# Comparing substation modelling approaches for dynamic district heating network building coupling

***Mazarine Roquet[a], Pierre Dewallef[b]***

[a] *University of Liège, Liège, Belgium, mazarine.roquet@uliege.be , CA*
[b] *University of Liège, Liège, Belgium, p.dewallef@uliege.be*

**Abstract:**
District heating networks are increasingly used to supply thermal energy at a district scale, offering significant flexibility in energy production and distribution. Their performance and reliability depend strongly on their ability to operate under transient conditions and respond to variations in user demand. Understanding this temporal behaviour is essential to accurately assess interactions with end users. In dynamic simulations of district energy systems, buildings are often represented by simplified thermal loads. Consequently, most existing models focus on energy balance at the network level while neglecting building thermal inertia and indoor comfort conditions. This paper presents a fully dynamic district heating network model coupled with detailed dynamic building models, developed in Dymola. The proposed framework enables the analysis of the entire system dynamics, from the energy plant through the distribution network to the indoor air temperature. By explicitly modelling building thermal behaviour, the approach goes beyond conventional load-based coupling and allows for the assessment of indoor thermal comfort. A particular focus is placed on substation modelling, the critical interface between primary and secondary circuits. Several modelling approaches are investigated to identify an optimal trade-off between physical accuracy and numerical robustness. A detailed reference model based on the $\epsilon$-NTU method is compared to a simplified approach assuming constant heat exchanger effectiveness to improve numerical stability. A small-scale comparative analysis evaluates the impact of the constant effectiveness assumption on thermal performance. Results show that, under certain operating conditions, this simplification has a limited influence on accuracy. The simplified model is then applied at a larger scale, demonstrating that dynamic coupling between a network and multiple buildings is numerically feasible and computationally efficient. Finally, this framework aligns with current trends in district energy systems, as it can accommodate various energy plants, different temperature levels, and both heating and cooling networks.

**Keywords:**
District Heating Network, Dynamic Simulation, Indoor Thermal Comfort, Integrated Building-Network Modelling, Substation Modelling.

# 1. Introduction

The district heating sector is currently undergoing a profound transformation, marked by a shift from traditional high-temperature systems, historically designed for heat distribution only, toward low-temperature networks that are more flexible when low-temperature heat sources have to be used. This evolution reflects a major change in urban energy management, where district heating systems are becoming key interfaces connecting multiple energy sources with buildings [1]. By operating at temperature levels closer to ambient conditions, these networks significantly reduce distribution losses. They also enable the efficient integration of low-grade renewable energy sources, such as geothermal and solar thermal, as well as industrial waste heat. As a result, low-temperature district heating networks are emerging as a crucial lever for advancing the energy transition in urban areas.

The viability of these low-temperature regimes depends on achieving low return temperatures, which are a key factor for improving both system efficiency and sustainability [2]. A reduced return temperature increases the temperature difference across the network, directly enhancing heat transfer efficiency while significantly lowering pumping requirements and pipe sizing. In addition, low return temperatures improve the performance of heat production units. However, achieving consistently low return temperatures remains challenging, as conventional control strategies, often based on outdoor temperature, do not fully account for end-user behaviour and substation performance, highlighting the need for more advanced, system-integrated control and modelling approaches. Addressing this need requires moving beyond static approaches toward fully dynamic modelling of district heating networks [3]. This involves capturing the thermal capacity of all key components – including pipes, fluid mass, substations and building structures – to accurately represent transport delays and thermal inertia [4, 5]. Precise modelling of heat demand is essential [6], and performance assessment must extend beyond energy consumption to include indoor thermal comfort as a central metric [7, 8]. Indoor temperature is influenced by multiple interacting factors, such as supply and return temperatures, heating system operation, building envelope properties, thermal inertia, internal heat gains, and solar radiation [9]. Altogether, these aspects highlight the need for integrated modelling approaches that simultaneously capture network dynamic, building behaviour, and user comfort.

