# Automated model generation and simplification for district heating and cooling networks

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## Abstract

The current operation of district heating networks often relies on static analyses and control parameters. In the future, possible integration of renewable energy sources like solar or geothermal energy are getting more and more important. To investigate the impact of these new energy source in combination with new control strategies, dynamic simulation models for district heating and cooling systems are getting more important. However, these models are often large and therefore have large computation times and require manual effort to create and optimize them. Thus, this paper investigates in the simulation of a large and meshed district heating network. We present a workflow for automated generation and model simplification of simulation models based on GIS data. The validity of the model simplification is proven and the usability of the model is demonstrated by a Use Case with two different control strategies.

*Keywords: District Heating and Cooling Networks, Model Simplification, Control Strategies*

## 1 Introduction

The current design and operation of district heating networks often relies on static analyses and control parameters. In the future, possible integration of renewable energy sources like solar or geothermal energy as well as distributed heat sources is getting more important. As the integration of renewable and distributed energy sources are influencing the dynamic behavior of thermal networks, understanding and representing these dynamic processes within such systems is of great importance. This applies not only to the design of these networks but in particular the operation and implementation of different control strategies. Dynamic simulation models for thermo-hydraulic systems provide an opportunity to gain insights in the dynamics of district heating and cooling (DHC) networks. Although various demonstration for complex district heating and cooling (DHC) systems, with high share of renewable energy have already been realized (Lund et al., 2014) and dynamic models have been applied to thermal networks (Schweiger et al., 2017), dynamic modeling of DHC networks are still rarely used for design and operational optimization. One of the reasons for this is the complex modeling of these systems.

In recent years, the IEA-EBC Annex 60 (Wetter et al., 2015) and the follow-up project IBPSA Project 1 develop models in the modeling language Modelica for building and urban energy systems. This cooperation has resulted in a thermo-hydraulic pipe model that meets the requirements for the simulation of complex district heating and cooling networks (van der Heijde et al., 2017). In addition, tools were developed for the automated generation of models of complex network structures (Fuchs et al., 2016). These tools make use of object-oriented programming in Modelica and GIS (Geographical Information Systems) data to generate network system models.

In the case of complex networks, which are characterized, for example, by several feed in or a meshed network topology, large and complex models are the consequence. These models have a large number of equations, state events and Jacobian-evaluations. This makes the translation and simulation of these models slow and often leads to instabilities. Optimizing the models with several hundred pipes and substation is very time-consuming and requires manual input as well as very detailed expert knowledge. One option to make the models faster and more stable is topological and parametric model simplification. Model simplification for heat network calculations has been widely used, (Larsen et al., 2004). However, these simplifications often involve a loss of spatial information. For distributed networks with multiple feed in with different temperature levels, the spatial distribution plays a decisive role.

For this reason, we present a methodology for model simplification for complex and meshed thermal networks. In a first step, GIS data is subjected to a topological simplification. Certain pipes are replaced by weighted analogous pipes. This is necessary to create an executable system model, which still reflects the spatial properties of the network. In the second step, particularly short pipe sections are identified and modeled with a static pipe model. This reduces the number of equations, state events and Jacobian-evaluations but still keeps the spatial resolution of the model.

The paper is divided into five chapters. After the introduction, the methodology section describes the models used. In addition, the methodologies for model simplification are presented in more detail here. The presented methodology is tested using the example of two control strategies for the thermal network of a research center in Germany. Before the paper ends with a summary, the limitations and an outlook, a verification of the model simplification as well as results of the use case are shown in the results section.

# 2 Methodology

In this section we present different models and tools used for the dynamic simulation of district heating and cooling networks. For this purpose, the dynamic simulation models of the individual components of a district heating or cooling system that are necessary to build a system model are presented first. Afterwards it is shown how these component models are used for the automated generation of a district heating system model using the Python tools *uesgraphs* and *uesmodels*, (Fuchs et al., 2016). Starting from a GIS data set, the process of model generation, parameterization and model simplification is described. Finally, the control strategies of the district heating network considered as an example are presented.

## Dynamic Simulation Models

For the dynamic simulation and analysis of district heating networks, dynamic, thermo-hydraulic simulation models are used which are developed in the modeling language Modelica. Modelica provides the possibility to text-only description of the models and a object oriented modeling approach. This makes it easy to provide a model generation process with the help of other frameworks, more suitable for large data handling, such as Python. In addition, Modelica is capable of a multi-physics simulation approach which is useful for future investigations regarding the flexibility of thermal networks to the electrical network for example.

