Dynamic simulation of district heating networks using discrete event simulation (DES)

Aalto University
School of Science

Zichan Xie

13/01/2024

Why district heating is important?

In Europe, energy for heating and cooling accounts for nearly **50%** of the total gross final energy consumption.

Households are the largest consumer of final energy for space and water heating purposes (**67%**).

75% of heating and cooling demand is supplied by fossil fuels.

District heating (DH) represents only about **8%** of total final heat consumption worldwide.

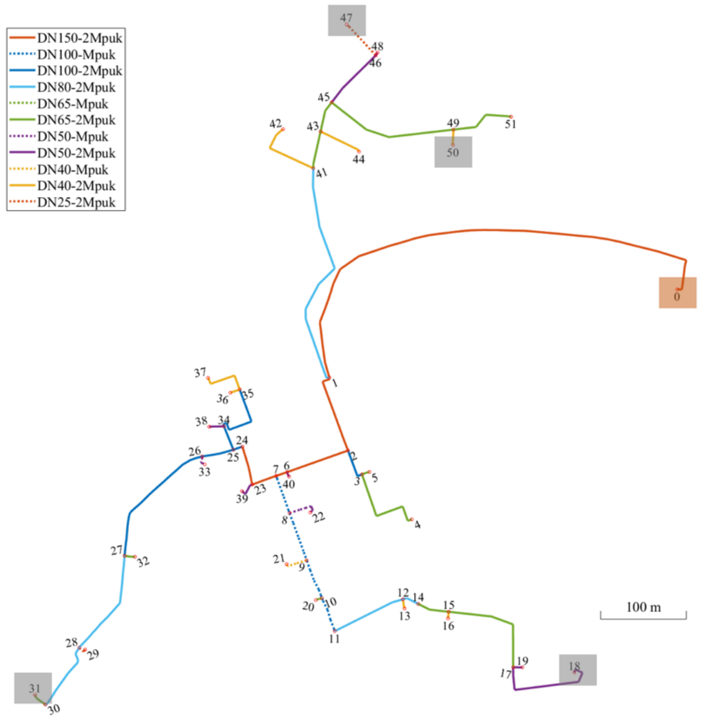
Research gap

1. Holistic system optimization studies involving network operation are hard to find.

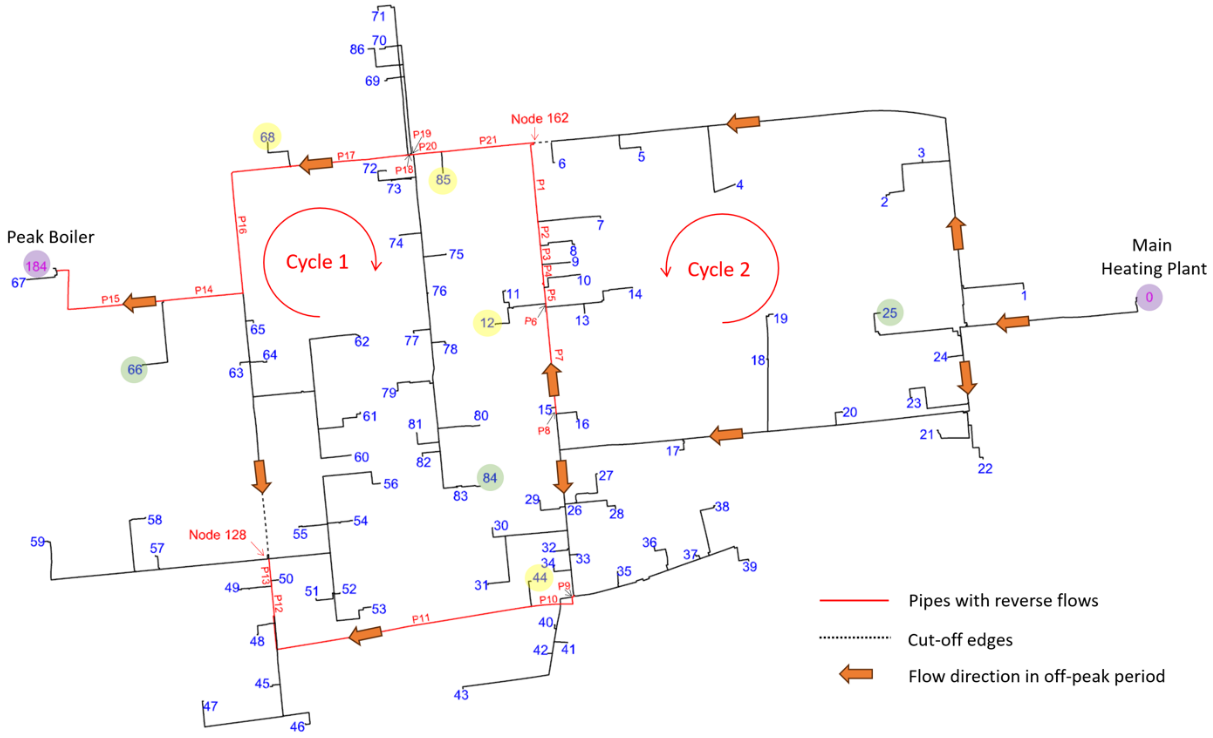
2. Existing network models are time expensive and incapable of handling large-scale system simulation and iterative computing in optimization.

