Modelling larger-scale district heating networks

TUHH
Technische
Universität
Hamburg

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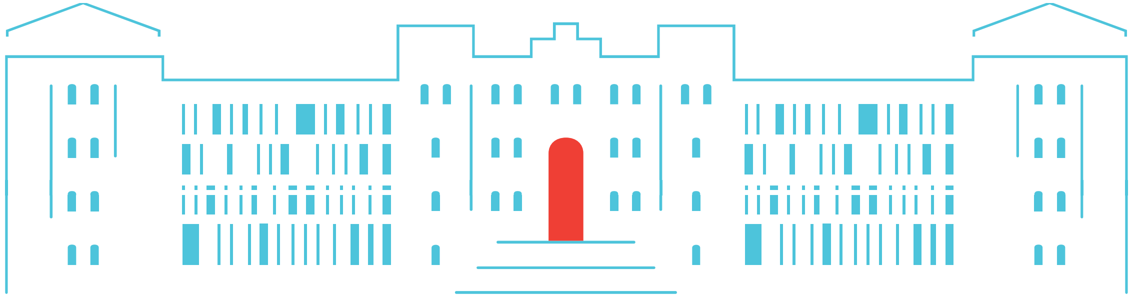
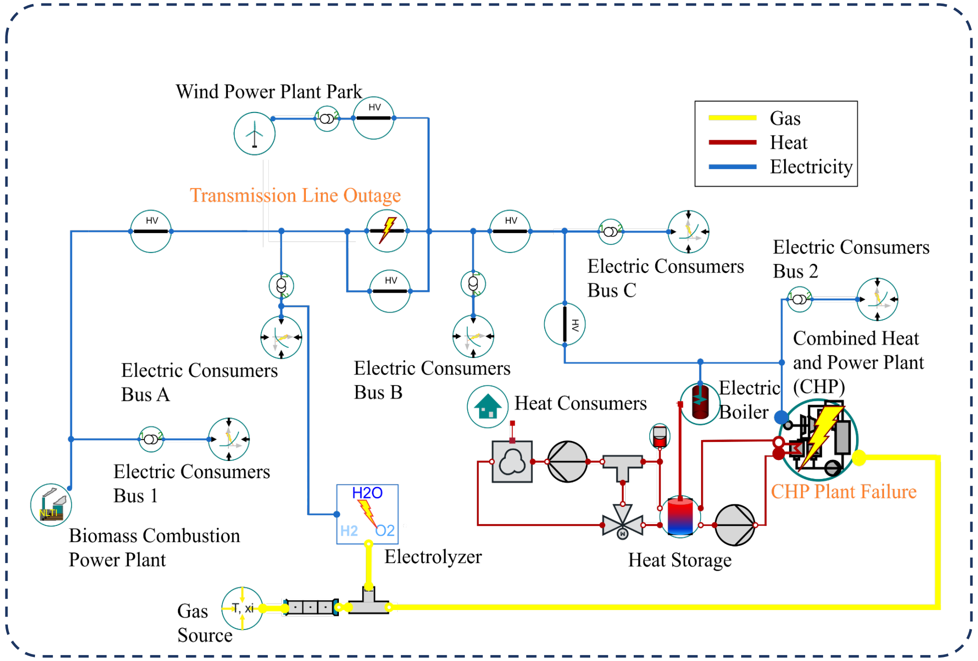


Prof. Dr.-Ing Arne Speerforck, Jan Westphal

Motivation

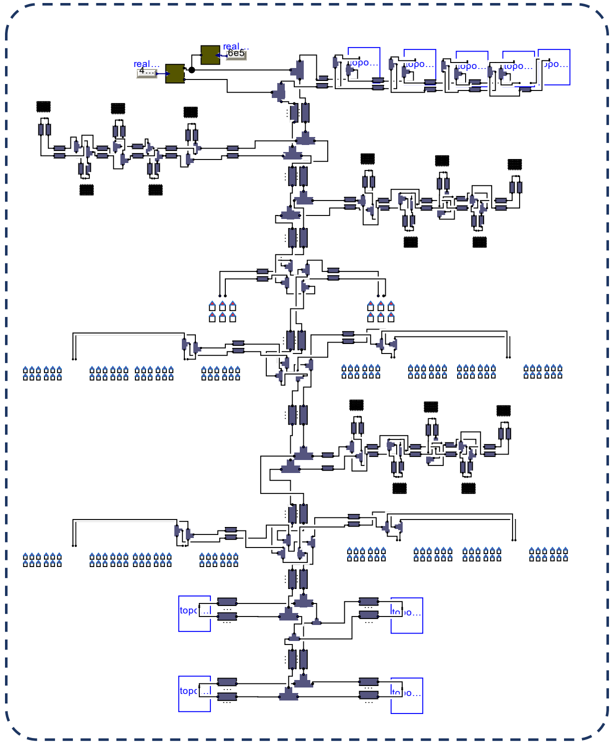
So far:

Using the transient library for the simulation of coupled energy grids



Now:

Simulation of largescale district heating networks **without** aggregation



Purpose of model:

Using the thermal inertia of largescale district heating networks as a storage

- Heat storages
- Thermal inertia of pipes
- Thermal inertia of consumers

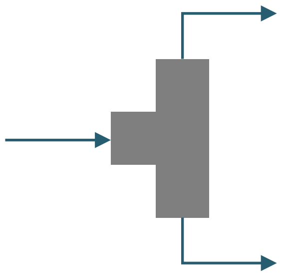
→ Dynamic models

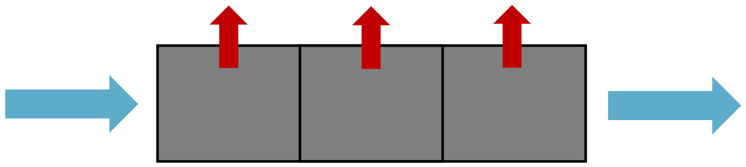
TransiEnt Library

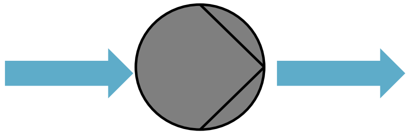
Modelling concept

Main concepts:

1. Use of mass flow states [1]
2. No use of fluid models
3. Exclusive discretization of the energy balance



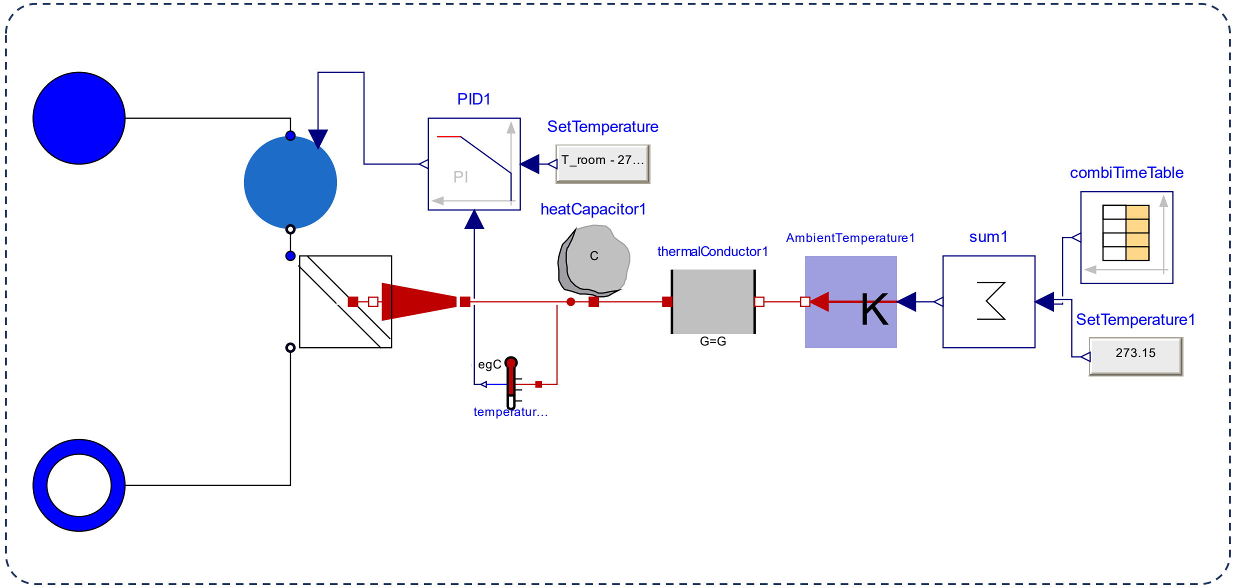




Basics of the modeling concept

- Constant material properties (no media models)
- Connectors (h, m_flow, p)
- Transient energy balance in pipe and junction models
- Steady-state momentum and mass balance + linear pressure loss model Except: Pipe model -> physical pressure loss model (fluid dissipation) & use of an unsteady momentum balance

Consumer model



$$\dot{V} = \frac{P_{\text{hyd}}}{\Delta p}$$

Pump model

$$m \cdot c \cdot \frac{dT}{dt} = \dot{Q}$$

Thermal Capacity

$$\dot{Q} = \dot{Q}_{\text{nom}} \cdot \left(\frac{(T - T_{\text{room}})}{\Delta T_{\text{nom}}} \right)^n$$

Heat exchanger

Consumer model

Target of the model:
Include thermal inertia of buidlings and determination of the heat demand at variable ambient temperature

Components:

- Heat exchanger
- Pump for specifying the mass flow and calculating the hydraulic capacity
- Thermal capacity
- Thermal resistance
- PI controller

Parameterization using a detailed model of a detached house [2]

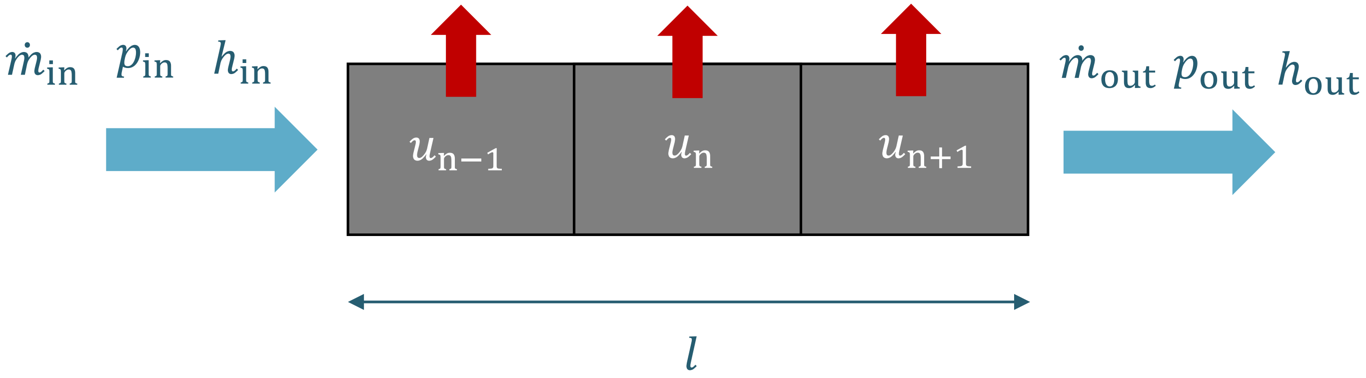
Pipe model with n control volumes

$$V \cdot \rho \cdot \frac{du_n}{dt} = \dot{m} \cdot (h_{n-1} - h_n) + \dot{Q}_{loss,n}$$