The system model of the district heating networks consists of three main components: The models for the hydraulic network (i. e. the pipes and junctions), the substation models that represent the consumers connected to the network and the model of the central heat supply. These models are combined according to the considered network topology to build a system model of the respective DHC network. The individual component models are connected to each other by fluid connectors, developed in the Annex 60 (Wetter et al., 2013). These connectors provide information on the state of the fluid, including the mass flow, thermodynamic pressure and the specific thermodynamic enthalpy of the medium. All used models are developed within the Modelica libraries Modelica IBPSA (Wetter et al., 2015) and AixLib (Müller et al., 2016).

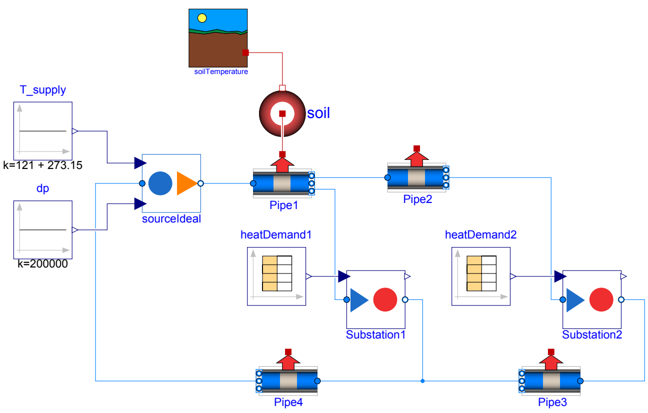


**Figure 1.** Exemplary system model of a district heating network

The pipe elements of a district heating network are modeled using a dynamic, equation-based thermo-hydraulic pipe model, the so-called plug-flow pipe model developed by (van der Heijde et al., 2017). This section explains the underlying idea of the plug-flow pipe model and describes additional work to use this model within a system model. The plug-flow pipe model is based on a plug-flow approach, which enables the dynamic simulation of long pipes, including the pipe network of district heating and cooling networks. Besides the hydraulic behavior, heat losses, heat storage effects of the medium and the pipe as well as the propagation of temperature waves along the pipe can be simulated. In addition, the pipe model is usable for various network layouts (e.g. branched and meshed networks), thus enabling a wide range of applications in the field of dynamic simulation of DHC networks. For this purpose, the properties of the pipe, such as the length, diameter as well as the thermal and hydraulic properties of the pipes and the pipe insulation can be specified with physical parameters. In order to be able to represent the pressure losses of a pipe segment more accurately, the plug-flow pipe model features the parameter *fac*. This parameter allows to take into account the flow resistances of e.g. bends and thermal expansion joints for each pipe section individually. In order to simulate the heat losses more accurately, we added a model that represents the surrounding soil as a combination of cylindrical thermal resistors (R) and capacitances (C). These RC-combinations model cylindrical heat transfer and thermal storage effects in the pipe and the surrounding soil. The pipes are connected by thermal connectors to the inside of the cylindrical thermal capacities. On the outside, the undisturbed soil temperature is used for the heat loss calculation. In contrast to the static design methods, dynamic simulation models allow to take into account changing soil temperatures during the year. Therefore, the annual profile of the undisturbed soil temperature is calculated according to Florides et al. (Florides and Kalogirou, 2005).

The pipe model is used to model the network topology and thus the system model. In a real network there are pipes and pipe sections of different length. Whereas the dynamic behavior along long pipe sections is of great interest, the effects in shorter pipes play a less important role (e.g. connection to buildings). The *spatialDisribution()* operator is used in the plug-flow pipe model to calculate the advection of fluid through the pipe and thus the temperature propagation along the pipe. For reducing the complexity of the system model and thus the number of


DOI
10.3384/ecp19157179

equations and the computation time, a pipe model without *spatialDistribution()* operator was developed based on the plug-flow pipe model. This simplified pipe model is used for short pipe length, see section 3.