Typical district heating networks

- **Tree-shaped networks**



- **Meshed networks**

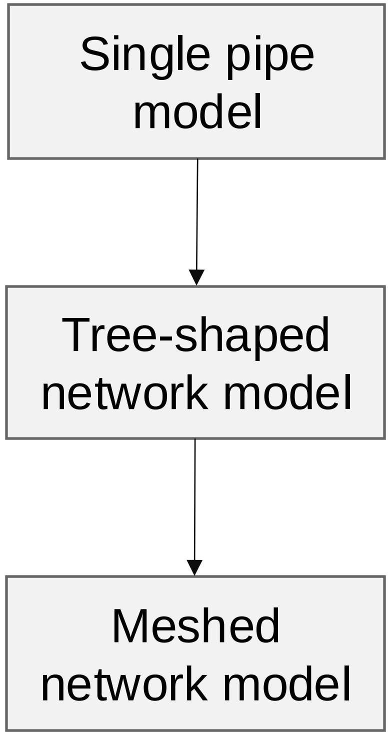


Publications

[1] Xie Z, Wang H, Hua P, Lahdelma R. Discrete event simulation for dynamic thermal modelling of district heating pipe. Energy 2023;285:129523. https://doi.org/10.1016/j.energy.2023.129523.

[2] Xie Z, Wang H, Hua P, Björkstam M, Lahdelma R. Dynamic thermal simulation of a tree-shaped district heating network based on discrete event simulation. Energy 2024;313:133775. https://doi.org/10.1016/j.energy.2024.133775.

[3] Xie Z, Wang H, Hua P, Lahdelma R. Discrete event simulation for dynamic thermal modelling of district heating pipe. (under review)



Aalto University
School of Science

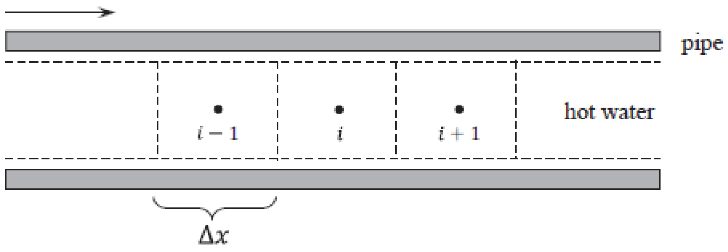
Computational methods

- **Eulerian approach**

(Observer focuses on fixed locations)

- Explicit method is limited by Courant criterion : $\frac{\mathrm{v}\Delta t}{\Delta x} \leq \text{Courant number}$

- Implicit method is computationally expensive



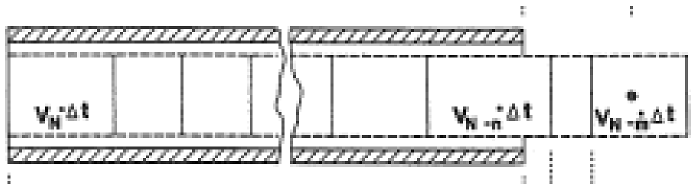
- **Lagrangian approach**

(Observer follows an individual fluid parcel)

$$\rho c_p A \frac{\partial T(t,x)}{\partial t} + \rho c_p A v \frac{\partial T(t,x)}{\partial x} = -q(t,x)$$