$$p_{in} - p_{out} = L \cdot \frac{d\dot{m}}{dt} + \dot{m}^2 \cdot \frac{\Delta p_{nom}}{\dot{m}_{nom}{}^2}$$

$$\dot{m}_{in} + \dot{m}_{out} = 0$$

$$\dot{Q}_{loss} = k \cdot (T_{in} - T_{out}) \cdot L$$



Constants parameters:

$k = 0.15 \frac{W}{Km}$

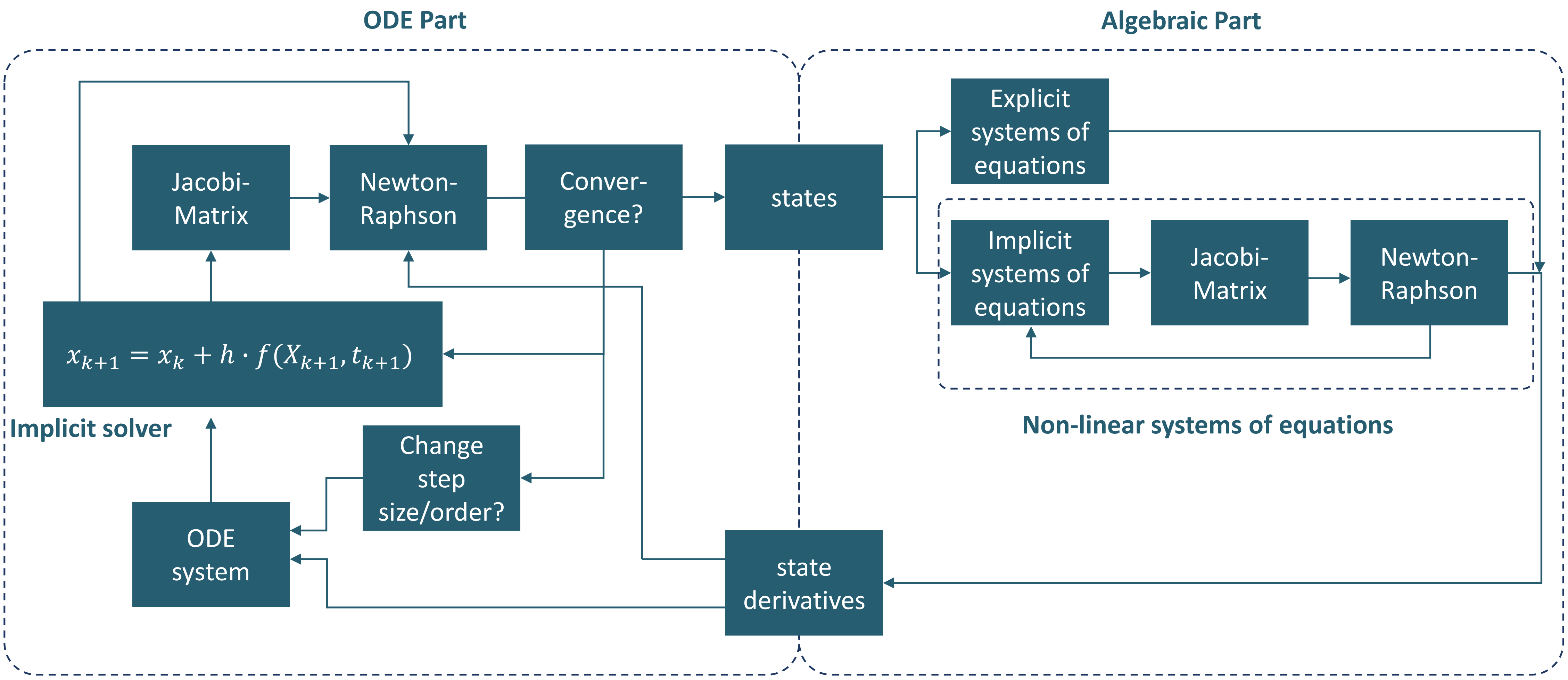
$c_f = 4200 \frac{kJ}{kgK}$

$\rho = 1000 \frac{kg}{m^3}$

Description of the model

- Discretized energy balance with n control volumes
- Calculation of a pressure loss along pipeline
- Steady-state mass balance
- Bidirectional flow through enthalpy as a stream variable
- Calculation of a heat loss using a constant heat transfer factor

Basic solution process of the model



Hydraulic parallel circuit

Structure graph of the model:

I. $\dot{m}_1 + \dot{m}_2 + \dot{m}_3 = 0$

II. $p_1 - p_2 = \dot{m}_2 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$

III. $p_1 - p_3 = \dot{m}_3 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$

IV. $\dot{m}_2 + \dot{m}_4 = 0$

V. $p_2 - p_4 = \dot{m}_2{}^2 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}{}^2}$

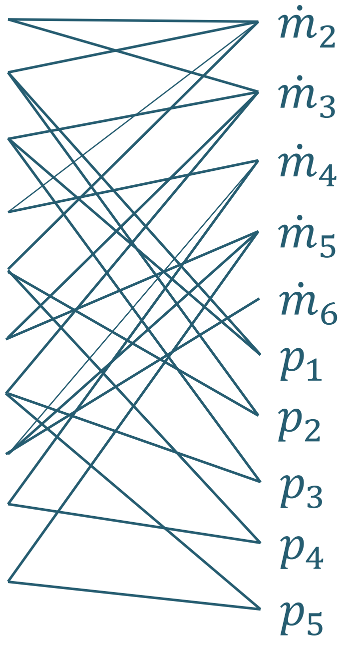
VI. $\dot{m}_3 + \dot{m}_5 = 0$

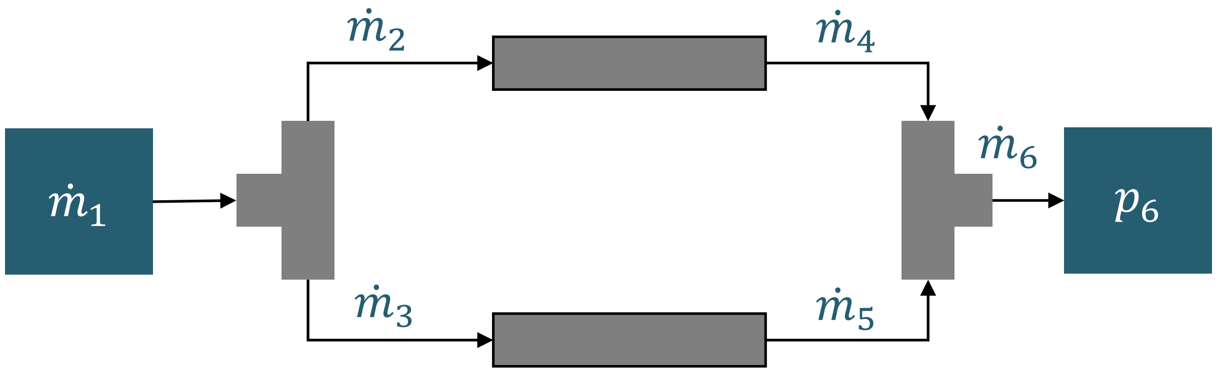
VII. $p_3 - p_5 = \dot{m}_3{}^2 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}{}^2}$

VIII. $\dot{m}_4 + \dot{m}_5 + \dot{m}_6 = 0$

IX. $p_4 - p_6 = \dot{m}_4 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$

X. $p_5 - p_6 = \dot{m}_5 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$





Screenshot of the Statistics:

Sizes of linear systems of equations: { }
Sizes after manipulation of the linear systems: { }
Sizes of nonlinear systems of equations: {7}
Sizes after manipulation of the nonlinear systems: {1}
Number of numerical Jacobians: 0

10 equations & 10 unknowns, but:
Implicit systems of equations

Solution: Adding a mass flow state

Structure graph of the model:

$$\text{I.}\quad \dot{m}_1 + \dot{m}_2 + \dot{m}_3 = 0$$

$$\text{II.}\quad p_1 - p_2 = \dot{m}_2 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$$

$$\text{III.}\quad p_1 - p_3 = \dot{m}_3 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$$

$$\text{IV.}\quad \dot{m}_2 + \dot{m}_4 = 0$$

$$\text{V.}\quad p_2 - p_4 = \boxed{\frac{d\dot{m}_2}{dt}} \cdot L + \dot{m}_2{}^2 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}{}^2}$$

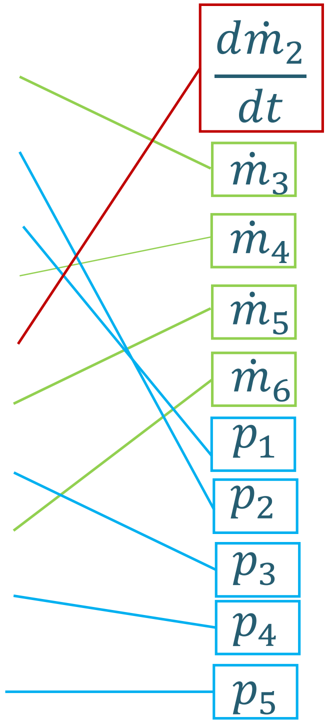
$$\text{VI.}\quad \dot{m}_3 + \dot{m}_5 = 0$$