Yet, few studies implement fully integrated approaches, exposing a gap in current research: most studies either simplify network dynamics or rely on aggregated building load profiles [10–15]. Aggregated load-based approaches fail to represent thermal inertia, demand peaks, and aggregation effects, and do not assess how network fluctuations affect end-users, often assuming that the network can fully meet building needs. As a result, potential issues such as thermal discomfort or hydraulic constraints remain unaddressed. Closing this gap requires modelling the network and buildings together in a fully dynamic framework, with the substation at the center of this interaction. The substation governs heat transfer between the network and the building and directly influences return temperatures [16]. The literature has compared various substations configurations [17, 18]. Physically detailed models, such as those based on the $\epsilon$-NTU or Logarithmic Mean Temperature Difference (LMTD) methods, capture off-design performance but introduce strong nonlinearities that can cause numerical instabilities and excessive CPU times when scaled to hundreds of buildings. Simplified approaches, assuming constant effectiveness, improve numerical robustness by linearizing heat transfer equations, but may overestimate pumping requirements and result in errors in predicting the required heating power and energy delivered to end-users. This trade-off between physical fidelity and computational efficiency motivates the present study, which compares variable and constant effectiveness substation models within a fully integrated building-to-network framework.

The novelty of this work lies in using indoor thermal comfort as the primary criterion for evaluating substation modelling approaches. The study employs a fully dynamic district heating network model directly coupled with physically detailed building models, allowing comprehensive analysis of the interactions between the network and end-users. It conducts a comparative evaluation of constant, versus variable, effectiveness substation models, assessing both physical performance - including mass flow rates, return temperatures, thermal load fulfilment, and occupant comfort - and numerical performance, such as solver stability and CPU time. By utilizing existing modelling blocks, this approach provides a replicable framework for supporting both the design and operation of district heating systems, and is applicable across networks with varying temperature levels, including low-temperature systems.

The paper is organized as follows. Section 2. describes the methodology and the technical characteristics of the models - network, buildings, and substations - as well as the case study and the scenarios. The results of the comparison are then analysed and discussed in Section 3..

# 2. Methodology

## 2.1. District heating network model and test case

The test case used in this study is an extension of the one proposed by [19], focusing on the Sart Tilman university campus in Belgium. Specifically, the network involves 10 buildings, with a total peak power of 9.8 MW and a total supply-and-return pipe length of 3.7 km. The configuration is shown in Fig. 1. The operating temperatures of the network are 60 ℃ for the supply and 40 ℃ for the return.