In the system model, the substation models represent the heat consumption of the connected buildings. For this purpose, the heat demand profiles of the individual buildings serve as model input and can either be determined using dynamic building simulations or defined using measured values. The demand profiles are loaded with *Combi Time Tables* and assigned to the corresponding substations. The model parameters of the substation are the nominal return temperature on the one hand, and the minimum temperature difference between flow and return line on the other. These parameters are used in combination with the heat demand profiles to control the mass flow of the substations. For this purpose, the flow temperature at the inlet of the substation is measured with a temperature sensor. Based on the heat demand profile and the measured flow temperature, the required mass flow is calculated using the defined return temperature. Using this equation-based control approach, the substation ideally covers the heat demand of the building at every time step. By combining several substations in one system model, the total mass flow in the DHC network is determined.
In order to provide the mass flow with the required flow temperature, a heat source is used in the model of the central heat supply of the district heating system. For testing different flow temperature controls, the supply temperature of the district heating network is defined as model input. Constant supply temperatures but also temporal temperature profiles, such as outside temperature-dependent heating curves, are possible. In addition, the return pressure and the pressure difference between flow and return are parameters of the supply model. Using a mass flow sensor and temperature sensors that measure the flow and return temperatures, the heating power of the heat supply is calculated.

Figure 1 shows exemplary the structure of the system model of a simple district heating system with one heat supply, two substations and four pipes. The upper two pipes represent the flow line, the lower two pipes the return line of the district heating network. For one pipe, the connection to the RC-model of the surrounding soil and the connection between the RC-model and the undisturbed soil temperature are also shown. The heat demand profiles of the two substations are integrated with two *Combi Time Tables*. The inputs of the supply model (supply temperature and pressure drop) are defined as constant values in the example.

## Workflow and Model Reduction

The used workflow for district heating grid simulations presented in this paper is divided into 4 steps:

- GIS data import
- Network topology optimization
- Model reduction
- Model export

Whereas, the first two steps (GIS data import and network topology optimization) is handled by an Open-Source tool called *uesgraphs* (Fuchs et al., 2016), the last two steps are handled by a tool called *uesmodels*. *Uesgraphs* handles information of district networks (electricity, heating, cooling and gas) as a graph with edges and nodes and is written in Python. In the context of this paper, we use a GIS network topology of a real network in Germany. This data, stored in a *Postgres SQL* database, is imported in *uesgraphs*, which can represent the related buildings and building substation as nodes, as well as pipes as edges. To each node and edge individual information are assigned, for example the address of the building or the diameter and the insulation standard of the pipe.

Figure 2 shows an exemplary cutout of the investigated district heating network, substations in green dots, network edges and nodes in red lines / dots and the central supply as a green dot with a red circle. Using all edges of the network as a representation of single pipes in the simulation model, it is obvious that the resulting simulation model will have a high complexity and a huge number of used components. Therefore we reduce and optimize the shown network topology to reduce the number of nodes and edges. This step, which is carried out on the graph,

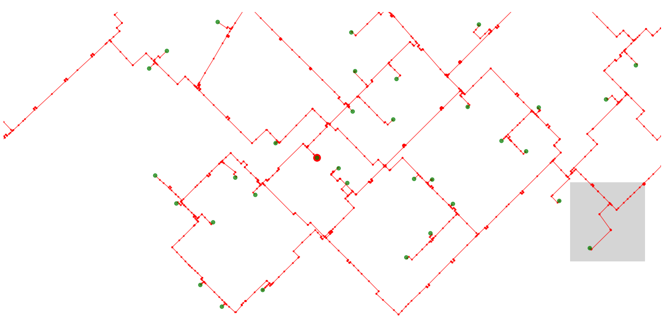

**Figure 2.** Original model cutout of an exemplary district heating grid

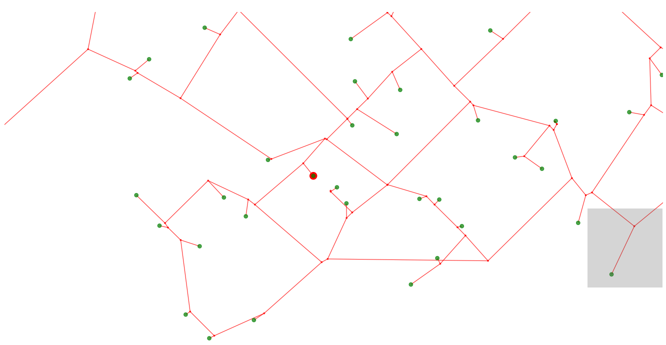

**Figure 3.** Simplified model cutout of an exemplary district heating grid

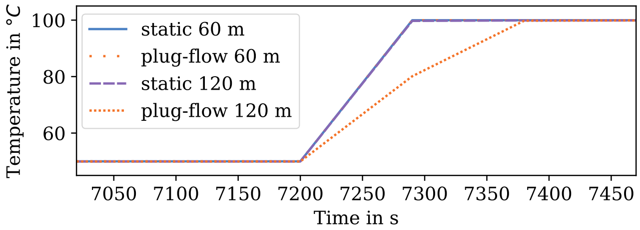


**Figure 4.** Step response to a temperature step of dynamic and static pipe model with different lengths

refers to the simplification of the network typology (Network topology optimization).