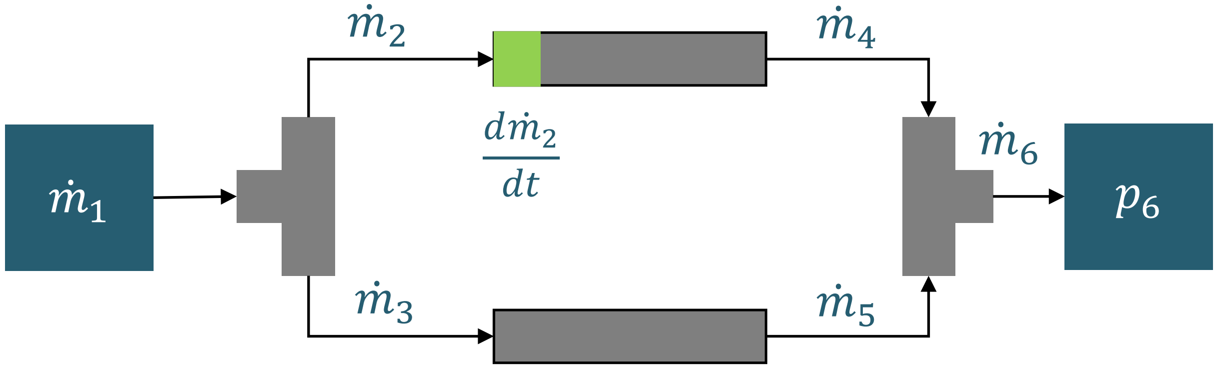
$$\text{VII.}\quad p_3 - p_5 = \dot{m}_3{}^2 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}{}^2}$$

$$\text{VIII.}\quad \dot{m}_4 + \dot{m}_5 + \dot{m}_6 = 0$$

$$\text{IX.}\quad p_4 - p_6 = \dot{m}_4 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$$

$$\text{X.}\quad p_5 - p_6 = \dot{m}_5 \cdot \frac{\Delta p_{\text{nom}}}{\dot{m}_{\text{nom}}}$$



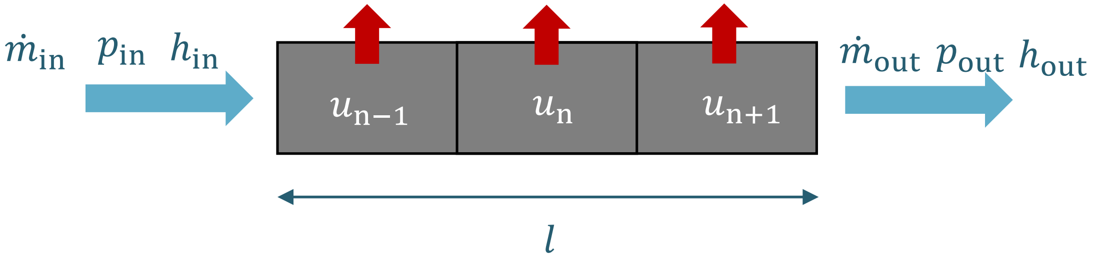


Screenshot of the Statistics:

Sizes of linear systems of equations: { }
Sizes after manipulation of the linear systems: { }
Sizes of nonlinear systems of equations: { }
Sizes after manipulation of the nonlinear systems: { }
Number of numerical Jacobians: 0

System of equations can be solved explicitly!

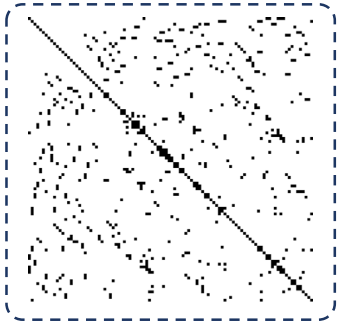
Sparse-Solver



Jacobian

$$J(x) = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & 0 & 0 & 0 & 0 \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} & 0 & 0 & 0 \\ 0 & \frac{\partial f_3}{\partial u_2} & \frac{\partial f_3}{\partial u_3} & 0 & 0 \\ 0 & 0 & \frac{\partial f_4}{\partial u_3} & \frac{\partial f_4}{\partial u_4} & 0 \\ 0 & 0 & 0 & \frac{\partial f_5}{\partial u_4} & \frac{\partial f_5}{\partial u_5} \end{bmatrix}$$

The discretization of the pipe models leads to a sparse Jacobian matrix



Problem:

- Large matrices for large numbers of states (>50,000).
- Handling might require large computational effort

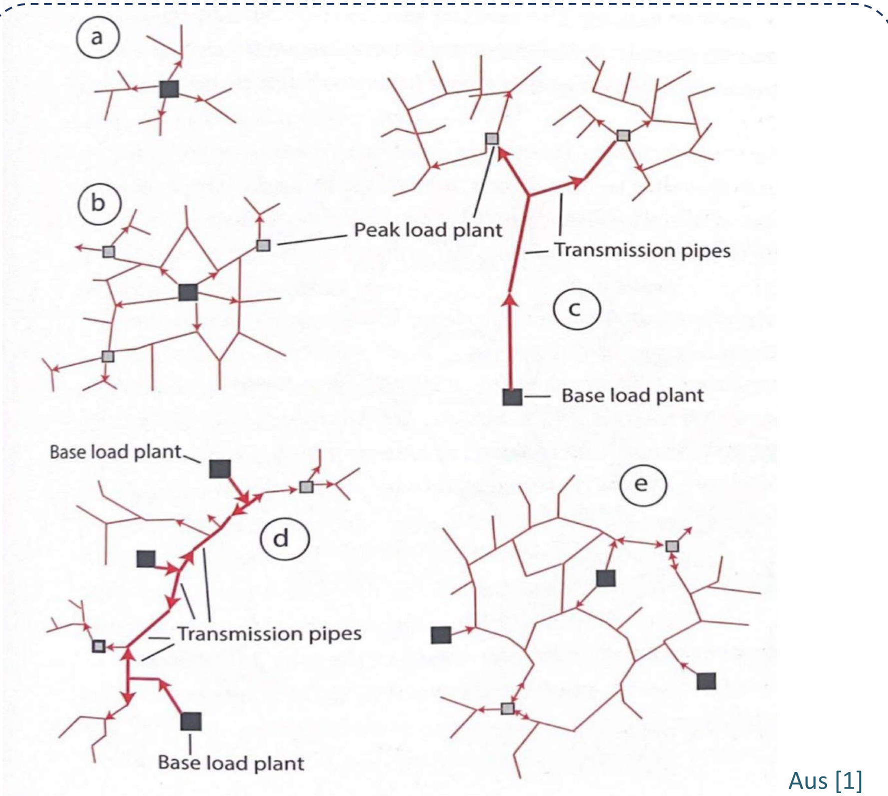
Approach / requirement:

- Utilization of the sparse properties of the matrix: more efficient storage and handling

https://upload.wikimedia.org/wikipedia/commons/8/8a/Finite_element_sparse_matrix.png

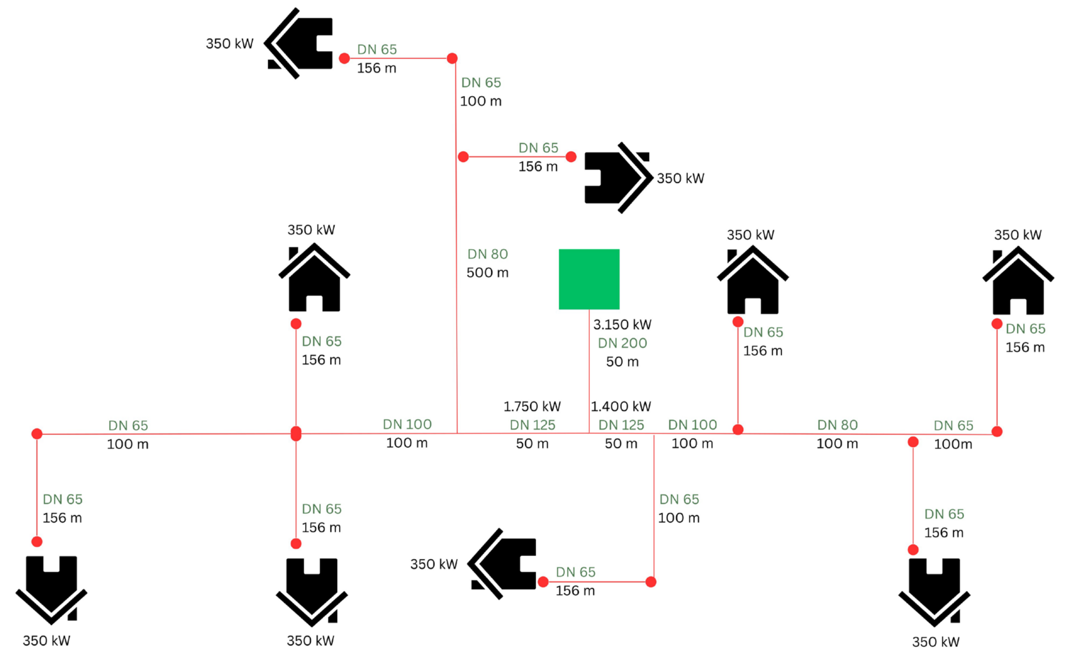
Modeling of representative network topologies

Main lines



Aus [1]

