientific studies show that the decarbonisation of the heating sector in Germany can only be successful with a nationwide expansion and simultaneous transformation of district heating grids (Gerhardt et al., 2019). The goal of this transformation is to transform the grids into district heating (DH) grids supplied with renewable energy, which are characterised by e.g. increased energy efficiency and low temperature levels. There are a number of measures for implementation, such as the conversion of generation plants to renewable technologies or adapted operation modes (Lund et al., 2014). However, there are also obstacles such as costs or regulatory framework conditions. Against this background, approaches of digitalisation, such as model-based planning of grid operation and optimisation through predictive methods e.g. machine learning (ML) algorithms, appear promising. Some reasons are that they are associated with low costs, provide efficiency gains and create increased transparency for further measures (Schmidt, 2020). In particular, the use of digital twins (DT), based on the definition of (Rasheed et al., 2020), seams promising, as this enables the targeted coupling of software and hardware.

Research is required regarding the question of how the transformation towards decentralised and multivalent low-temperature heating networks can be supported with the help of the DT and ML method. This need for research also became apparent during a literature review on the combined use of DT and ML, especially in the context of DH. The most important findings of this research are:

- A large number of theoretical studies exist, especially in the context of ML (Ntakolia et al., 2021).
- There are some experimental applications in the context of the EU Horizon 2020 programme (Atta & Birk, 2018; Moustakidis et al., 2019). However, these investigations are limited to conventional DH grids with a centralized structure.
- No experimental investigations were found on multivalent heating grids with decentralised volatile feed-in and feed-out of low-temperature heat and thus no investigations of transformation measures are mentioned.

The lack of studies of this kind was then taken as an opportunity to initiate a doctoral project with the working title: "Predictive optimisation of the operating strategy of decentralised and multivalent

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district heating systems by using a digital twin of the “District LAB” test facility”. This takes place in the context of the publicly funded research project “UrbanTurn”, which is led by the Department of Thermal Energy System Technology of Fraunhofer IEE Kassel, and is supervised by the Department of Technical Infrastructure Management at HCU Hamburg. The planned methodological approach and some first results will be presented in this paper.

Methods

The main method to be used in the work is the experimental investigation supported by simulations. The investigations are to be carried out at the experimental facility for district heating applications “District LAB” of the Fraunhofer IEE in Kassel (Kallert et al., 2021). For this, however, it is first necessary to equip the flexible heating network of the test facility with the corresponding digital infrastructure. This is to be done within the framework of the PhD project presented here. The following working points are planned:

- Design software part of DT: Software implementation through mathematical modelling of the thermo-hydraulic state changes in the individual components and the overall system. In the course of previous analyses, MATLAB/Simulink proved to be a suitable software due to advantages in implementation. On this basis, the Carnot toolbox (Wemhöner et al., 2000) was selected as a suitable extension, as it contains most of the main component models needed, e.g. heat exchangers, heat pumps, pipes and pumps. Some of these component models will be validated and proven with data from the manufactures as a part of the work.
- Carrying out simulations of different grid configurations, such as renewable-based volatile prosumers in the heating grid.
- Create DT through implementation of the software in the test facility via the software interface (MATLAB/Simulink Coder) to the hardware interface (Beckhoff) of the District LAB. This should enable the readout and storage of the measured data from the sensors and the control of the actuators in real time. According to the definition of (Rasheed et al., 2020), this step creates the DT.
- Carrying out tests with the District LAB to ensure functionality and subsequent collection of measurement data.
- Validation of the DT using the measured data for the purpose of checking the previously determined calculation results and, if necessary, adjustment of the DT to reduce deviations.
- Creation of time series forecasts: Creation and integration of a sub-model to carry out weather-based time series forecasts for demands and availabilities of heat. The starting point for this is findings on ML methods from the literature (Ntakolia et al., 2021).
- Optimisation of the operation management strategy: Development and implementation of an algorithm for the predictive optimisation of the operation strategy within the framework of a “unit commitment” optimisation problem. For the software implementation, it is planned to start with a linear model (Mixed Integer Linear Programming (MILP)) (Tahanan et al., 2015) and to extend this successively. For example, the aim is to expand it to a multi-node system, as this enables the spatial separation of generators, consumers and storage units.
- Conducting tests in the District LAB to quantify the potential of developed solutions (which could be characterised as Model-Predictive-Control (MPC)) in different grid configurations compared to conventional control strategies.
- Interpretation and critical evaluation of the results

Results

In the course of the doctoral project, the first partial results have already been produced. A selection, namely the validation of some component models as well as a simulation model for the test scenario “conventional heating network”, will be explained in the following.