Figure 3 shows the exemplary result of the automated simplified network topology for the same cutout of the district heating grid. The simplified network contains much less pipe network representations by nodes and edges. This is mainly done by a weighted reduction of the existing pipes between nodes which represent junctions, substations or supplies. Therefore, all pipe edges between two network nodes which have more then two connecting edges are summarized and replaced by one pipe edge, representing the weighted diameter and the total length of the pipes reduced. An good example is the substation in the lower right corner, where three edges are simplified to one straight edge, representing the sum of the total length of the original three edges. In addition, the new representing edges summarize the pressure losses of the replaced pipe sections caused by bends and take these into account by increasing the already described parameter *fac* in the plug-flow pipe model.

In the two last steps, the network model and its features are further processed and exported. Therefore, a further model simplification is applied, to reduce simulation time and numerical complexity. In this case, the used Python tool *uesmodels* is able to replace all pipes below a certain length with a static pipe model instead of the IBPSA plug-flow pipe model, which reduces the simulation complexity through the reduction of the system of equations of the system model while causing only minor losses in accuracy. Regarding the impact of this replacement, responses on a temperature step on both models were investigated. Figure 4 shows the comparison of the plug-flow pipe model with the static pipe model, used for the replacement, on a temperature step of 50 $K$. Two different length with typical pipe diameters and mass flows are compared with a simulation output of 90s. One can see that with longer pipe length, the dynamic behavior of the two models are different, but with shorter pipes, in this case 60 meters of length, there is no difference observed. This leads to the conclusion that shorter pipe length can be replaced with static pipe models with no huge deviation in terms of the dynamic behavior. In addition, its shown that the steady state behavior before and after the temperature step is equal, resulting in a feasible assumption for the replacement.

Afterwards, the network graph and its features gets translated to *Modelica* code with the use of mako templates (Mayer, 2016). The resulting simulation model is ready to run in the simulation environment *Dymola*.

### Control Strategies

The control of district heating and cooling networks has a big impact on the operation and efficiency of a district energy system. Especially for the integration of renewable energies into conventional heating and cooling networks as well as into 4th generation heating and cooling networks (Lund et al., 2014), the control of these networks is important because generation and demand are temporally decoupled (Vandermeulen et al., 2018). Since these control strategies and the resulting network operations are becoming increasingly complex, dynamic system models are important for developing and testing these strategies. In this paper, two different simple control strategies of a district heating network are exemplary examined and compared on the basis of dynamic simulations. For this purpose, a constant flow temperature is compared with a variable flow temperature that is dependent on the outdoor air temperature.

## 3 Use Case

The subject of the presented Use Case is the research center Jülich in Germany. The research campus consists of over 200 buildings with different usage, for example of-

