

Software-in-the-Loop-simulation of a District Heating System as Test Environment for a Sophisticated Operating Software

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Abstract: With the expansion of renewable energies, district heating (DH) systems are becoming increasingly complex. Various heat sources like solar thermal plants and combined heat and power (CHP) plants are integrated in parallel, in addition thermal energy storages (TES) are often used to balance load and heat generation. Sophisticated software solutions are required to optimise the plant operation. Based on deterministic physical models and artificial neural networks, the software *Heating Network Navigator (HN-Navi)* is being developed to optimise the operation of such systems. Since tests in the real system are not possible for reasons of supply security, the *HN-Navi* is first tested in a software-in-the-loop (SiL) environment. TRNSYS (version 18) is used as simulation software to create a complex reference model (CRM) as basis for the SiL environment. The complexity of such real energy systems can lead to potentially high computing costs when it comes to simulating or optimising their operation as realistically and accurately as possible. For this reason, both software tools, i.e. *HN-Navi* and CRM, will be developed and tested with regard to the Brühl solar DH system in Chemnitz (Germany), whereby the finished software will also be used for other heat supply systems. TRNSYS offers the possibility to develop own models for all system components, with which a proper reproduction of the real system can be achieved. Within the scope of the project, practical tests and extensive quantitative software comparisons with the real system will also be carried out. The article reports on the development of this SiL environment and its practical feasibility.

1 INTRODUCTION

More and more district heating systems in Europe combine different heat sources like solar thermal plants and combined heat and power (CHP) plants (solar district heating, 2019). In most cases a thermal energy storage (TES) is applied for balancing load and heat generation, e. g. the solar district heating (DH) systems in the Brühl quarter in Chemnitz (Urbaneck et al., 2015; Urbaneck et al., 2017, Shrestha et al. 2017; Urbaneck et al. 2017; Urbaneck et al. 2017). The different components within such systems lead to complex structures with mutual influences. This means that a quantitatively optimal operation can only be guaranteed through the use of sophisticated software solutions.

For this reason, numerous projects are now dealing with the optimization of energy supply systems. Widely used approaches include the use of

prediction models to estimate the availability of renewable energies and energy demand (Kuboth et al., 2019) and improved simulation models to predictively describe the plant behaviour of such systems (Schweiger et al. 2018).

The approach of this project, which has been running since July 2017, is the optimization of the supply facilities. One of the advantages is the direct contact with the network operator without troubling the end customers and the optimization of the control of all system components. The developed software system is named *Heating Network Navigator (HN-Navi)* (Oppelt et al., 2018; Oppelt et al., 2018) and is intended to help heating network operators to achieve an optimal system operation despite difficult boundary conditions (integration of fluctuating renewable energy sources, varying electricity prices, etc.) and complex technical demands.