Validation of component models

So far, the Carnot Toolbox (Release 7.1, © 2020 Solar Institut Juelich) models for heat pumps and pumps have been compared with the manufacturers' characteristic diagrams with regard to their steady-state behaviour. This comparison showed operation points with good agreement, but also working points with bad agreement. For the last mentioned some potential for improvement of the component models with regard to the specific application was found. As an example, Fig. 1 shows the comparison of manufacturer specifications and the corresponding calculation results. These are pressure difference mass flow curves at different speeds of a pump used in the District LAB. The figure shows the characteristic curves for speeds of 100 % ... 40 % according to the manufacturer's data sheet and according to the calculation with the "Pump_Main" model of the Carnot-Toolbox. It can be seen that the simulation results match the manufacturer's data well at high speeds. However, this changes with decreasing speeds. Here, increasing offsets of the curves can be observed, which show an inversely proportional behaviour. The lower the speeds, the greater the errors, although the shape of the curves is well reproduced at all operating points. Since lower speeds are also to be expected in the District LAB, the equations of the original model were supplemented with terms for better consideration of the speed dependency. These "improved" simulation results can also be seen in Fig. 1. Here, good matches between the calculation results and the manufacturer's specifications can be seen for all speeds.

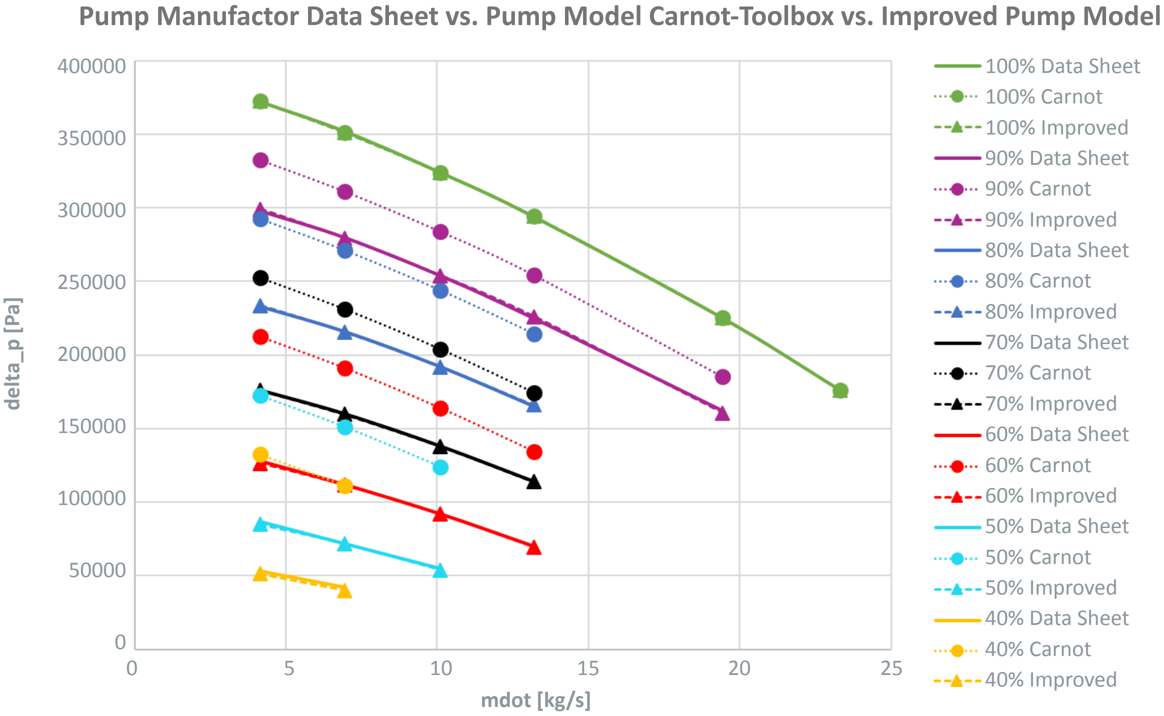

Fig. 1: Result of Pump Validation (own representation)

The identified improvements were subsequently implemented and, thus, optimised calculation models were created for the specific application. It is planned to carry out further investigations with regard to the transient behaviour. However, this will require further measurement data from the manufacturers. Furthermore, it is planned to check the models for pipelines and heat exchangers in a similar form on the basis of measurement data.