Branch lines

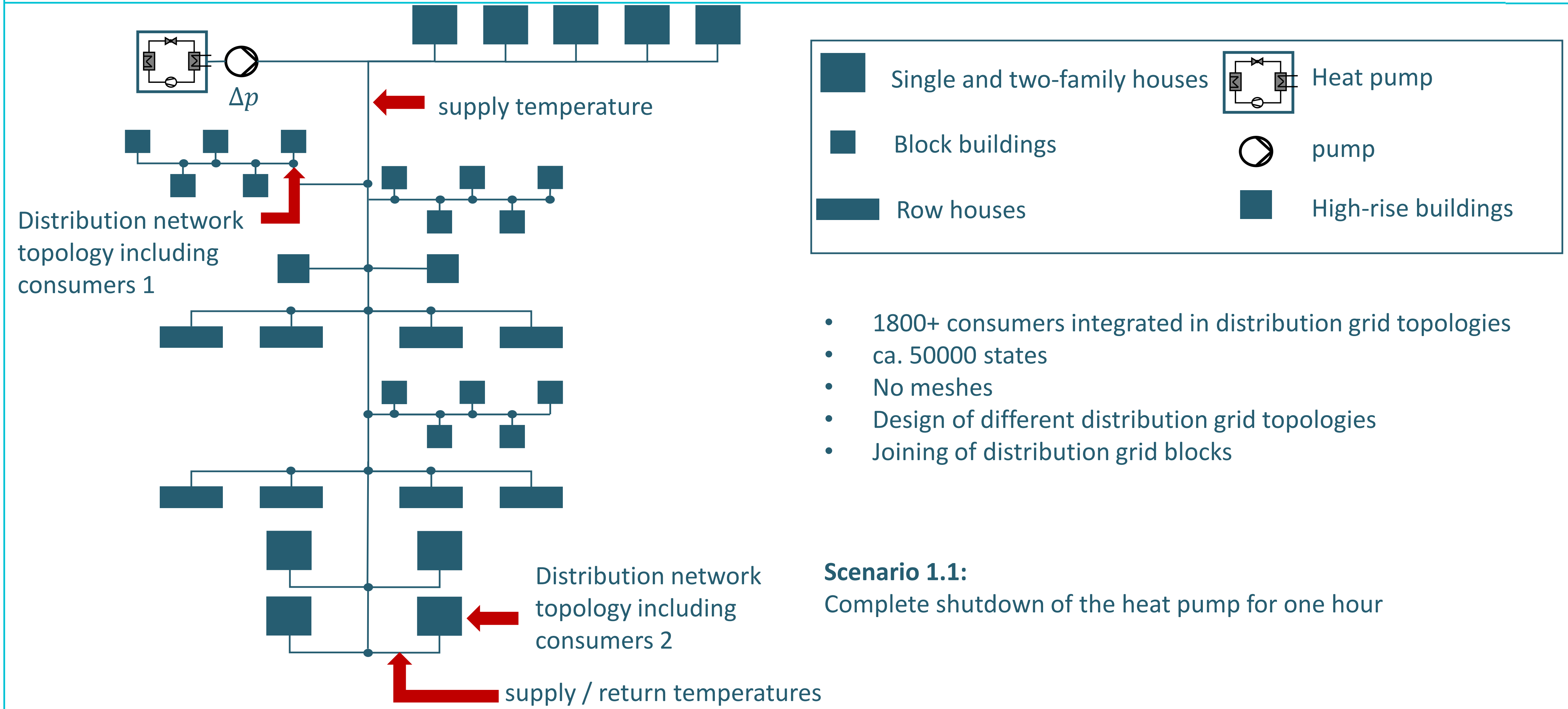


Aus [2] auf Grundlage von [3]

Combination of representative main and branch topologies to form representative heating network topologies

District Heating and Cooling (Sven Frederiksen, Sven Werne) [3] ;Bachelor Thesis Elkhoundary [4]; „Integranet Abschlussbericht Fraunhofer“ UMSICHT and GWI Essen [5]

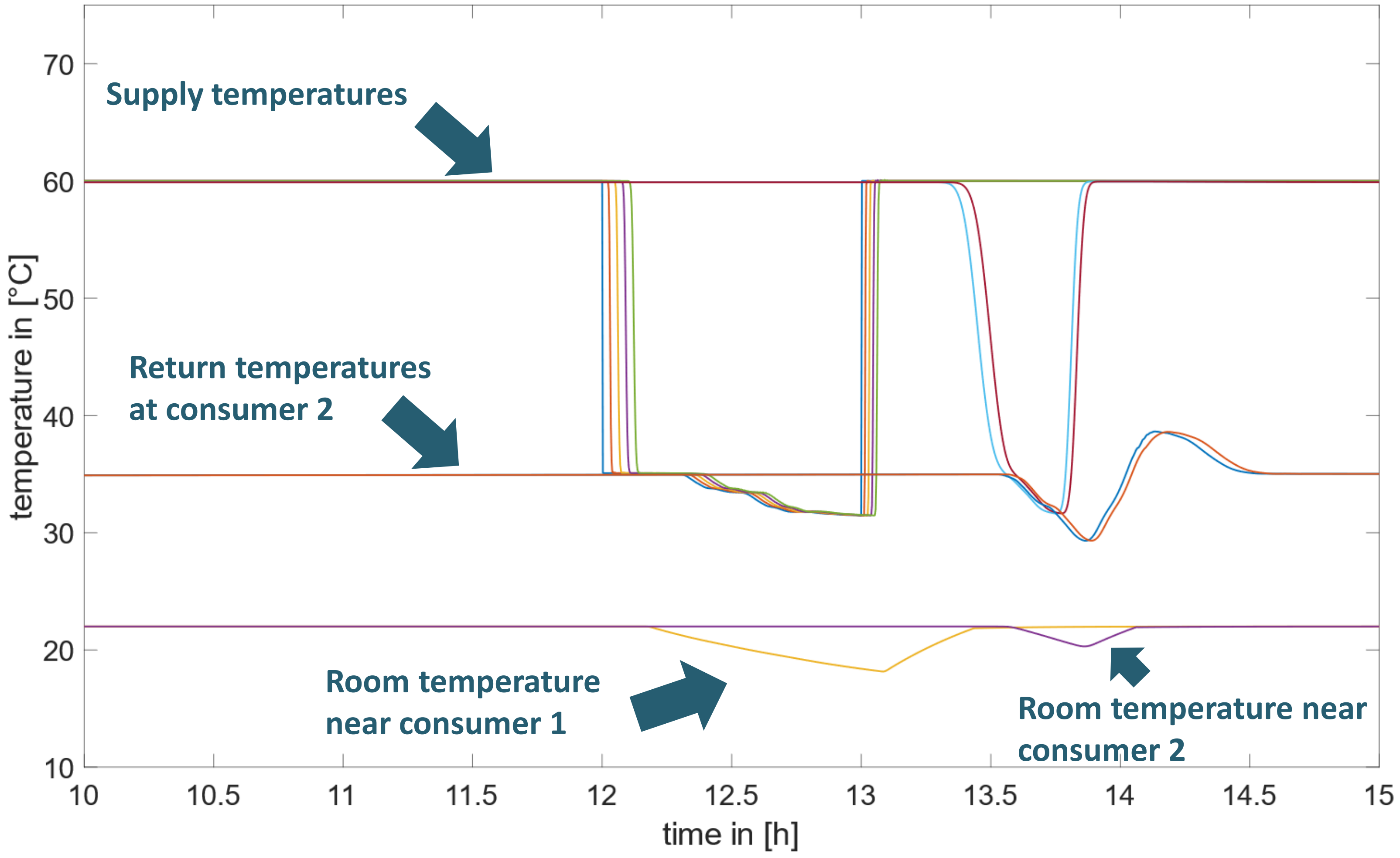
Model of a largescale district heating network