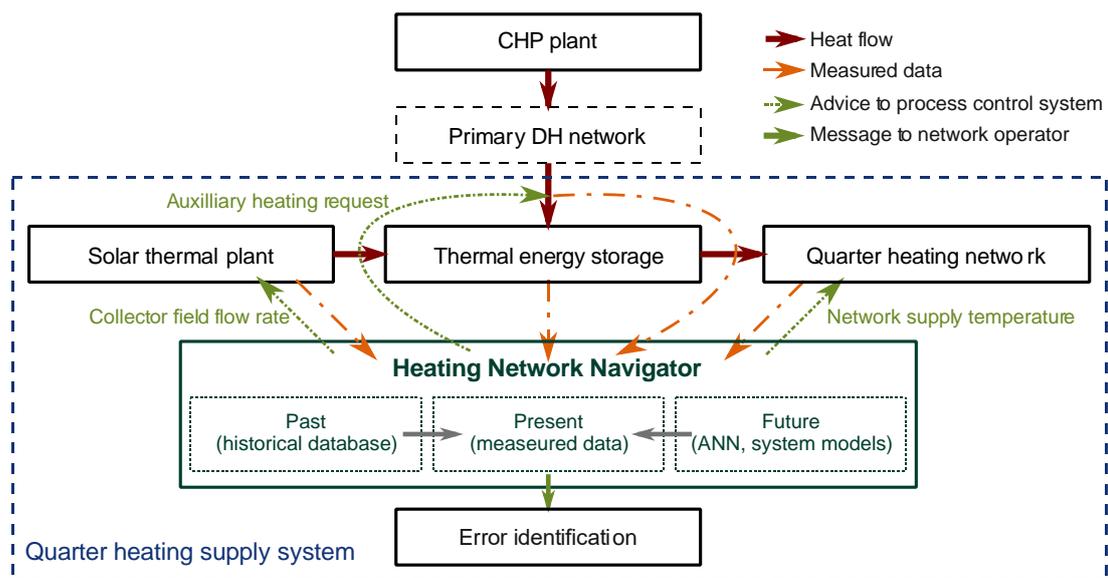


Figure 1: Integration of the *Heating Network Navigator* into a quarter heating system.

Figure 1 schematically shows the planned application of the *HN-Navi* to the particular town quarter DH system (in this case: Brühl quarter, Chemnitz, Germany) (Urbaneck et al. 2017). Considering the specific requirements:

- optimal operation of TES,
- best possible utilisation of solar irradiance,
- minimize competition of solar heat and CHP,
- minimize network supply temperature,
- maximize temperature difference between supply and return line of the network.

The *HN-Navi* generates recommendation for optimal operation from stored (Past) and currently received (Present) measurement data as well as load and demand forecasts (Future). This advice for a defined time horizon is then sent back to the process control system in order to be considered. Additionally, the *HN-Navi* continuously compares operational data from past and present in order to detect errors in the system (Error identification).

The project consists of three stages of development:

1. Software developments: Development and abstraction of simulation and prognosis models,
2. Software tests: Conducting the tests in a Software-in-the-loop (SiL) environment,
3. Software application: Performing the practice tests in the Brühl solar DH system at Chemnitz (Brühl system) supported by the network operator *inetz*.

The first development stage has already (status: May 2019) been completed, so the first SiL-tests of the optimization software have already been started.

Section 2 describe the developing of a complex reference model (CRM) to the real system and the *HN-Navi* while section 3 explains the creation of the Software-in-the-Loop (SiL) environment. Section 4 gives an outlook on the following project steps.

2 SOFTWARE DEVELOPMENT

As stated above the aim of this to project is to use the *HN-Navi* in the real Brühl system. Since tests in the real system are not possible for reasons of supply security, the *HN-Navi* is first tested in a software-in-the-loop (SiL) environment. TRNSYS (version 18) is used as simulation software to create a CRM as basis for the SiL environment.

In response to the requirements, the development is done in the following steps:

1. Analysis of the real Brühl system with a heat transfer station (HTST), two solar thermal fields, a TES and a low temperature network,
2. Development of accurate models of the system components for the CRM.
3. Development of the forecast models and abstraction of the system component models for the *HN-Navi*.

2.1 Analysis of the Brühl System

The main components of the plant are two solar thermal collector fields, a two-zone-storage TES and a HTST which connects the low-temperature network