Simulation model for the "conventional heating network" scenario

Furthermore, a first simulation model for the whole system for the "conventional heating network" scenario of the District LAB test facility has already been created. The District LAB essentially consists of a building that houses the system technology (central heat sources and sinks, as well as decentralised hardware-in-the-loop (HIL) units), a pipe test section for carrying out mechanical tests and a flexible heat network (District Heat Circuit (DHC)) for system tests, which consists of several underground pipe coils. These pipe coils connect the three HIL units with each other and allow heat to be fed into or extracted from the DHC at any temperature level in a decentralised and defined manner. To make this possible, the HIL units consist of separate hydraulic circuits and are connected to the DHC via heat exchangers (HEx). Since the District LAB does not have a supply contract, heat is dissipated via another HEx into the cold circuit (CC), which is connected to the central heat sink. Heat is fed into the DHC via the hot circuit (HC), which is connected to the HILs via another HEx. For more details on the structure and performance spectrum of the test facility, please refer to (Kallert et al., 2021).

In the scenario mentioned, heat from a central generation unit is fed into DHC at a temperature level of 90 °C- 140 °C. The HIL units represent consumers, such as residential buildings, which withdraw the heat from the DHC in a defined form which should represent the heating system of a residential buildings. Accordingly, a flow temperature of 70 °C with a spread of 15 °C is assumed here. This corresponds to the temperatures that are common in conventional heating circuits (Frederiksen & Werner, 2013). The extraction power can be set in a generic and time-variable way for each HIL unit. The CC works on a temperature level of approx. 20 °C. This basic test configuration and other specifications can be found in Fig. 2.

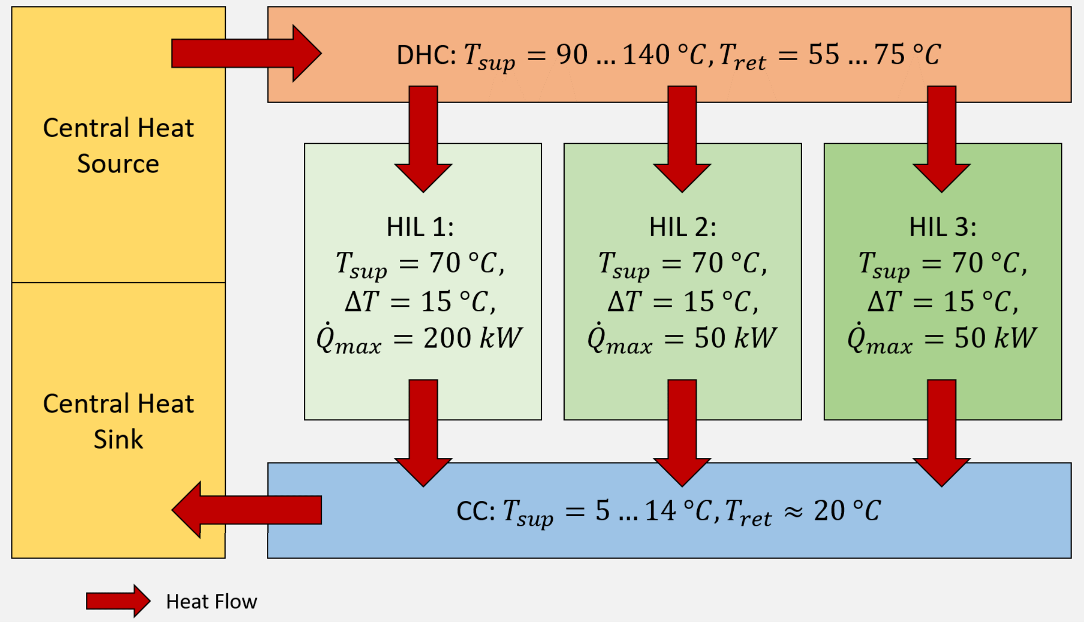

Fig. 2: Schematic representation of the test configuration in the "conventional heating network" scenario (own representation)

Each of the structures shown in Fig. 2 consist of several thermo-hydraulic components that have been mapped to create the complete simulation model of the system. Tab. 1 provides an overview of the thermo-hydraulic components that make up the structures. In addition, the dimensioning of the components is given. It should be noted that the planning process for the test facility has not yet been completed and that these are partly assumptions and initial designs.

In addition, the control structures have also been included in the simulation model. These are based on the specifications of the components to be controlled. The developed control structures can be found in the following Tab. 2. There, the components that are controlled in the model are assigned to their control and manipulated variables. In addition, the type of control used is described. The tuning of the PI-controllers has been done with the Ziegler–Nichols method (Ziegler & Nichols, 1942).