- 1800+ consumers integrated in distribution grid topologies
- ca. 50000 states
- No meshes
- Design of different distribution grid topologies
- Joining of distribution grid blocks

Scenario 1.1:
Complete shutdown of the heat pump for one hour

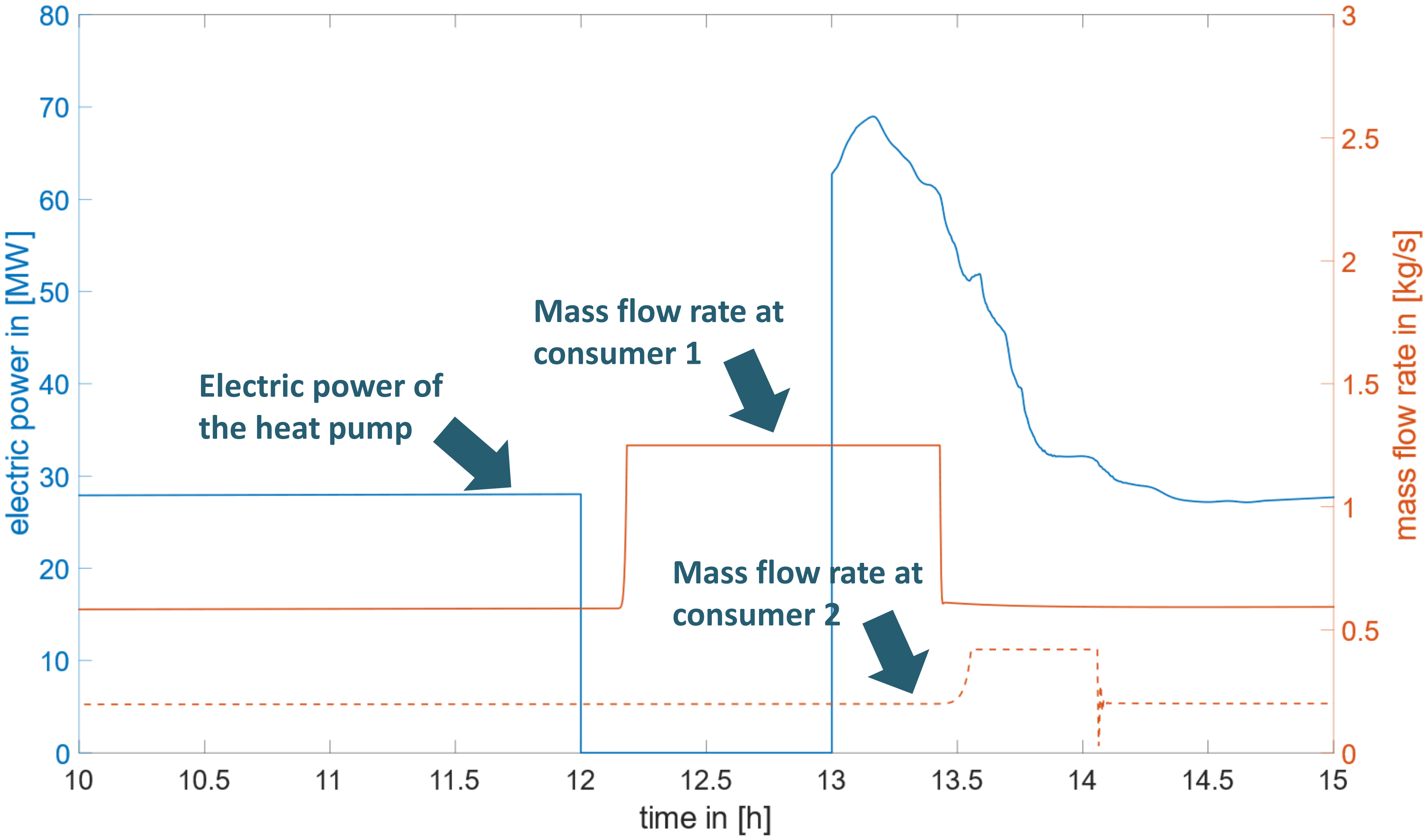
Simulation results: Temperature curves



- Room temperature near the producer drops first
- Room temperature at the end of the network drops significantly less and with a time delay
- lower supply temperature -> increase in mass flow
- Increasing the mass flow reduces the time constant of the network

Conclusion: Switching off the heat pump for an hour is not possible without loss of comfort

Simulation results: Electric power and mass flow rates



- Consumers request more mass flow
- More electric power is required after the reduction
- Electrical output increases due to increased mass flow
- Increase in mass flow for the last consumer 1.5 hours later

Summary and Outlook

1. Modelling concept enables the dynamic simulation of largescale district heating networks
2. The avoidance of implicit systems, especially non-linear systems, leads to a robust modelling concept
3. Models can be simulated even with a high number of states because of sparse solver
4. Further investigations of the possibilities for the usage of the district heating network flexibility are planed

TransiEnt Library

EffiziEntEE

Dankeschön

Technische Universität Hamburg (TUHH)
Prof. Dr.-Ing Arne Speerforck
Jan Westphal
Institut für Technische Thermodynamik
www.tuhh.de

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Technische
Universität
Hamburg

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