Combined with Finite Volume Method

$$\Delta x = \mathrm{v}\Delta t$$

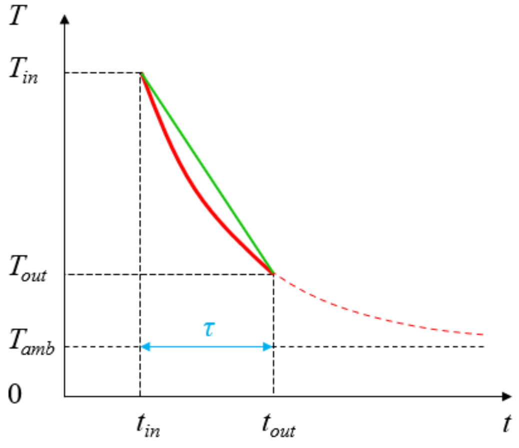


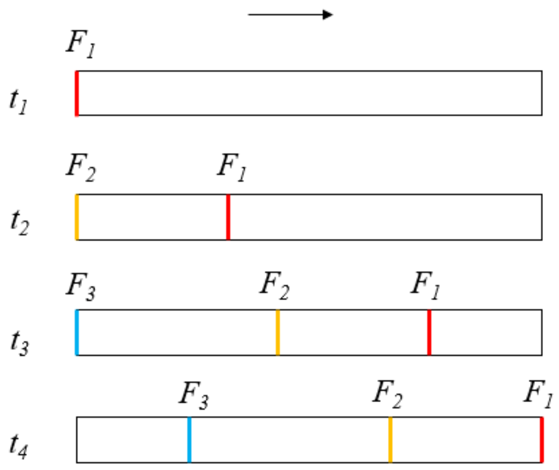
Review of the prior study

Water frontiers are sampling points, which are defined as infinitely thin sections of water moving within a pipe.

DES model can provide the water temperature profile at any location over any given period without numerical errors, by directly computing current temperature based on inlet temperature and travel time.

Water temperature is related to inlet temperature, travel time and ambient temperature.





Initial condition: inlet temperature is T_1 and flow speed is v_1

t_1: Inlet temperature increases from T_1 to T_2
t_2: Flow speed increases from v_1 to v_2
t_3: Flow speed decreases from v_2 to v_3
t_4: Water frontier F_1 arrives at the pipe end

Figure 1 DES schematic diagram of an example

Conclusion of the prior study

Important findings from pipe model validation

- Travel time is a piecewise linear function when flow speed is a step function
- Temperature profile is a piecewise exponential function when inlet temperature is a step function or a piecewise exponential function
- Approximating the exponential temperature profile between breakpoints by linear interpolation is accurate and efficient.

Contribution of this study

1. Consider the mutual heat transfer between parallel supply and return pipes
2. Extend the pipe model to tree-shaped network model
3. Integrate the advanced techniques for fast simulation, like lazy evaluation, customized priority queue, and tolerance threshold.

This DES network model is accurate, efficient, and flexible.