Structure	Components	Dimensioning
Central Heat Source	Boiler	Nominal Heating Power: 300 kW
	Thermal Storage (Hot)	Storage Volume: 15 m³
	Pump	Nominal Engine Power: 0.2 kW
DHC	Pipes (HIL 1)	2 x DN80/180, Length: 80 m
	Pipes (HIL 2 & 3)	4 x DN65/160, Length: 80 m
	Pump	Nominal Engine Power: 0.8 kW
HIL 1	Heat Exchanger (DHC)	Heat Transfer Coeff.: 50 kW/K
	Valve (DHC)	Flow Coefficient: 100 m³/h
	Pump	Nominal Engine Power: 0.4 kW
	Heat Exchanger (CC)	Heat Transfer Coeff.: 50 kW/K
	Three-Way-Valve (CC)	-
HIL 2&3	Heat Exchanger (DHC)	Heat Transfer Coeff.: 12.5 kW/K
	Valve (DHC)	Flow Coefficient: 63 m³/h
	Pump	Nominal Engine Power: 0.2 kW
	Heat Exchanger (CC)	Heat Transfer Coeff.: 12.5 kW/K
	Three-Way-Valve (CC)	-
CC	Pipes (HIL 1)	2 x DN80/180, Length: 10 m
	Pipes (HIL 2 & 3)	4 x DN65/160, Length: 10 m
	Pump	Nominal Engine Power: 2.3 kW
Central Heat Sink	Central Heat Pump	Nominal Cooling Power: 300 kW
	Thermal Storage (Cold)	Storage Volume: 19 m³
	Recooling Plant	Nominal Cooling Power: 550 kW
	Pump	Nominal Engine Power: 5.3 kW

Tab. 1: Allocation of thermo-hydraulic components and their dimensioning

Component	Controlled Variable	Manipulated Variable	Control Type
Central Heat Pump	Cold Storage Temperature	On-Off Signal	Two-Point Control
Boiler	Hot Storage Temperature	On-Off Signal	Two-Point Control
DHC Pump	Pressure Difference DHC	Pump Speed	PI Control
DHC Valve HIL	Heating Power taken from DHC	Valve opening	PI Control
HIL Pump	-	Pump Mass Flow	Feed Forward Control
CC Valve HIL	Return Temperature within HIL	Valve opening	PI Control

Tab. 2: Overview of the control structures used

Fig. 3 below shows some selected results of the described simulation model over a time of 20,000 seconds. Four plots with different focus are shown. The following observations can be made:
The first plot shows the target and actual heat outputs that each of the three HIL units take from the DHC. The set points are 100 kW, 45 kW and 40 kW for HIL 1, 2 and 3 respectively. It is clear that the actual outputs reach and then maintain their set points after different transient behaviour.
The second plot shows the limit values and the actual value of the supply temperature as well as the return temperature of the DHC. It can be seen that the supply temperature is kept between the limits of 97.5 °C and 102.5 °C after an initial heating process. The return temperature reaches a steady state of about 55 °C. The third plot shows the inlet temperatures of the three HIL units.