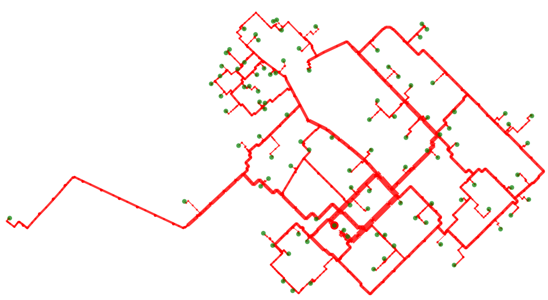

**Figure 5.** District heating network of the investigated research center in Germany

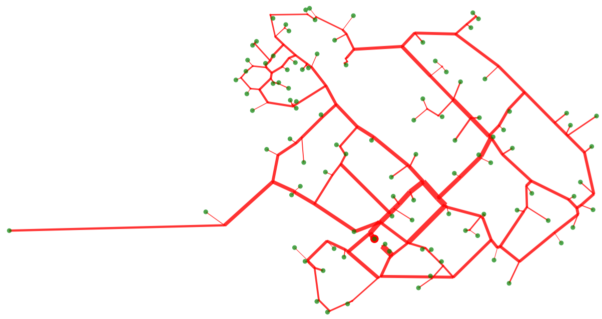

**Figure 6.** Simplified district heating network of the investigated research center in Germany


DOI
10.3384/ecp19157179

**Table 1.** *Modelica* translation and simulation information of original and reduced model

| *Model Characteristics* | *Original Model* | *Reduced Model* | *Difference in %* |
|---|---|---|---|
| Number of equations | 82527 | 81411 | -1.4 |
| Simulation Time in s | 116920 | 64107 | - 45.2 |
| Number of Components | 15475 | 15357 | - 0.8 |
| Number of state events | 13551 | 10162 | - 25.0 |
| Number of Jacobian-evaluations | 27855 | 22681 | - 18.6 |

fices and laboratories. The building stock varies between different construction periods, with a peak between the year 1958 and 1968. Nearly all buildings on the research center are connected to a district heating network, which is supplied by waste heat of a nearby lignite-fired power plant. The annual peak load of around 28 MW are supplied with the help of more then 100 substations to the buildings for space heating, domestic hot water and process heat. Figure 5 shows the district heating network of the described Use Case. The green dots represents the substations for the buildings, the red edges the actual heating network and the green dot with the red circle the central supply unit. The network diameters are qualitatively indicated by the width of the red edges of the graph. The network itself has a total pipe length of 37 km and pipe widths between DN 32 and DN 400. The pipes are all plastic jacket pipes to ensure low heat losses while having high flow temperatures between 90 - 140 °C.

In the context of the presented paper, the Use Case shows the application of a dynamic simulation model with the presented methodology. Leading to a simulation model where the influence of different control strategies can be tested. This will be illustrated in this paper using examples of two different control strategies. In this case, the used geographical network information shown in Figure 5 are reduced with the methodology described in section 2, leading to a simplified, weighted network layout shown in Figure 6. Ones can see that the complexity in terms of the representing network edges is reduced, especially regarding the representation of the thermal expansion joints and exact directions of the pipe edges. The simplified representation is then translated to a dynamic model representation in *Modelica*.

Regarding the application in the context of this paper, different simulation exercises are present in section 4. Starting with the comparison and evaluation of the simulation model reduction in terms of complexity. Basis for this is the graph where the network topology optimization has already been applied. This graph is used to create a simulation model where all pipes are modelled with the plug-flow pipe model. For comparison a simulation model, which is simplified by the step of model reduction described in section 2 is automatically generated. The simplification is verified by a comparison of both simulation results.

The simplified model is used to compare two different control strategies for the heating network. A fixed temperature control strategy and a control strategy with variable flow temperature that is dependent on the outdoor air temperature are applied to present the capability and usability of the simplified dynamic simulation model to answer control strategy related questions of district heating grids.

# 4 Results

The presented Use Case is used to examine different simulations already described in section 3. Starting with the comparison of a complex model and a simplified model. Evaluating the translation characteristics as well as simulation time and results. Followed by a comparison of two control strategies to exemplary show the capability of the presented methodology and simulation models.

## Model Reduction

The presented simulation model reduction takes the network topology optimization, known from Figure 6, as a starting point. Exporting the raw simplified network data to a simulation model, a *Modelica* system model with 100 substations and 258 pipes is created. Translating this model, in the following called *original* model, *Dymola* creates the translation information shown in Table 1. Using a standard workstation with 32 GB of RAM and 12 Cores for the simulation of this model, we are not able to create a stable and reproducible simulation. Replacing 59 pipes of the original 258 pipes with the static pipe model, a simulation model with the characteristics shown in Table 1 was created, following the described methodology. In this simplified case, *uesmodels* replaces all network pipes with a length shorter then 20 m with static pipes, while ensuring that a reduced pipe is not followed by another reduced pipe. Meaning that in the presented case, 64 pipes were shorter than 20 m but only 59 got replaced to ensure that no further error gets introduced by replacing a lot of connected pipes with static pipes.