Heat transfer between pipes

$$\rho c_p A \frac{dT(t)}{dt} = -q_{s\to g}$$

$$T(\tau) = (T_0 - k_2)e^{k_1 \tau} + k_2$$

T_0 Initial temperature

τ Travel time

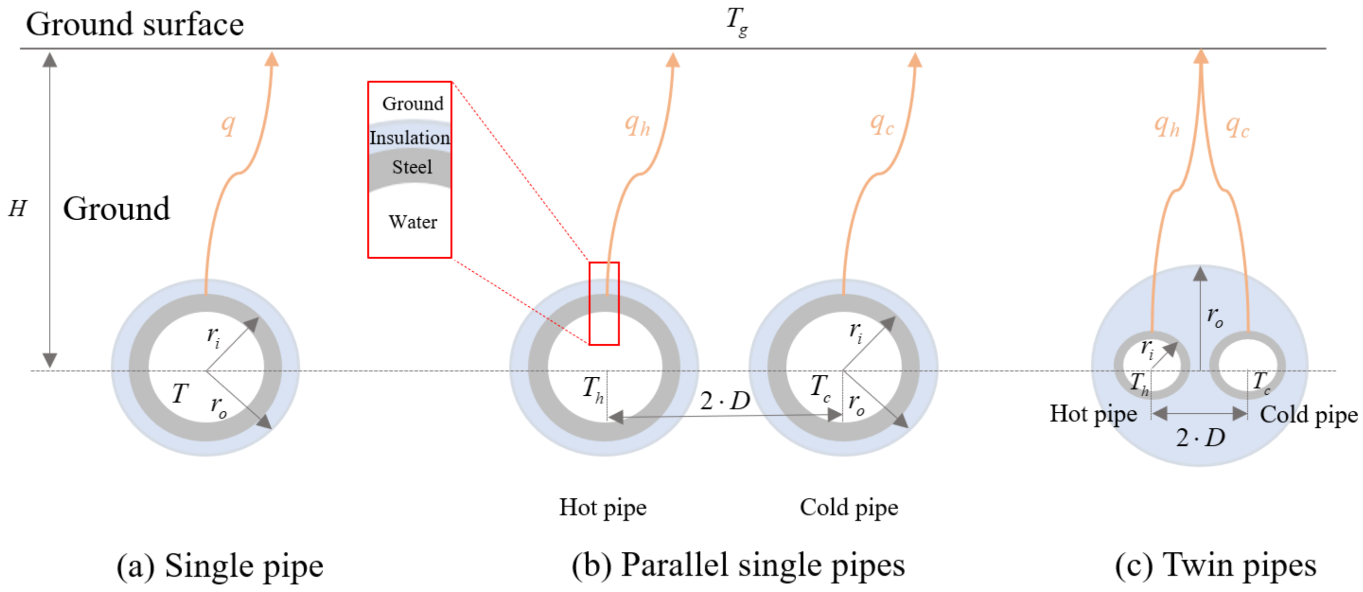


Figure 2 Heat loss from the pipe wall to ground surface for different pipes based on Wallentén's steady-state formulas

Table 1 Different coefficients k_1 and k_2 in the outlet temperature formula.

Pipe types	(a) Single pipe	(b) Parallel single pipes	(c) Twin pipes
k_1	$-\frac{1}{CR}$	$-\frac{R_s + R_a}{2CR_sR_a}$	$-\frac{\pi\lambda_i(h_s + h_a)}{C}$
k_2	T_g	$\frac{(R_s - R_a)T_p + 2R_aT_g}{R_s + R_a}$	$\frac{(h_a - h_s)T_p + 2h_sT_g}{h_s + h_a}$