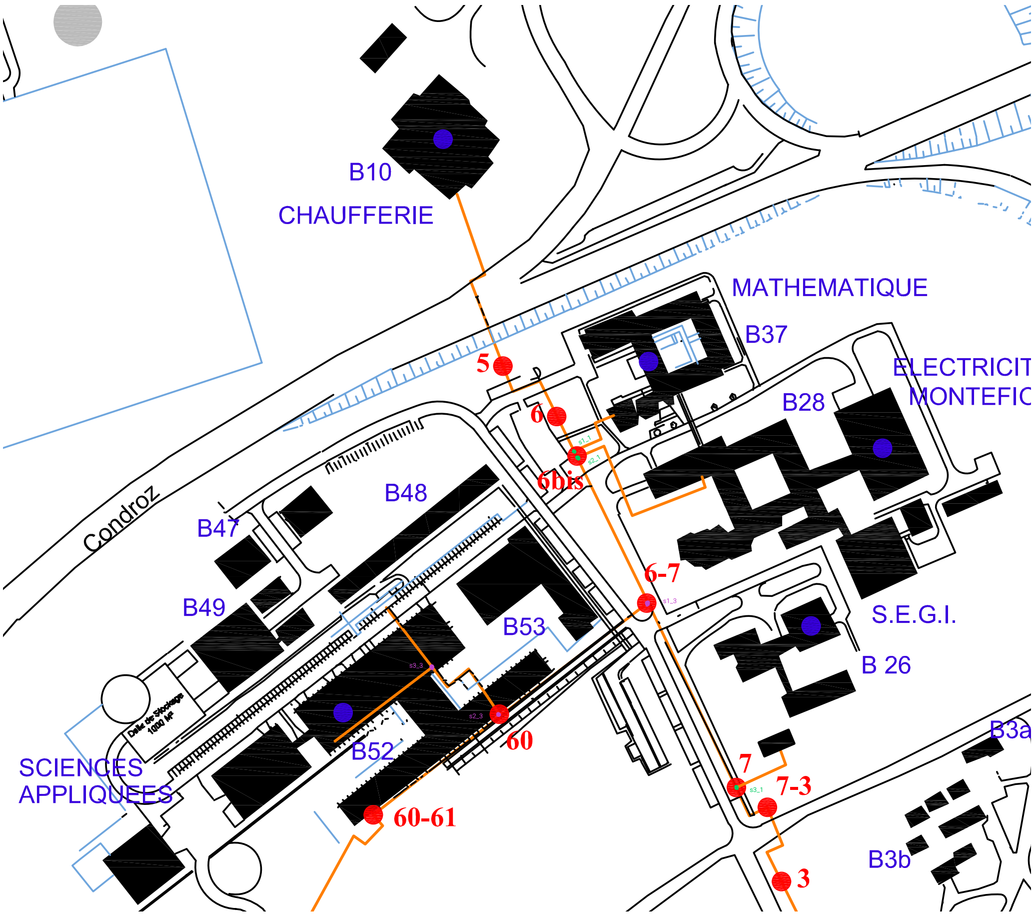



Figure 1: Map of the test case with the 10 considered buildings and the district pipes.

The integrated approach consists of a dynamic district heating network model fully coupled with dynamic building models, developed in the Dymola environment using the Modelica language. The global model includes a heat source, supply and return pipes, substations, a circulation pump, and a terminal bypass valve. Both the network and its components follow the methodology described in [19], while each user is represented by a dynamic building model as detailed in [20]. These buildings are parametrized using real-world data based on a digital twin from [21].

A key feature of this model is proposed decentralized control strategy, which is based on individual building return temperatures rather than the mix plant return temperature. This substation-level approach ensures that local heat demands are satisfied more effectively across the network. This approach allows for a precise assessment of energy consumption while ensuring that the heat supply matches demand to maintain a constant 20 °C setpoint.

## 2.2. Substation modelling approaches

The primary motivation for simplifying the substation model through a constant efficiency assumption is to mitigate numerical complexity. While variable efficiency models provide high fidelity, they can become computationally expensive, thereby limiting their scalability to large-scale building stocks. The study compares two heat transfer approaches within the substation, both based on the substation model presented [19] and illustrated in Fig. 2.

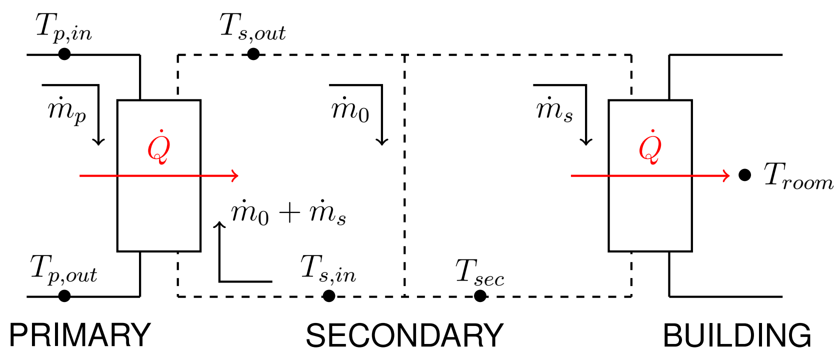



Figure 2: Diagram of the substation indicating various temperatures studied at the primary, secondary, and within the building. The diagram also includes representations of mass flow rates and exchanged power.

The first model employs variable effectiveness for the heat exchangers, where the value is recalculated at each time step using the $\epsilon$–NTU method. In contrast, the second model assumes a constant effectiveness $\epsilon$, fixed at nominal values (e.g., $0.8$ for the primary-to-secondary heat exchanger and $0.7$ for the radiator). This constant value is intentionally conservative to ensure that the actual heat exchange capacity is never overestimated.