Comparing the simulation log for this two models, a significant reduction in the number of state events as well as the number of Jacobian-evaluations is achieved. In addition a more stable and reproducible simulation was achieved on the same machine, while reducing the simulation speed by 45.2 %. All simulations were tested on different workstations with comparable hardware specifications, whereas only one of them was able to translate the *original model* without running into a bad allocation er-

**Table 2.** Results of the control strategy comparison

| | *Fixed Temperature* | *Variable Temperature* |
|---|---|---|
| Temperature | 120 °C | 95 - 120 °C |
| Provided Energy | 83.9 GWh | 82.6 GWh |
| Heat Loss | 9.9 GWh | 8.6 GWh |
| Pumping Energy | 45.0 MWh | 61.5 MWh |

rors. After the reduction, all of the testes machines could run the model without errors. Leading to the assumption, that with the current models and level of detail, the investigated network with its meshed structure is on the edge of possible thermal network simulations with the used computers. Nevertheless, the reduction needs to be compared in terms of actual simulation variables. Thus, we present a comparison of the *original* model with the *reduced* model by comparing their supplied heat. In addition, the calculated mass flow rates at the supply and the calculated return temperatures at the supply are compared with a time step of 15 minutes. The total supplied heat of the *original* model is 82.7 GWh, while the total supplied heat of the *reduced* model is 82.6 GWh, showing good accordance.

The comparison in Figure 7 and Figure 8 shows the difference between the both results. It is shown that the overall maximum difference in mass flow calculation is $+0.7\frac{kg}{s}/-1.97\frac{kg}{s}$ (total average mass flow: $55.2\frac{kg}{s}$), while the maximum difference in return temperature is $0.1K/-0.2K$ (total average return temperature: 60 °C). For a better visualization of the small error, Figure 9 shows the error as a histogram, underlining the small errors between the two models, with an expected value of $-0.00032K$. Nevertheless, ones can see e.g. in Figure 8, that there are some spikes and thus a deviation between the two compared simulations. The reason for this behavior could be the heat loss calculation of the static pipe model. Leading to smaller heat losses and smaller temperature drops on nearly zero mass flows compared to the plug-flow model. Keeping in mind that these spikes at the central supply are very small compared to the absolute average temperature values of 60 °C, we further investigated the deviations between the *original* and the *reduced* model. Figure 10 shows the mean value of the calculated deviations of the flow temperature for one year at all substations. It is shown, that the majority of the deviation is smaller then 1 $K$. Nevertheless, there are higher deviations which need to be further investigated in future work. In the scope of this paper, the *reduced* model compares good enough to the *original* model in terms of accuracy to further investigate top level control strategies, while improving overall stability and simulation speed.

## Control Strategies

As already described in section 3, the presented district heating network is used to apply an exemplary comparison of two control strategies for district heating networks. In the context of this paper and based on the simplified simulation model, two simple control strategies are compared, showing the exemplary usage and capability of the workflow and the simulation models. One simulation is performed with a fixed flow temperature of 120 °C in the flow line of the heating network to fulfill the temperature requirements of the buildings on cold days. A second simulation is performed with a variable flow temperature curve based on the ambient temperature. The results for the overall supplied heat, the overall heat loss in the network and the used pumping energy are shown in Table 2.

On the one hand, comparing the total supplied heat, the variable flow temperature reduces the amount of heat use by 1.3 GWh due to lower heat losses in the network. On the other hand, regarding the used pumping energy, the variable flow temperature increases the energy demand by 16.5 MWh. Compared to the reduced amount of heat input, the slight increase of pumping energy is small, that the variable flow temperature should be preferred against the fixed flow temperature.