Water frontier propagation

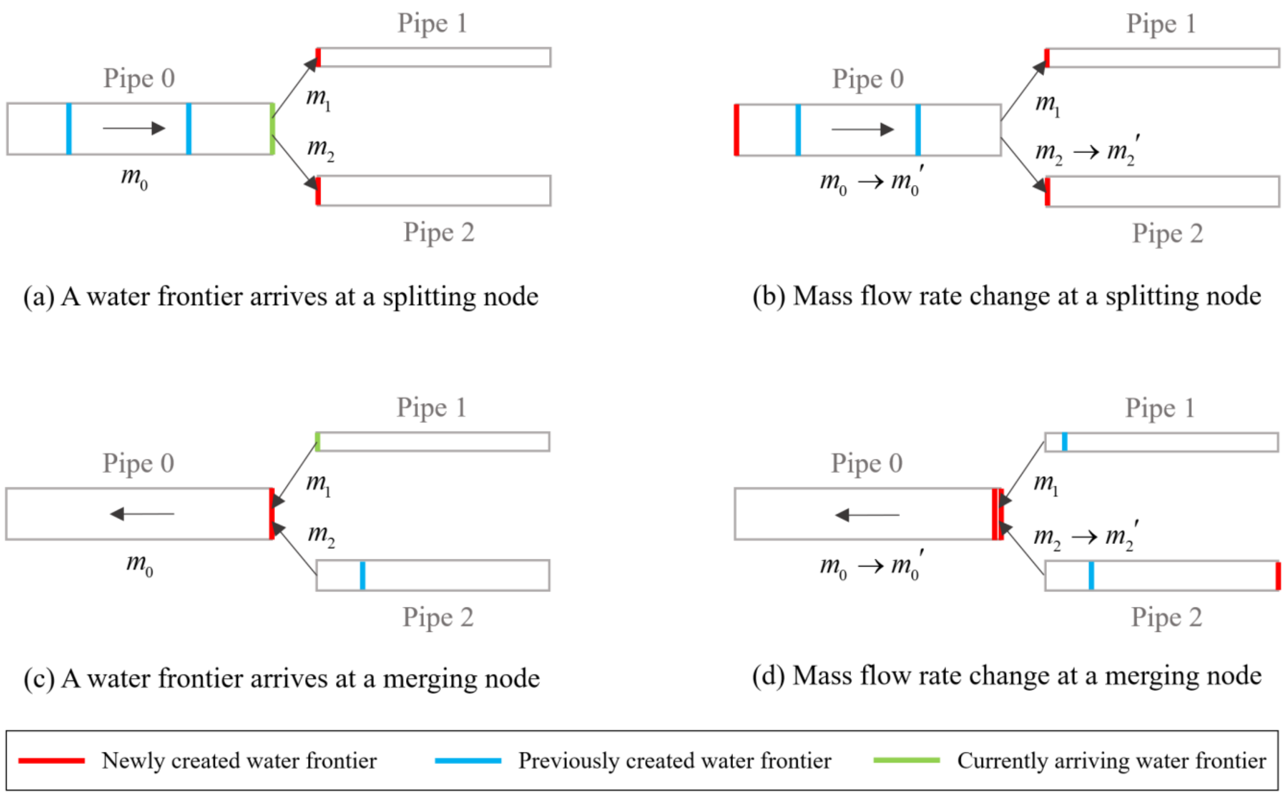


Figure 3 Water frontier propagation between connected pipes

Discrete Event Simulation

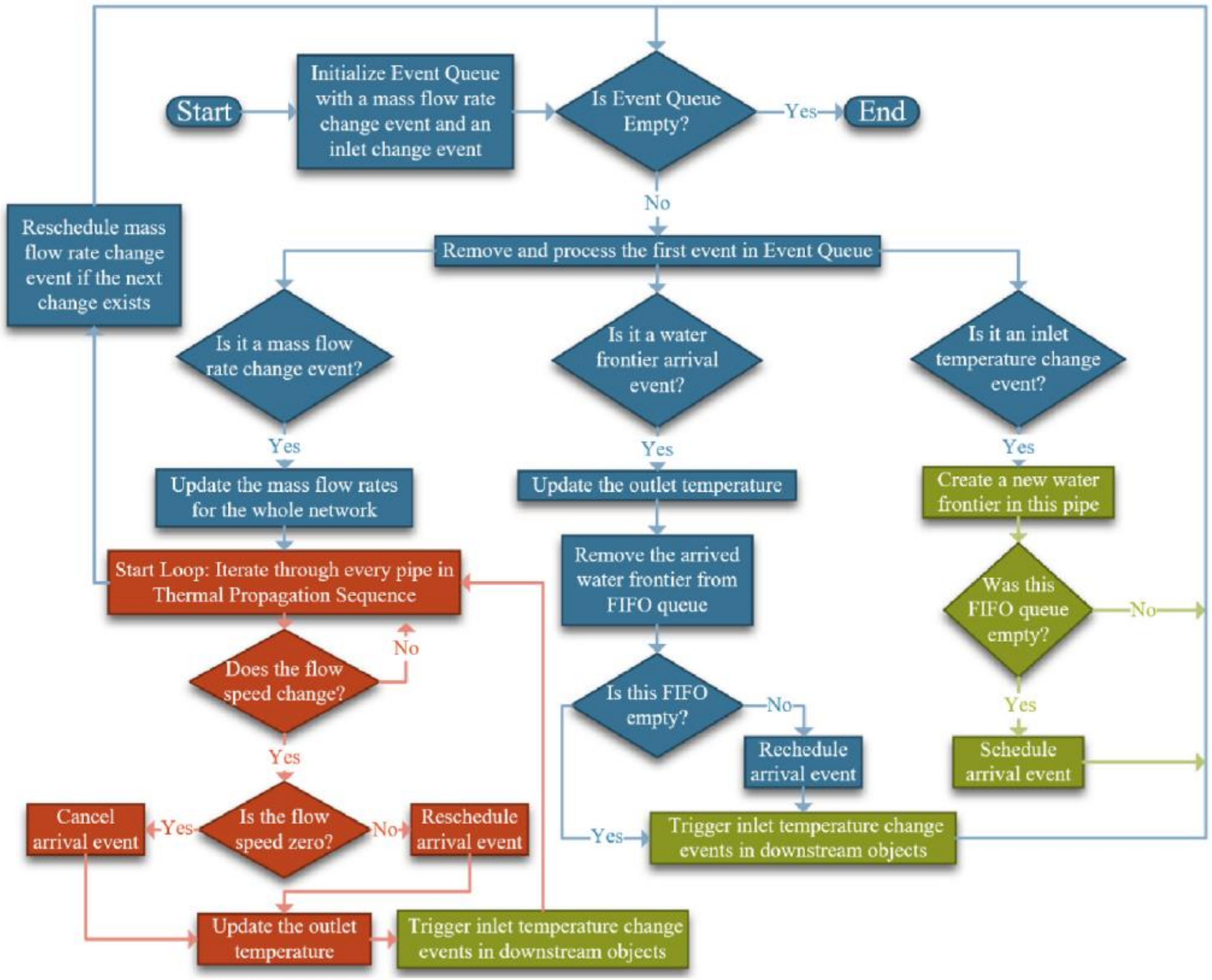


Figure 4 Flowchart for DH Network modelling

An *event* can be considered as a state change. Events can be created, cancelled, and modified during the simulation.

Scheduled events are managed in a common Event Queue ordered by their activation time.

Advanced techniques:
- Lazy evaluation
- Customized priority queue
- Tolerance threshold