## 2.3. Simulation scenarios

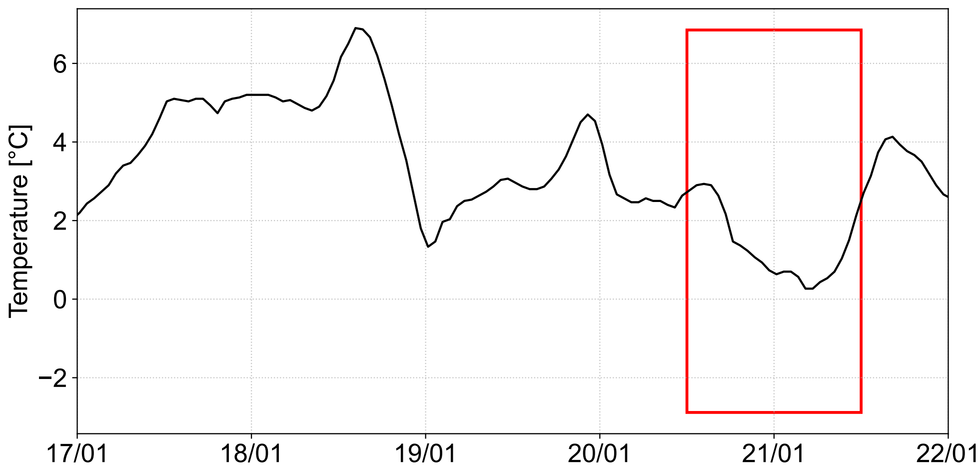
The physical analysis focuses on the potential errors introduced by the constant efficiency simplification. The objective is to assess whether the constant efficiency hypothesis can yield reliable and conservative results and to identify specific operational conditions where the hypothesis might lose accuracy.

The two models are compared over two representative periods of time: a winter week (January 17$^{th}$ to 21$^{st}$), with a mean outdoor temperature of 3.33 °C, and a mid-season week (April 18$^{th}$ to 22$^{nd}$), with a mean temperature of 12.8 °C. These periods cover Monday morning through Friday evening, as the university buildings are not heated during weekends. The temperature profiles for these two time frames are represented in Fig. 3. The boxed area in Fig. 3a identifies the day chosen for a more in-depth study of the network performance.

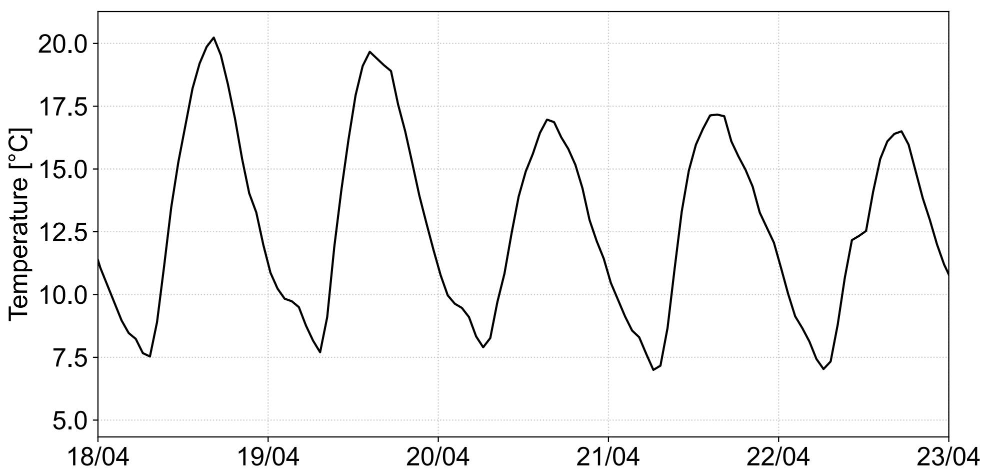
## 2.4. Performance indicators and numerical assessment

To ensure a comprehensive evaluation, the study is conducted for both the largest and the smallest consumer. The following performance indicators are evaluated for each typical week, comparing the results obtained with both variable and constant efficiency models:

- Return temperatures, both at the power plant and at the substation primary outlets;




(a) Winter week (January 17th to January 21st), average temperature over the week = 3.33℃.