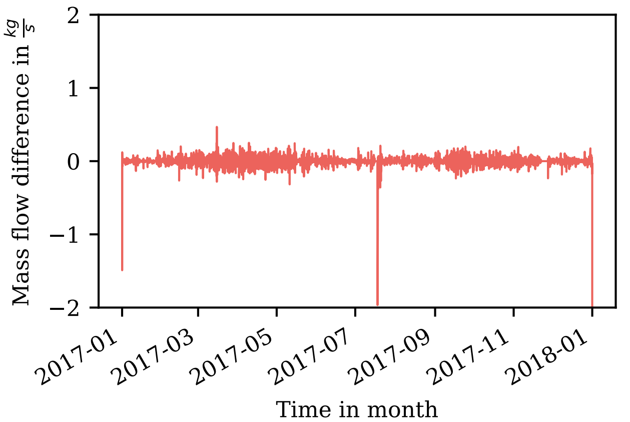


**Figure 7.** Mass flow difference between the results of the reduced and complex model at central supply unit

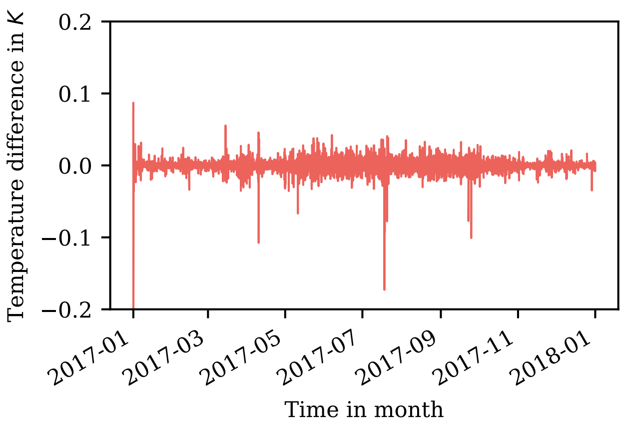


**Figure 8.** Return temperature difference between the results of the reduced and complex model at central supply unit


DOI 10.3384/ecp19157179

# 5 Conclusion and Limitations

The presented paper describes a workflow for automated generation and simplification of DHC network simulations with Python and Modelica. Two different type of simplifications are applied, on the one hand the network topology is optimized by reducing the total number of pipes in the model. On the other hand the model itself is reduced by using static pipe models for short pipe sections. The dynamic simulation models are based on internationally develop district heating and cooling components such as the IBPSA plug-flow pipe model. The automated workflow is applied to an existing district heating network of a research center in Jülich, Germany. The comparison of the simulation model reduction shows good accuracy between the *original* and *reduced* simulation model in terms of the simulation results, while reducing the simulation time by 45.2 %. To show the capability and usability of the presented workflow and simulation models, two different basic control strategies where examined, showing significant improvements for a variable flow temperature. The system model was not validated as part of this work. However, this is essential for the use of the model to optimize operation of DHC and will be done in future investigations. The paper shows the usability of the modeling language Modelica for DHC control optimization. Future work will include a comparison of the used models with even more simplified models, to elaborate which model detail is necessary for the evaluation of top level control strategies as well as the detail comparison of different models at different points at the network. Nevertheless, the paper present possible network simplification and their results of an Modelica user oriented view. However, future research needs to include the investigation of the impact on the numerical system, especially regarding the agebraic loops and blocks.

# Acknowledgments

Grateful acknowledgement is made for financial support by BMWi (German Federal Ministry of Economic Affairs and Energy), promotional references 03ET1352A. This work was supported by the Helmholtz Association under the Joint Initiative “Energy System 2050 - A Contribution of the Research Field Energy”.

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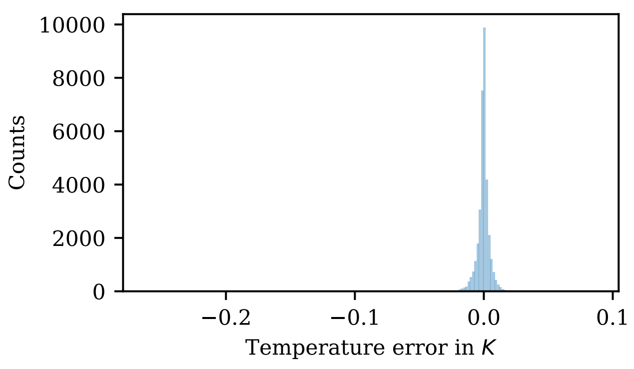


**Figure 9.** Histogram of temperature difference between the results of the reduced and complex model at central supply unit

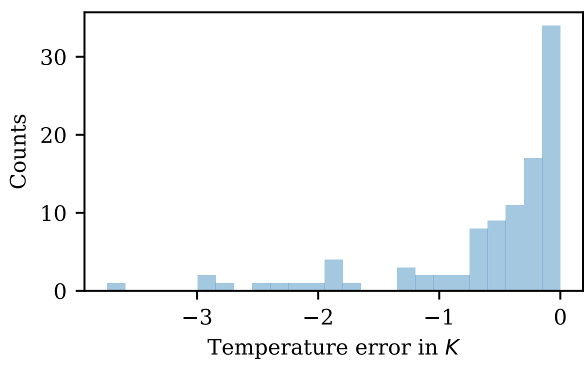


**Figure 10.** Histogram of the mean values of the quarter hourly deviations of one year for all substations

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