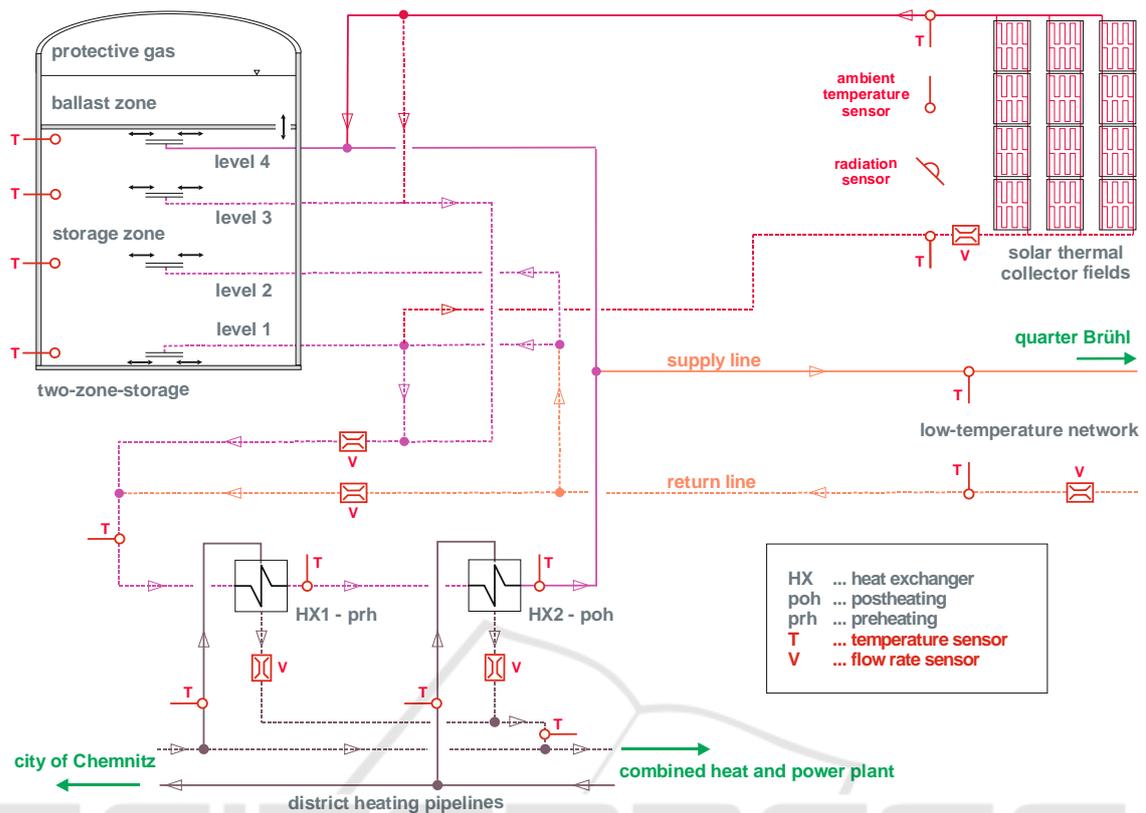


Figure 2: Simplified structure of the heat transfer substation (supply center), solar collector fields and two-zone storage of the solar DH system Brühl (without pumps) and schematic representation of the most important measured system values required by the Heating Network Navigator.

to the primary DH network. The supplied city quarter (Brühl Chemnitz (Shrestha et al., 2018) includes mainly apartment buildings with more than 1,300 residential units, a school and the university library.

Figure 2 schematically shows the hydraulic design of the Brühl system. The TES can be charged either via the HTST, the solar thermal collector fields or the return flow from the supply system. Similarly, the quarter can be supplied via the solar collector fields, the TES, the HTST or in combination thereof. The possible operating modes are listed in Table 1. A more detailed description can be found by Shrestha et al. which demonstrates the entire complexity of the system (Shrestha et al., 2018).

In addition to the various operating modes, each system has its own specific requirements, which has to be taken into account in the software tools.

The most important points concerning the solar DH system Brühl are:

Network and HTST:

- Low-temperature network with supply temperatures of about 70 °C.
- Hydraulic decoupling of the primary DH network from the Brühl system due to pressure and

Table 1: Operating modes of the supply center for supplying the Brühl quarter.

Operating modes of the supply center	Heat source		
	HTST	TES	Collector fields
A	Yes		
B		Yes	
C	Yes	Yes	
D			Yes
E		Yes	Yes

temperature differences in both systems.

- Consisting of a preheating (prh) and a postheating (poh) stage each with two heat exchanger groups (HX).
- Preheating stage using the return flow from the primary DH network Chemnitz.
- Postheating stage using the supply flow from the primary DH network Chemnitz (Differences between DH systems in Table 2).

TES:

- Two-zone TES storing with a maximum operation temperature up to 108 °C.

- Charging and discharging with radial diffusers in levels 1...4 (Figure 2), depending on operation mode.