(b) Mid-season week (April 18th to April 22nd), average temperature over the week = 12.8℃.

Figure 3: Outdoor temperature profiles for the two simulated weeks.

- Mass flow rates, specifically at the main primary circulation pump, to investigate whether it remains stable while meeting the thermal load;
- Transferred thermal load, to evaluate the accuracy of the heat exchange;
- Indoor temperatures, to ensure that the buildings' thermal comfort is maintained throughout the periods.

To quantify the divergence between the models, the Root Mean Square (RMS) errors are calculated for these different indicators:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{i,\text{var}} - y_{i,\text{const}})^2}$$

where $n$ is the number of simulation time steps, $y_{i,\text{var}}$ is the value from the variable efficiency model, and $y_{i,\text{const}}$ is the value from the constant efficiency model.

Following the physical validation, the numerical performance is compared based on two metrics: the CPU time, to evaluate computational speed, and the convergence of the model.

# 3. Results

The physical accuracy of the constant efficiency hypothesis is evaluated by comparing variable and constant efficiency models. This assessment is conducted for both the largest and smallest consumers across the cold and intermediate seasons. The resulting RMS errors for the various performance indicators are summarized in Tables 1 and 2. The 'Operating Range/Full Scale' column defines the reference scale for each indicator (representing either the expected variation range or the maximum nominal value). This reference column is essential for putting the absolute RMSE into perspective. By benchmarking the error against expected fluctuations or peak values, it allows for a better quantification of the impact of model simplification. The RMSE values remain below 5% of the operating range for the majority of the indicators, confirming the possibility to use a constant efficiency model instead of a variable one. The only significant outlier occurs for the smallest consumer's thermal load during the mid-season week, where the error reaches 45 kW, representing 73% of its nominal capacity.

Table 1: RMS errors and their reference scale for the different indicators over the winter week.

| | RMSE | Unit | Operating range/ Full scale |
|---|---|---|---|
| Mass flow rate at the central pump | 2.2 | kg/s | $\Delta$ 80 kg/s |
| Return temperature to the power plant | 0.2 | ℃ | $\Delta$ 20℃ |
| Largest consumer primary return temperature | 0.3 | ℃ | $\Delta$ 20℃ |
| Smallest consumer primary return temperature | 1.1 | ℃ | $\Delta$ 20℃ |
| Largest consumer exchanged thermal load | 2.5 | kW | $P_{nom}$ = 2410 kW |
| Smallest consumer exchanged thermal load | 1.1 | kW | $P_{nom}$ = 62 kW |

Table 2: RMS errors and their reference scale for the different indicators over the mid-season week.

| | RMSE | Unit | Operating range/ Full scale |
|---|---|---|---|
| Mass flow rate at the central pump | 0.1 | kg/s | $\Delta$ 80 kg/s |
| Return temperature to the power plant | 0.1 | ℃ | $\Delta$ 20℃ |
| Largest consumer primary return temperature | 0.1 | ℃ | $\Delta$ 20℃ |
| Smallest consumer primary return temperature | 0.2 | ℃ | $\Delta$ 20℃] |
| Largest consumer exchanged thermal load | 1.3 | kW | $P_{nom}$ = 2410 kW |
| Smallest consumer exchanged thermal load | 45 | kW | $P_{nom}$ = 62 kW |

A 24-hour focus during the cold period of time is presented in Fig. 4 and 5 to illustrate instances where the thermal load is imperfectly transferred. The objective is to evaluate the impact of these instances on the stability of the indoor temperature, which serves as the main performance indicator for the model comparison. These heat transfer gaps result from using a fixed efficiency value, which underestimates the actual heat exchanger performance during high-demand periods. This behaviour is particularly evident in Fig. 4, where the thermal load is not met during peak demand. This is due to the fixed efficiency of 0.8, which significantly underestimates the actual instantaneous performance, approaching 0.95, calculated by the $\epsilon$-NTU model. However, the primary objective of this study is to show that the constant efficiency model reliably represents network dynamics by accurately transmitting demand fluctuations to the central plant without compromising occupant thermal comfort. As shown in Fig. 4, the impact of underestimating the efficiency remains minimal. Due to the high thermal inertia of the buildings, indoor temperature deviations from the 20 ℃ setpoint are negligible. Furthermore, these periods of imperfect heat transfer are merely punctual and do not compromise the overall stability of the indoor climate.