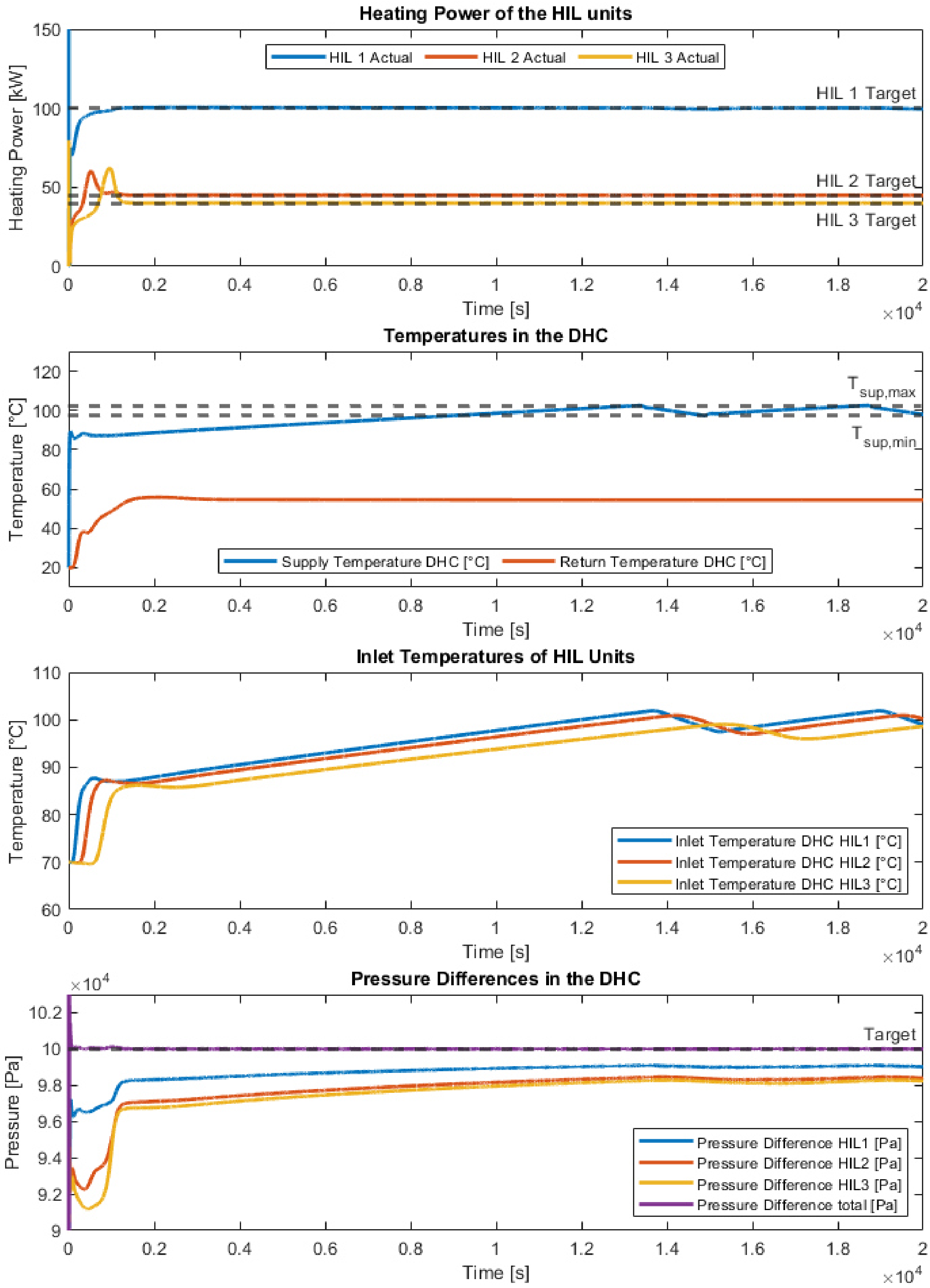

Fig. 3: Selection of some simulation results
(own representation)

First of all, the height of the peaks after heating up at about second 15,000 shows the influence of the different heat losses of the flexible heat network. In addition, the phase shift between the HIL units can be seen from the curves. Both effects are the result of the different distances that the fluid has to cover from the central generation unit to the respective HIL units. The fourth plot shows the pressure differences of the HIL units as well as the desired and actual values of the total pressure difference at the primary pump. Here, the desired total pressure difference can be set and maintained after a short time. Furthermore, the different transient behaviour of the HIL units is also evident here. It results from the phase shift already described due to the pipelines and the interaction between the HIL units.

Finally, it should be noted that a simulation model for the transient calculation of the study scenario “conventional heating network” has been developed. This is to be expanded in the future for the simulation of other scenarios (e.g. low-temperature networks with prosumers). In addition, it is intended to work out algorithms for optimising the operating strategies in the form of a unit-commitment optimisation problem.

Conclusion

In this paper, the background for a doctoral thesis on the identification and testing of technical solutions in the context of digitalisation in relation to district heating was presented. In addition, the empirical investigation of predictive optimisation approaches at the District LAB test facility was highlighted as an essential method. For this purpose, a simulation model is to be set up and transformed into a digital twin by coupling it with the test facility. Furthermore, it is planned to apply demand and availability forecasts with the help of machine learning methods in order to calculate the best possible operating strategy on the basis of the forecasts. This overall system will then be tested in the District LAB.

Furthermore, some first results were presented. First, it was described that some of the components intended for use in the simulation model were subjected to validation. This showed good agreement between simulation and manufacturer data in some cases, but also areas with large deviations. Using the example of the pump model, it was shown that the deviations can be reduced by adapting the models for the application case of the District LAB.

Subsequently, the simulation model for the entire system in the scenario “conventional heating network” was discussed. The scenario was explained, the dimensioning of the thermo-hydraulic components was discussed and the control structures used were presented. Eventually, selected simulation results were shown and the further work steps were explained.

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