Table 2: Maximum pressure and temperature in the supply line of the primary DH network and the low temperature network (Brühl system).

Supply line	Primary DH network	Solar DH system Brühl
Pressure [bar]	17	5,5
Temperature [°C]	140	85

Collector fields:

- Water is used as heat transfer medium.
- No heat exchangers between solar circuit and supply system are required.
- Frost protection is provided by an active hot water flow, obtained from the TES or the return flow from the Brühl quarter (not shown in Figure 2).

2.2 The Complex Reference Model

TRNSYS (version 18) is a software environment to simulate a variety of energy systems (TRNSYS, 2017). TRNSYS is a *Fortran 95* based and well-validated software package to consider models of many components of energy systems. It is also possible to the end user to implement own models. The user-specific components can be inserted modularly into the simulation, which facilitates the adaptation to extensions and to future systems. In addition, TRNSYS offers various interfaces for data exchange (import and export) as well as for other programs (e.g. MATLAB). For these reasons the CRM developed here is based on TRNSYS.

To map the DH system, the most important step is the selection of suitable components in TRNSYS which

are called Types. The various available Types were compared to the real system on the basis of their reproduction quality. For example the model of the solar collector should match the efficiency curve, the matched flow control and the collector connection, while taking the multi-node model, the incident angle modifier and the heat capacity of the collector into account. Table 3 shows available Types for the model of the flat plate collector.

Due to the high database (minute values since May 2017) from the monitoring of the real plant, the simulation results can be verified directly to the measured values (Figure 2). In the example of the solar collector the Type 539 TESS library is sufficient accurate and is used in the simulation (TRNSYS, 2017).

For other components (e.g. TES, HTST) no adequate models are available in TRNSYS. These had to be created within the scope of this project. Another important aspect in simulating complex DH systems in TRNSYS is the realistic control of the interaction of the individual model components. A separate Type (Control Unit) was developed for this purpose, see Figure 3.

This Type establishes the link between quarter network, HTST, collector fields and TES. It determines the mass flows in the four diffuser levels in the TES as well as the temperatures of the mass flows. The Type also determines the correct diffuser level for the mass flows from the network and from the collector planes. Furthermore, it determines the operating condition of the storage tank and the HTST and calculates the heat flows required for evaluation. The boundary conditions of the simulation (weather data and heat demand) are also considered by the Control Unit Type.

Table 3: Evaluation of the TRNSYS models on the basis of the most important parameters, e.g. model for solar collectors.

Type	Efficiency curve	Matched flow control	Collector inter-connection	Mutli node model	Incident angle modifier	Heat capacity
001: Flat-plate collector	Yes		Yes		Yes	
301: Matched flow collector model	Yes			Yes	Yes	Yes
539: Flat plate collector with capacitance effects	Yes	Yes	Yes	Yes	Yes	Yes
832: Dynamic collector model	Yes			Yes	Yes	Yes

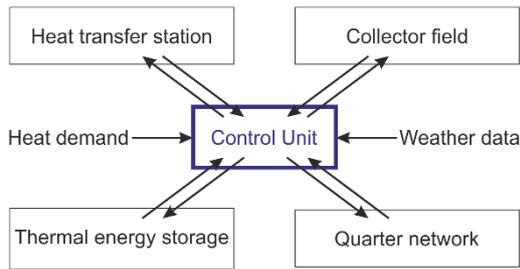


Figure 3: Schematic representation of the Brühl system in as TM in TRNSYS with the central Type to connect and control the individual model components.

The main part is to determine the respective operating modes based on iteration methods. Thus the type represents the core of the CRM (Figure 3).

Figure 4 compares the actual output of the collector arrays with that calculated by the CRM for three days. The correlation coefficient amounts 0.93 and an average deviation of -3.14 % is calculated for this period. Deviation between measurement and CRM for the whole year 2018 is about +4.4 %, which demonstrates that the CRM is sufficient accruable.

By this approach the models of all system components are developed and tested. Analogously, all other model components were tested and positively validated.