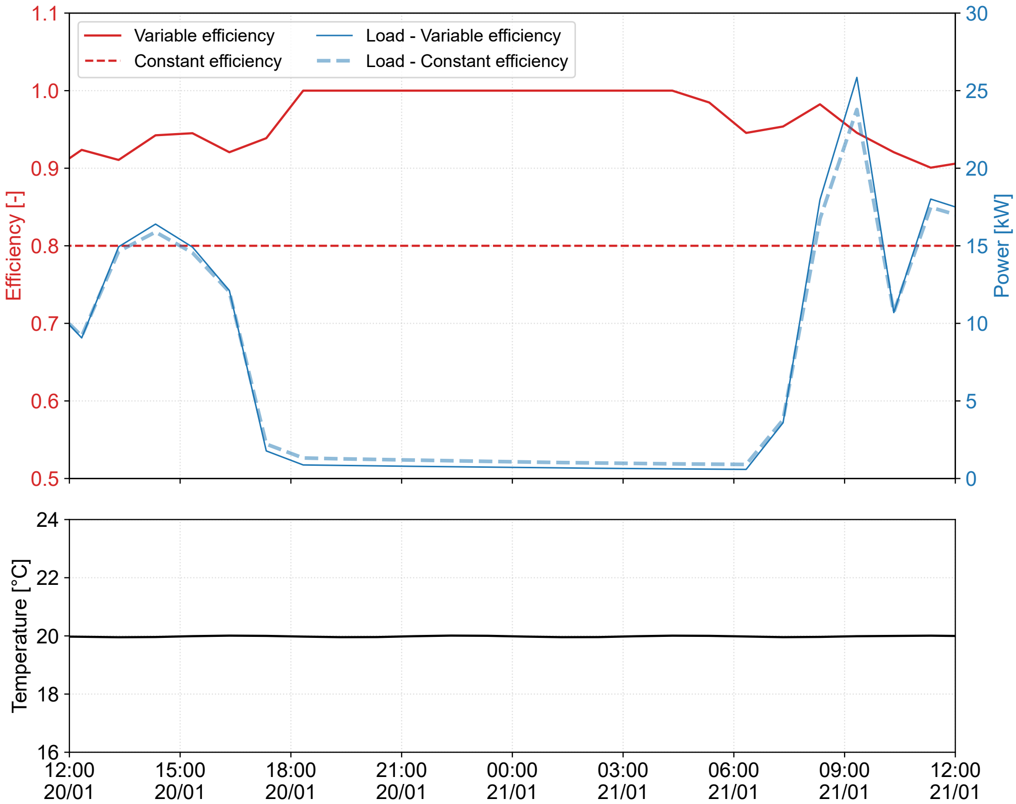



Figure 4: Impact of efficiency modelling on heat transfer and indoor thermal comfort for the smallest consumer.