…

Validation

Validated by 72-day temperature measurement from Pohja network with 102 pipes

The average weighted mean error across 24 customers is 0.43 °C

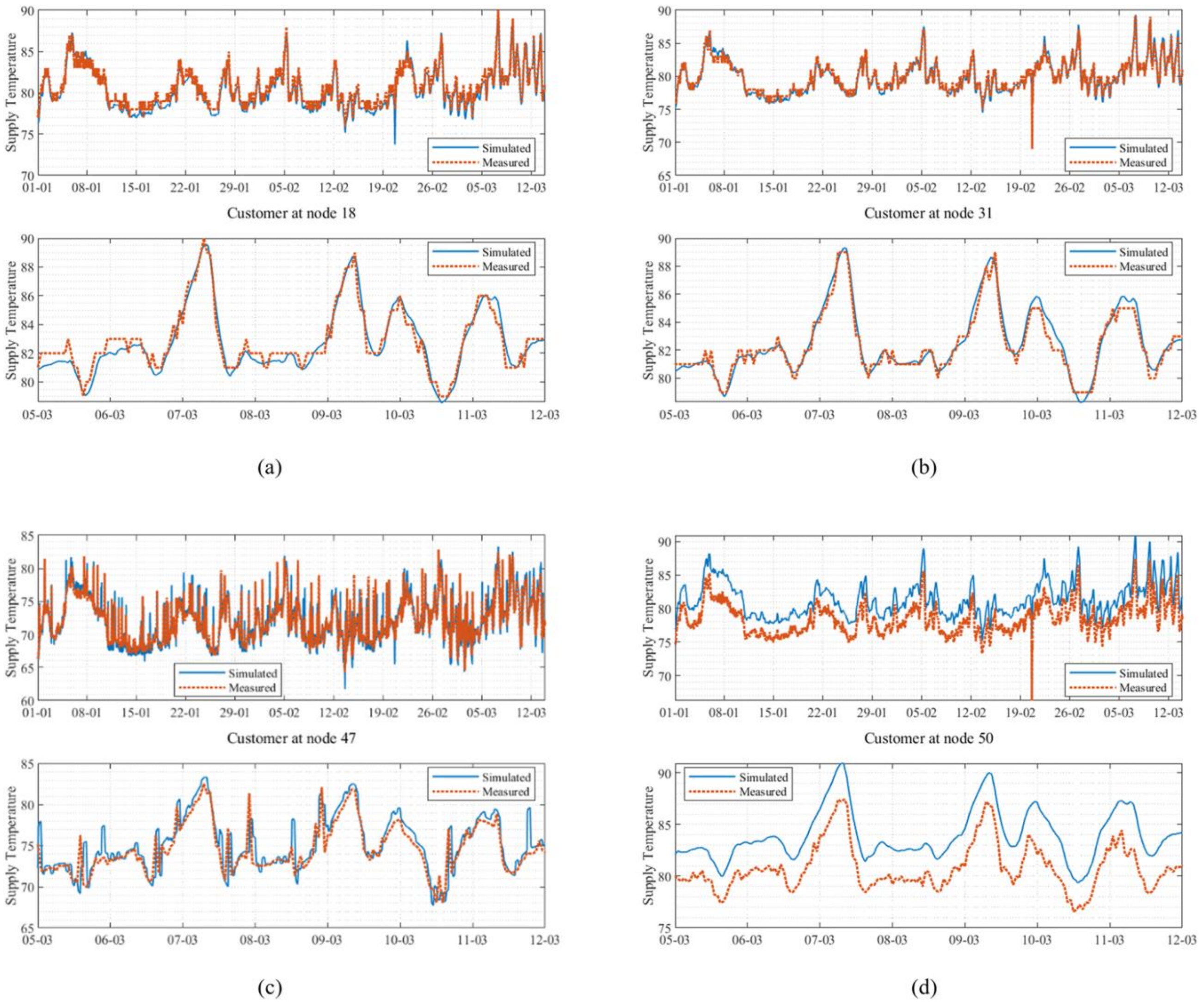


Figure 5 Comparison of measured and simulated temperatures at representative nodes

Computational speed

The computation time for 72-day simulation is 0.2 seconds on average over 100 tests

Simulation time increased linearly with the number of water frontiers

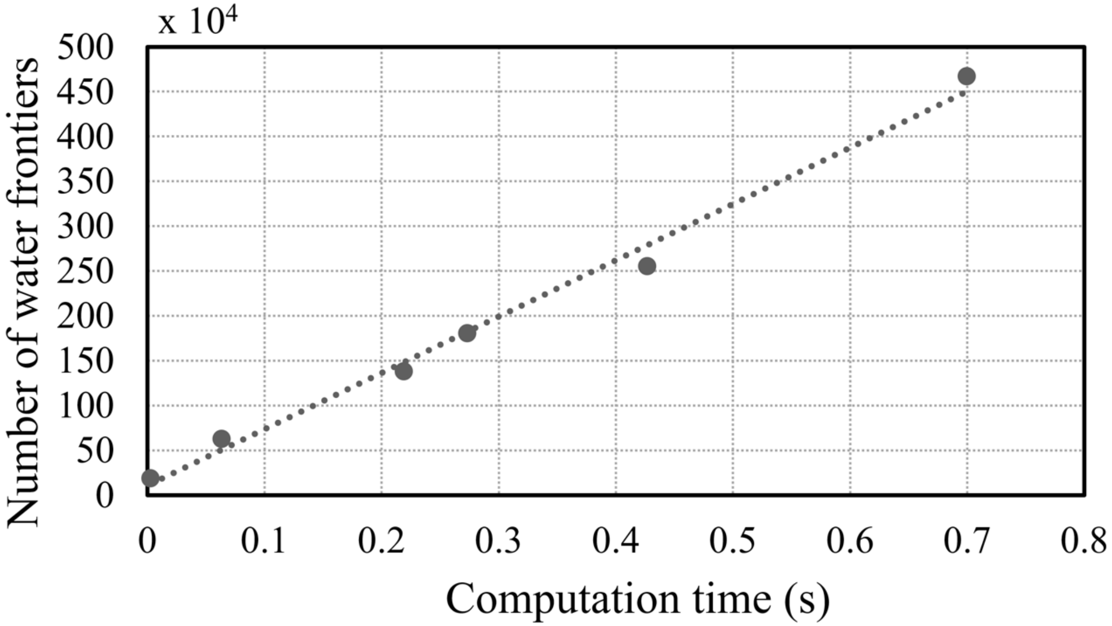


Figure 6 Relationship between the simulation time and number of water frontiers.

Limitations and future studies

1. This network model need to be extended to meshed network with multiple heating plants, including bidirectional flow and hydraulic simulation
2. Test computational speed with large-scale networks
3. Develop calibration methods
4. Integrate DES model into online optimization models for DH systems

Thank you !