Using an intel@Core™ i7, one year in calculation steps of three minutes can be simulated with the CRM in less than 4.5 minutes. This allows various tests such as parameter variation, algorithm verification and error detection.

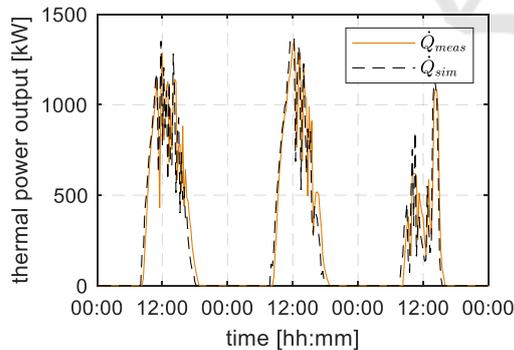


Figure 4: Comparison of the measured (\dot{Q}_{meas} , orange) and simulated (\dot{Q}_{sim} , dashed black) thermal power of the collector fields. From 19. to 21. July 2018. The time resolution is 15 min.

2.3 The Heating Network Navigator

The *HN-Navi* is intended to replace the control and must therefore specify the optimum volume flows and

temperatures of the individual components (Figure 2) for a defined time step. Therefore the *HN-Navi* contains weather (radiation and temperature), electricity price and load (supply temperature and flow rate) forecasts based on artificial neural networks. For each optimization run, are also the current state values from the CRM (later measured values from the real system) are used for the initial values. On the basis of the forecasts and the initial values, the determined numerical optimization is carried out in the main part of the *HN-Navi*. Like the CRM, the main part contains models for the respective system components.

Table 4: Classification of the parameters into “absolutely necessary”, “necessary”, “expense-dependent” and “unnecessary”, e.g. solar thermal plants.

Criteria	Parameter
absolutely necessary	- field size - collector efficiency - collector orientation - collector tilt
necessary	- field shadowing - angular influence - sky model - heat loss at frost protection - soiling
expense-dependent	- heat capacity (collector) - separate consideration south/ north field
unnecessary	- heat loss field connection

In order to keep the numerical effort low and the solvability within the framework of an at most quadratic optimization problem, the model components are abstracted in comparison to the CRM. For the abstraction of the individual elements an investigation with variation of all parameters and correlations was conducted, using the models from the SiL environment. The classification is based on the resulting deviation of important parameters (yield, heat quantities, operating hours, etc.) from the real system in four categories:

- “absolutely necessary”: Parameter or correlation should be considered in the same way as in the SiL environment.
- “necessary”: Parameter or correlation should be considered, but can be simplified, e.g. in a black box model. Abstraction must be justified.
- “expense-dependent”: Depending on the computing effort to be taken into account or not.
- “unnecessary”: No consideration required.

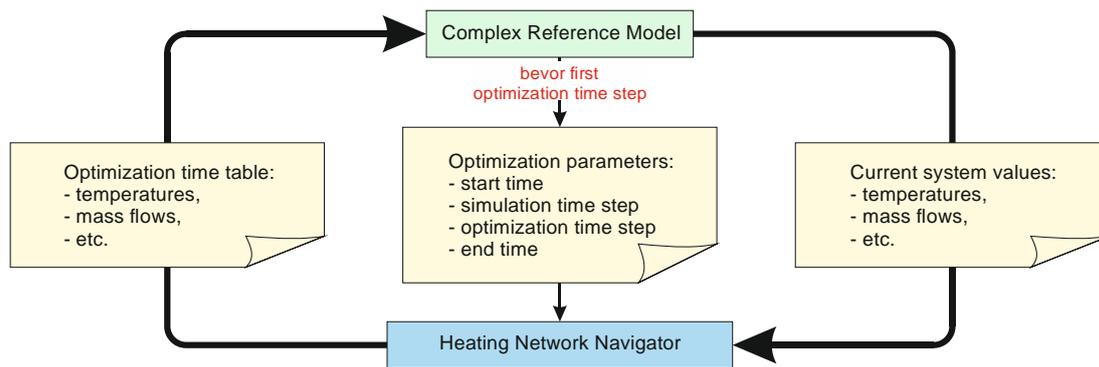


Figure 5: Test procedure for the SiL Simulation; for details of the *Heating Network Navigator* see Figure 1.