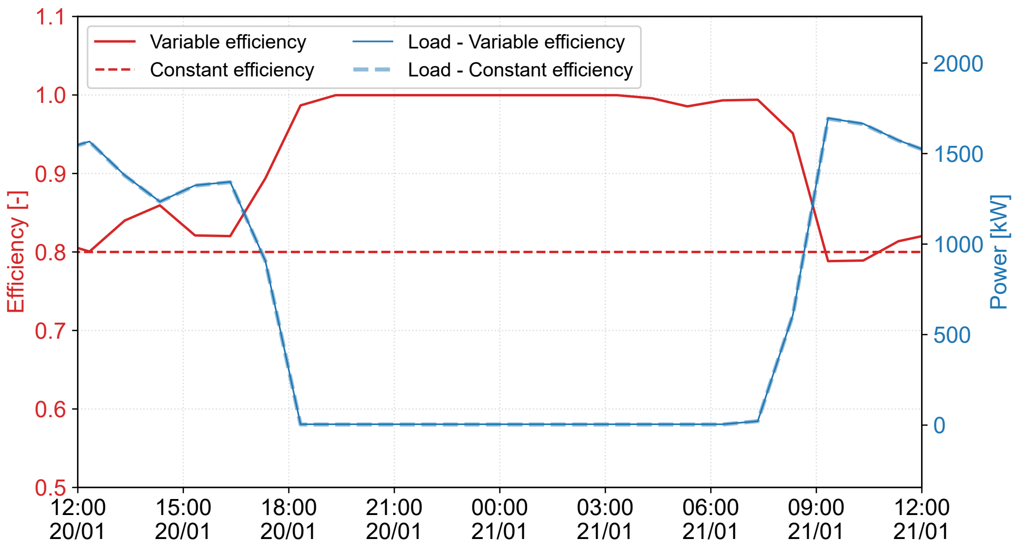



Figure 5: Impact of efficiency modelling on heat transfer for the largest consumer.

The choice of 0.8 for the fixed efficiency was made to remain conservative across all buildings in the network. Figure 5 confirms that this specific value is necessary if the constant efficiency must remain strictly lower than the instantaneous values calculated by the $\epsilon$-NTU method at all times. Figure 5 shows that this approximation is appropriate. The largest differences in efficiency values between the two models occur when heat consumption is near zero, meaning they have no real impact on the network's overall performance. The constant efficiency hypothesis is considered valid since the primary focus is on the overall network performance rather than the heat exchanger alone. This approach successfully captures essential system metrics, including return temperatures, mass flow rates, and total thermal loads. The only risk is an over-sizing of the heat exchanger during the design phase, a factor that could be mitigated by performing a standalone, high-fidelity exchanger analysis once the network requirements are established.

Beyond physical considerations, the constant efficiency hypothesis significantly enhances the numerical stability of the model. The variable efficiency model reaches its numerical limits when the network is expanded beyond 10 substations, failing to converge once an $11^{\text{th}}$ building are connected. By adopting the constant efficiency approach, the computational robustness is significantly enhanced, allowing the model to scale up to 37 buildings. This fulfils the objective of maintaining a stable yet precise network model. Additionally, the constant efficiency approach offers a reduction in computational cost. For example, during the winter week simulation, the CPU time is reduced from 866 seconds to 825 seconds. Future work will apply this approach to the entire campus to create a complete real-world test case. This will enable a global validation and provide the community with reusable models, filling a common gap in current literature [22].

# 4. Conclusion

This paper presents a fully integrated modelling framework coupling a dynamic district heating network with detailed building models. By shifting the control focus to the substation level and using indoor temperature as the primary metric, this approach allows for accurate forecasting of energy consumption and occupant comfort.

A core contribution of this study was the evaluation of the constant efficiency hypothesis for substations. A comparative analysis between the variable $\epsilon$-NTU model and the simplified constant effectiveness approach leads to several key findings. The physical validity of this hypothesis is demonstrated by the accurate results produced by the constant efficiency model. Efficiency deviations primarily occur during periods of near-zero demand, resulting in a negligible impact on global thermal performance. Regarding user comfort, despite slight underestimations of heat transfer during peak periods, due to the conservative 0.8 efficiency setting, indoor temperatures remained stable at the 20°C setpoint, thanks to the buildings' thermal inertia. In terms of numerical robustness, the simplification significantly enhanced numerical stability, allowing the model to scale from 10 to 37 buildings where the variable efficiency model failed to converge. This also resulted in reduced CPU time, making it suitable for large-scale applications.

In conclusion, the constant efficiency approach offers an optimal trade-off between physical fidelity and computational efficiency for system-wide studies. This framework provides a robust tool for assessing the performance of low-temperature networks while ensuring user comfort. Future work will focus on scaling up the number of buildings to reach a full-scale real-world test case. Validating the model at this campus-wide level will then provide a replicable district heating network model.

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