New models were created for each system component, which was simplified on the basis of the criteria.

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Table 4 shows the classification of the parameters using the example of solar thermal collector arrays. New models were created for each system component, which was simplified on the basis of the criteria.

The *HN-Navi* optimizes the entire system considering all underlying physics. Various optimisation strategies can be considered (minimum operating costs C_{OP} , minimum CO₂ emission m_{CO_2}). The time resolution is arbitrary. The software generates optimal control suggestions (mass flows \dot{m} , temperatures T) for all models and elements.

3 SOFTWARE IN THE LOOP

To test the *HN-Navi*, communication between it and the CRM is necessary. A separate type was created for this process. It checks every 10 seconds a defined exchange folder for the existing file containing the next schedule. A maximum number of queries can be specified to prevent hanging in the loop and must be adjusted to the optimization time.

The procedure is shown in Figure 5.

Before the first optimization time step, the CRM provides the optimization parameters (start time, simulation time step, optimization time step and end time) as well as the current system data (temperatures, mass flows, etc.). The *HN-Navi* starts the optimization, meanwhile the CRM is in a sleep mode until the necessary values for the system operation (temperatures, mass flows) are returned.

The state values of the simulation are written to the same exchange folder parallel to the simulation. This allows the optimizer to perform a continual comparison with its forecasts, just as it would later do in the real system.

The development of the SiL environment is already finished (status: May 2019) and first tests are still ongoing. Quantitative results will be presented in future works.

4 OUTLOOK

The next steps are an iterative process, in which the *HN-Navi* will be improved. The test purposes are the solution of different operating scenarios, the examination of the solutions and the increase of the performance.

Therefore, there will be four stages of testing:

1. Forecasting models:
Comparing the forecasted heat demand and weather data in their daily forecast to the real data;
2. System control:
Checking the control mechanisms (appropriate specifications and control parameters), Solvability of different operating scenarios;
3. Optimal operation:
Software training to find the optimal solution, while considering the lowest costs or lowest CO₂ emission;
4. Error detection:
Implementation from error detection algorithms to find acute and creeping errors and secure the system operation.

After this last step the software will be tested in the real Brühl System. As soon as the tests have been completed to the satisfaction of all project partners, the software will be brought to market by LEM

GmbH. The experiences of the project shall be used to adapt the software to other district heating supply systems.

5 CONCLUSIONS

SiL simulations are an important instrument to develop and test software solutions. The development of simulation and optimization tools for complex systems is necessary because these systems can no longer be calculated manually. In this case TRNSYS is used to simulate a complex district heating system with solar thermal plants and a short-term thermal energy storage (Brühl system).

To warranty the supply safety, it is not possible to test the software solution *Heating Network Navigator* in the real system. This is the reason to combine simulation and optimization to test the software in advance. The example shows that TRNSYS as modular and flexible simulation software is able to fulfil such complex requests. Especially since own models can be easily created and implemented.

In the context of this article, the creation of the CRM and the *Heating Network Navigator* as well as the linking of the two in the Software-in-the-Loop test were presented. In the next step, the software tests can begin.

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NOMENCLATURE

ANN	artificial neural network
C	charging
CHP	combined heat and power
CRM	complex reference model
DC	discharging
FP	frost protection
HM	heat maintenance
HTST	heat transfer station
HX	heat exchanger

in	inlet
out	outlet
prh	preheating
prim	primary
poh	postheating
RL	return line
sec	secondary
SiL	software in the loop
SL	supply line
TES	thermal energy storage

C_{OP} [€]	operating cost
\dot{m} [kg/s]	mass flow
m_{CO_2} [kg]	mass of CO ₂
T [°C]	temperature
\dot{V} [m ³ /s]	flow rate

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